KLAIPĖDA UNIVERSITY

Gabriela de los Angeles ESCOBAR SANCHEZ

MACROLITTER IN COASTAL ZONES: AN ASSESSMENT OF MONITORING METHODS, POLLUTION SOURCES AND MITIGATION MEASURES ACROSS DIFFERENT GEOGRAPHICAL REGIONS

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KLAIPĖDOS UNIVERSITETAS

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MAKROŠIUKŠLĖS KRANTO ZONOJE: STEBĖSENOS METODŲ, TARŠOS ŠALTINIŲ IR TARŠOS MAŽINIMO PRIEMONIŲ VERTINIMAS SKIRTINGUOSE GEOGRAFINIUOSE REGIONUOSE

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Abstract

Single-use plastics are among the most common polluting items at coastal zones, and tourism and recreation are important pollution sources in different geographical regions. Having an understanding of emission quantities, pollution levels, common macrolitter items, transport dynamics and accumulation areas is crucial for developing effective management strategies to reduce plastic pollution. This thesis investigates plastic pollution from an integrated view of the coastal interface across three geographical regions, considering environmental, economic and socio-political contexts. The state of macrolitter pollution was investigated at highly polluted beaches of the southern Mediterranean addressing a main research gap in the region. Here a modified 10m transect method demonstrated to be sufficient to represent the litter abundance and characteristics with less effort, where the most common 25 macrolitter items (comprising 82% of the litter pollution) were found within five transects. Aerial drone experiments were tested for their potential for long-term beach litter monitoring in southern Baltic beaches, considering litter detection accuracy and cost-efficiency of long-term implementation. Litter detection was assessed using supervised object-based classification with three algorithms. Accuracy of classification at recovery experiments was high, however it decreased at 100 m beach transects across all algorithms, with kappa values ranging 0.11–0.64, indicating that classification was close to random. The cost-efficiency analysis revealed that drones share similar cost-efficiency as the OSPAR method and can be further explored as a complementary tool. Pathways of litter transport were assessed using a high-resolution (20 m) hydrodynamic model of the Warnow estuary (Rostock, Germany) coupled with particle tracking. The model results revealed that wind direction and estuary morphology are key factors influencing particle retention at microtidal systems. Following predominant southerly winds, only 0.4% of the emitted particles reached the estuary opening (ca. 11 km away from the emission point), indicating high retention and suggesting that estuaries may act as sinks of litter. Finally, mitigation measures for litter reduction were critically evaluated through a mixed-methods approach, across different geographical regions. The evaluation of six bio-based, biodegradable and compostable tableware materials as alternatives to single-use plastics revealed a discrepancy between policy ambitions and waste management realities, hindering effective treatment. Low disintegration rates were observed at an industrial composting site, where only polylactic acid (PLA) achieved complete disintegration. In contrast, in an estuarine environment, PLA and wood items were the only materials that did not disintegrate after one year of exposure, indicating that material disintegration cannot always be guaranteed. Public surveys showed high acceptance of alternative materials; however, perception is biased in favour of non-plastic substitutes and public knowledge on appropriate disposal is low, suggesting a high risk of littering behavior. To reduce beach litter, an evaluation of beach and tourism ecolabels revealed that only 24 ecolabels address beach litter (out of 142 tourism ecolabels) and among these, only two include over 50% of the 43 litter-reduction measures in their criteria. Most ecolabels failed to target common beach litter items or the most effective measures, as identified by stakeholders, lacked thresholds for acceptable pollution levels, nor did they prioritize direct and actionable practices for the tourism and recreation sector. Moreover, the ecolabels prioritized management actions (limited to the ecolabel´s validity period) over measurable outcomes, suggesting they are not effective to address plastic pollution in the long-term. This thesis provides new insights into the plastic pollution research, particularly regarding monitoring, transport pathways and management across the studied regions and provides recommendations for policy and management.

Keywords

High-pollution sites, Aerial drones, Tourism, Single-Use Plastics, Litter transport, Policies, Bio-based plastics, Ecolabels, Cross-regional analysis.

Reziumė

Vienkartiniai plastikiniai gaminiai yra vieni labiausiai paplitusių teršiančių objektų kranto zonose, o turizmas ir rekreacija yra svarbūs taršos šaltiniai skirtinguose geografiniuose regionuose. Supratimas apie išmetamų teršalų kiekius, taršos lygius, dažniausiai pasitaikančius makrošiukšlių objektus, jų pernašos dinamiką ir akumuliacijos vietas yra labai svarbus kuriant veiksmingas valdymo strategijas, skirtas mažinti taršą plastiko atliekomis. Šiame darbe tiriama taršos plastiku problema, integruojant sąveikas pakrantėje trijuose skirtinguose geografiniuose regionuose ir pateikiant problemos apžvalgą skirtingomis aplinkosaugos, ekonomikos ir socialinės politikos aplinkybėmis. Taršos makrošiukšlėmis būklė tirta labai užterštuose Pietų Viduržemio jūros pakrantės paplūdimiuose, siekiant užpildyti pagrindines tyrimų spragas regione. Čia modifikuotas 10 m transektų metodas pasirodė esąs pakankamas nustatyti šiukšlių charakteristikas mažesnėmis pastangomis, kadangi 25 dažniausiai aptinkami objektai, rasti penkiose 10 m transektose, sudarė 82 % nustatytos taršos. Taip pat atlikti eksperimentai su bepiločiais orlaiviais (UAV), siekiant įvertinti jų potencialą ilgalaikei makrošiukšlių stebėsenai Pietų Baltijos jūros pakrantėse, atsižvelgiant į šiukšlių aptikimo tikslumą ir ilgalaikio įgyvendinimo ekonomiškumą. Šiukšlių aptikimas įvertintas naudojant kontroliuojamą objektais paremtą klasifikacijos su trimis algoritmais metodą. Atgaunamo kiekio eksperimentų metu klasifikavimo tikslumas buvo didelis, tačiau visuose algoritmuose jis sumažėjo ties 100 m paplūdimio transektomis, o *kappa* vertės svyravo nuo 0,11 iki 0,64. Tai rodo, kad klasifikavimas buvo beveik atsitiktinis. Sąnaudų efektyvumo analizė parodė, kad bepiločiai orlaiviai pasižymi panašiu sąnaudų efektyvumu kaip ir OSPAR metodas, todėl juos galima toliau tirti kaip papildomą priemonę. Šiukšlių pernašos keliai įvertinti naudojant didelės skiriamosios gebos (20 m) Warnow estuarijos (Rostokas, Vokietija) hidrodinaminį modelį kartu su dalelių sekimu. Modelio rezultatai parodė, kad vėjo kryptis ir estuarijos morfologija yra pagrindiniai veiksniai, darantys įtaką dalelių kaupimuisi. Dėl vyraujančių pietinių vėjų tik 0,4 % išmestų dalelių pasiekė estuarijos žiotis (apie 11 km atstumu nuo išmetimo taško). Tai rodo didelį užsilaikymą ir leidžia manyti, kad estuarijos gali veikti kaip galutinės šiukšlių kaupimosi vietos. Galiausiai taikant mišrų metodą skirtinguose geografiniuose regionuose kritiškai įvertintos šiukšlinimo mažinimo priemonės. Šešių biologinės kilmės, biologiškai skaidžių ir kompostuojamų stalo reikmenų, kaip vienkartinių plastikinių gaminių pakaitalų, vertinimas atskleidė tarp politikos siekių ir atliekų tvarkymo realybės egzistuojantį neatitikimą, kuris trukdo šias medžiagas veiksmingai tvarkyti. Pramoninėje kompostavimo aikštelėje pastebėtas lėtas irimo greitis, kur tik polipieno rūgštis (PLA) suiro visiškai. Priešingai, estuarijų aplinkoje PLA ir medienos gaminiai buvo vienintelės medžiagos, kurios nesuiro po vienerių metų, ir tai rodo, kad medžiagų suirimas ne visada garantuotas. Visuomenės apklausos parodė didelį alternatyvių medžiagų pripažinimą, tačiau nuomonė į neplastikinių pakaitalų savybes yra nepagrįstai palanki, žinios apie tinkamą tvarkymą ribotos, o tai kelia didelę šiukšlinimo elgesio riziką. Įvertinus paplūdimių ir turizmo ekologinius ženklus, skirtus mažinti šiukšlinimą paplūdimiuose, paaiškėjo, kad iš 142 galimų ekologinių ženklų tik 24 skirti šiukšlinimui paplūdimiuose, o iš jų tik du į savo kriterijus įtraukia daugiau nei 50 % šiukšlinimo mažinimo priemonių. Dauguma ekologinių ženklų nebuvo skirti dažniausiai paplūdimiuose randamų šiukšlių rūšims ar veiksmingiausioms priemonėms, kurias nurodė suinteresuotos šalys, taip pat nebuvo teikta pirmenybė tiesioginei ir veiksmingai praktikai turizmo ir poilsio sektoriuje. Be to, ekologiniuose ženkluose trūko priimtinų taršos lygių ribinių verčių, o pirmenybė teikta ne išmatuotiems rezultatams, bet valdymo priemonėms, ribotoms ekologinio ženklo galiojimo laikotarpiu. Tai rodo, kad ekologiniai ženklai nėra veiksmingi kovojant su tarša plastiku. Šis darbas pateikia naujų įžvalgų apie taršos plastiku problemą, atsižvelgiant į stebėseną, pernašos kelius ir valdymą, pabrėžia makrošiukšlių tyrimų spragas tirtuose regionuose ir pateikia rekomendacijas dėl politikos ir valdymo.

Reikšmingi žodžiai

Didelės taršos vietos, bepiločiai orlaiviai, turizmas, vienkartiniai plastiko gaminiai, šiukšlių pernaša, politika, biologinės kilmės plastikas, ekologiniai ženklai, tarpregioninė analizė.

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II - Escobar-Sánchez, G., Haseler, M., Oppelt, N., Schernewski, G. (**2021**). Efficiency of Aerial Drones for Macrolitter Monitoring in Baltic Sea beaches (Published in ***Frontiers in Environmental Science,*** **IF: 3.7,** https://doi.org/10.3389/fenvs.2020.560237).
III - Schernewski, G., Escobar-Sánchez, G., Felsing, S., Gatel Rebours, M., Haseler, M., Hauk, R., Lange, X., Piehl, S. (**2024**). Emission, transport and deposition of marine macro-litter: The relevance of harbor festivals. (Published in ***Sustainability***, **IF: 3.3,** https://doi.org/10.3390/su16031220)
IV – Escobar-Sánchez, G., Robbe, E., Baccar Chabaane, A., Gatel Rebours, M., Schernewski, G. (**2025**). Replacing Single-Use Plastics (SUPs) in coastal festivals: A critical evaluation of biodegradable and compostable tableware, the role of policy and social perspectives (Published in ***International Journal of Environmental Research*****, IF: 3.5,** doi: https://doi.org/10.1007/s41742-025-00842-3).
V - Escobar-Sánchez, G., Weischedel, J., Robbe, E., Haseler, M., El Fels, L., Ben Abdallah, L., Hassan, G., M´hiri, F., Hense, P., Schernewski, G. Beach and tourism ecolabels: Can they effectively reduce beach litter? An assessment of ecolabel criteria, measures effectiveness and implementation challenges (Submitted to ***Discover Sustainability***, **IF: 3.0**, November 11th, 2025).

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Author´s contribution

I – G. Escobar-Sánchez supported in the methodology development, participated in the field work, counting and categorization of litter at Morocco, Tunisia and Egypt, supported data interpretation and contributed to the review and editing of the manuscript.
II – G. Escobar-Sánchez contributed to the conceptualization, developed the methodology, organized and carried out the fieldwork with UAV at beaches, carried out

image classification and data analysis with GIS, developed the visualization and led the manuscript writing, review and editing.
III – G. Escobar-Sánchez supported the conceptualization and methodology development, supported field sampling for floating litter during the *Hanse Sail*, supported calculations of waste generation/litter emissions from sailing festivals, and contributed to the review and editing of the manuscript. She also co-supervised student Margaux Gatel Rebours, who carried out data acquisition from sailing festivals around the Baltic and provided calculations on waste generation/litter emissions.
IV – G. Escobar-Sánchez led the conceptualization and methodology, carried out the literature revision for policy analysis and waste management concepts, organized and carried out the field work to estimate tableware waste at coastal festivals, carried out the disintegration experiments at the industrial composting site, adapted the first version of the online survey and collected data, carried out the data analysis, visualization and led the manuscript writing, review and editing.
V – G. Escobar-Sánchez led the conceptualization and methodology, participated in the field work in Morocco, Tunisia and Egypt, revised literature and acquired data on seasonal litter quantities, revised and updated the compilation of tourism ecolabels and the list of mitigation measures, carried out the data analysis, visualization and led the manuscript writing, review and editing. She also co-supervised student Juliet Weischedel who carried out the compilation and first analysis of ecolabels.

Additional papers by the author of the thesis

I – Escobar-Sánchez, G., Markfort, G., Berghald, M., Ritzenhofen, L., Schernewski, G. (**2022**). Aerial and underwater drones for marine litter monitoring in shallow coastal waters: factors influencing item detection and cost-efficiency (Published in ***Environmental Monitoring and Assessment,*** **IF: 3.0**, https://doi.org/10.1007/s10661-022-10519-5)
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Perez, J.P., Nelms, S.E., Ortiz-Alvarez, C., Porter, A., Thiel, M., Galloway, T.S. (**2024**). Plastic pollution transcends marine protected area boundaries in the eastern tropical and south-eastern Pacific (Published in ***Marine Pollution Bulletin*****,** **IF: 4.9**, https://doi.org/10.1016/j.marpolbul.2024.116271)

IV – Schernewski, G., Escobar-Sánchez, G., Wandersee, P., Lange, X., Haseler, M., Nassour, A. (**2023**). Marine Macro-Litter (Plastic) Pollution of German and North African Marina and City-Port Sea Floors (Published in ***Applied Sciences***, **IF: 2.5,** https://doi.org/10.3390/app132011424).

V – Schumacher, J., Horn, D., Escobar-Sánchez, G., Markfort, G., Schernewski, G., von Weber, M. (**2024**) Assessing macrophyte habitat and ecosystem service changes in shallow eutrophic coastal waters using remote sensing methods (Published to ***Land***, **IF: 3.2**, https://doi.org/10.3390/land14010004)

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VII – De Ramos, B., Escobar-Sánchez, G., González-Fernández, D., Gräwe, U., Lange, X., Schernewski, G. Floating macro-plastics retention in Baltic semi-enclosed coastal systems: A model study under different wind conditions. (Submitted to ***Current Research in Environmental Sustainability*****, IF: 3.8**)

Abbreviations

AI	Artificial Intelligence
BAU	Business as usual
C	Cardboard
CC	Coated Cardboard
CCI	Clean Coast Index
CDLB	Científicos de la Basura
CMOS	Complementary Metal-Oxide-Semiconductor sensor
CNN	Convolutional Neural Networks
COP	Circular Ocean-bound Plastic project
COVID-19	Coronavirus Disease 2019
CV	Coefficient of Variation
EC	European Commission
EMODNET	European Marine Observation and Data Network
EN	European Norm
EPR	Extended Producer Responsibility
EU	European Union
FOV	Field of View
GAMM	Generalized Additive Mixed Models
GDP	Gross Domestic Product
GES	Good Environmental Status
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GETM	General Estuarine Transport Model
GOTM	General Ocean Turbulence Model
GPA	Global Programme of Action for the Protection of the Marine Environment from Land-based Activities
GPML	Global Partnership on Plastic Pollution and Marine Litter
GPS	Global Positioning System
GSD	Ground Sampling Distance
GSTC	Global Sustainable Tourism Council
HELCOM	Helsinki Commission – Baltic Marine Environment Protection Commission
HORECA	Hotels, Restaurants and Catering
IBQI	Integrated Beach Quality Index
ICES	International Council for the Exploration of the Sea
ID	Identity Digit
IMAP	Integrated Monitoring and Assessment Program
IMDOS	Integrated Marine Debris Observing System
IMO	International Maritime Organization
INC	Intergovernmental Negotiating Committee
IOC	Intergovernmental Oceanographic Commission
ISO	International Organization for Standardization
JRC	Joint Research Center
LCA	Life Cycle Assessment

LMICs	Low- and Middle-Income Countries
MAP	Mediterranean Action Plan
MARPOL	International Convention for the Prevention of Pollution from Ships
MCA	Multi-Criteria Analysis
ML	Maximum Likelihood
MLRP	Regional Plan for the Marine Litter Management in the Mediterranean
MSFD	Marine Strategy Framework Directive
NABU	Naturschutzbund Deutschland
NGO	Non-governmental Organization
NIR	Near-Infrared
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PA	Producer´s Accuracy
PBAE	Programa Bandera Azul Ecológica
PE	Polyethylene
PET	Polyethylene Terephthalate
PL	Palm leaves
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PSU	Practical salinity unit
RF	Random Forest
RGB	Red-Green-Blue spectrum
rPS	Recycled Polystyrene
SC	Sugar cane
SCU	Sugar cane unbleached
SDG	Sustainable Development Goals
SE	Standard Error
SUP	Single-Use Plastic
SVM	Support Vector Machine
TA	Total Accuracy
TouMaLi	Tourism Marine Litter project
UA	User´s Accuracy
UAV	Uncrewed Aerial Vehicle
UBA	Umweltbundesamt
UNEP	United Nations Environmental Programme
VIS	Visible range from electromagnetic spectrum
W	Wood
WTO	World Tourism Organization
WTTC	World Travel and Tourism Council

1

Introduction

The pollution of seas and coasts with marine litter, especially plastics, is a growing global problem (UNEP, 2019). Marine litter is defined as any persistent solid material entering the marine and coastal environment deliberately or accidentally (UNEP, 2005), including plastics, paper, metal, glass/ceramics, wood, rubber or textile (Fleet et al., 2021). Plastics represent the dominant and most problematic material constituting up to 99% of marine litter on shorelines, sea surface or seafloor (Galgani et al., 2015). Industrialization, overconsumption and throw-away habits have led to a massive reliance and thereby an increase in plastic production (Andrady and Neal, 2009). In 2023, 413 million tonnes of plastics were produced globally (Plastics Europe, 2025), in contrast to only 2 million tonnes in 1950. Plastic production has even doubled in the last two decades (Geyer et al., 2017), which has led researchers to claim them as an indicator for the start of the Anthropocene (Rangel-Buitrago et al., 2022). The short lifetime of plastics is a major problem. About 40% of plastics production is aimed for packaging (Plastics Europe, 2023), having a lifespan of less than a year between production and disposal (Geyer et al., 2017). Because of increasing production trends, plastic durability, overconsumption, throw-away habits, harmful additives (Wagner et al., 2024) and incompatible waste management systems, plastics (especially single-use) have become major pollutants of concern and a pressure in coastal and marine environments globally (Hardesty et al., 2021).

Marine litter and plastic pollution have been extensively studied, providing a solid foundation on the state of the problematic regarding abundances and distribution (Galgani et al., 2015), sources and composition (Morales-Caselles et al., 2021), transport pathways (Maximenko et al., 2012; Chassignet et al., 2021) and sinks (Eriksen et al., 2014, 2023; Pham et al., 2014). Sources of pollution, defined as the economic sector or the activity that originated the litter item, can be land-based or sea-based. Land-based sources include recreation and tourism, mismanaged waste from dumpsites or landfills, and general consumption; while sea-based sources include fisheries (recreational and industrial), aquaculture, shipping and offshore industry (Veiga et al., 2016). Population density along the coast and the quality of waste management infrastructure are key factors determining the leakage of waste from land-based sources into the marine environment. Between 3.1–12.7 million tonnes of mismanaged plastic waste are estimated to enter the ocean annually from coastal populations (Jambeck et al., 2015; Lebreton and Andrady, 2019), a value that could triple by 2060 (Lebreton and Andrady, 2019). With 25% of the world´s population living within 50 km of the coast, showing a faster growth rate than inland (Cosby et al., 2024), coastal zones and the processes occurring at the land-sea interface represent a critical area for waste leakage. Sixteen from the top 20 countries with highest levels of mismanaged plastic waste are low- and middle-income countries (LMICs) (Jambeck et al., 2015), which are also countries that have significantly grown in the past 30 years (Barragán and de Andrés, 2015). Consequently, these regions, particularly Africa, Asia and Latin America, require greater research attention to improve assessments of litter abundances, emissions, pathways and management measures.

Besides population density, economic activities also contribute to litter pollution. Coastal tourism represents 40–52% of the global tourism sector (WTTC, 2025). International and domestic tourism generate a total of 35 million tonnes of solid waste globally per year (UNEP and WTO, 2012). Waste that, in many cases, cannot be handled at touristic sites (Wilson and Verlis, 2017; Garcés-Ordóñez et al., 2020; Grelaud and Ziveri, 2020). Thus, the tourism and recreation sectors are responsible for and affected by litter pollution. The Mediterranean Sea attracts almost a third of global international tourists (Plan Bleu, 2022) and is one of the most polluted seas (Prevenios et al., 2017; Vlachogianni et al., 2020). Similarly, in the Baltic Sea, tourism and recreation are predominant sources of beach litter (Schernewski et al., 2017). In the East Pacific coast of Latin America, tourism has experienced a rapid increase in visitor arrivals since 2005 (World Bank, 2023) and together with local recreation, is an important source of macrolitter at shorelines (Honorato-Zimmer et al., 2024). High litter abundances on beaches can lead to tourism revenue loss, through the direct loss of tourist numbers, loss of aesthetic value, negative publicity or increased costs incurred for cleaning (Mouat et al., 2010), which are estimated at 3,083–55,000 Euro per km of beach in Europe (Werner et al., 2016). Thus, touristic coastal sites are key areas of macrolitter generation and accumulation, and should be prioritized in the implementation of management measures.

Beaches are not the only sites for litter accumulation; litter and plastics can be transported from land to the sea through rainfall and urban run-off, rivers, sewage and rainwater outflows, wind, currents and tides (Veiga et al., 2016; Van Sebille et al., 2020), reaching rivers and estuaries and accumulating over long periods of time (Tramoy et al., 2020b; van Emmerik et al., 2022). While various studies assess litter transport and accumulation in the open ocean (Kaandorp et al., 2020; Chassignet et al., 2021; Onink et al., 2021), nearshore coastal dynamics driving litter transport have been less addressed. It is estimated that 91% of mismanaged plastic waste is discarded in large watersheds away from the coastline (Lebreton and Andrady, 2019), and that over 1000 rivers are responsible for 80% of river emissions into the ocean (Meijer et al., 2021), suggesting that rivers can act as pathways transporting waste from inland toward the coast and into the sea. However, once litter reaches rivers or estuaries, processes like tidal cycles (Schreyers et al., 2024), storms (Ramos et al. in review), and interaction with coastal vegetation and artificial structures (Tramoy et al., 2020a; Ledieu et al., 2022) cause litter trapping, deposition or remobilization.

Plastic transport models for the southern Baltic Sea have shown that macrolitter from touristic beaches accumulated back at the shores within days (Schernewski et al., 2017). Similarly, research at the Mediterranean Sea suggests that 54% of plastics coming from the coastal population is beached while 45% sinks to the seafloor (Kaandorp et al., 2020). In the East Pacific, the eastern boundary current plays an important role in litter accumulation at the shoreline, especially in North and South America, where the California Current and the Humboldt Current transport litter in on-shore direction (Honorato-Zimmer et al., 2024). However, current hydrodynamic models struggle to accurately resolve the fine-scale processes taking place in coastal and estuarine systems, leaving important knowledge gaps on coastal retention and redistribution. In this sense, rivers and estuaries may serve as temporary or permanent sinks that need to be further researched to assess their role in emission and transport to refine litter budgets.

Like this, coastal areas not only act as emission sources but also as major accumulation zones, emphasizing the importance to target monitoring and management at the land-sea interface. Anthropogenic litter can be found in different sizes, classified as nano (<1μm), micro (<5mm), meso (5-25mm) and macro (>25mm) (GESAMP, 2019). Macrolitter, due to its mostly intact shape, allows for an easier identification of pollution sources to derive management measures, which is more cost-effective than targeting microplastics. Beach litter monitoring by naked-eye is a simple technique for the assessment of macrolitter abundance (GESAMP, 2019). However, inconsistencies in monitoring protocols used across regions limit data comparability. For example, litter abundances in the Baltic and the Mediterranean are reported in linear units, per 100 m of beach, following the UNEP/IOC (2009) or OSPAR guidelines (2010), while in the East Pacific they are reported as items per unit area (following the method from *Científicos de la Basura*, Bravo et al., 2009). Although conversion between these units is possible, such conversions introduce additional uncertainty and reduce the reliability of cross-regional comparisons. Furthermore, litter classification lists and their level of detail differ by region, hindering harmonized analyses (Serra-Gonçalves et al., 2019; Haarr et al., 2022; Zielinski et al., 2022).

To address these discrepancies, the "Joint List of Litter" developed by Fleet et al., (2021) was adopted within the EU Marine Strategy Framework Directive to assess common materials and litter items in the European Seas, facilitating harmonization and comparability. In combination with an expert-based likelihood assessment, such as the Tudor Matrix (Tudor & Williams, 2006), potential pollution sources can be derived. Using such framework adapted for other regions would be beneficial. Monitoring in the East Pacific relies on a citizen science initiative with schoolchildren, using a simple litter categorization of only six classes (Bravo et al., 2009). While this approach is valuable for educational purposes and long-term engagement, it limits litter categorization and thereby the assessment of pollution sources and the development of effective mitigation measures to decrease predominant polluting items. Monitoring methods must, therefore, be scientifically robust, comparable, transferable and cost-efficient, and capable of informing management decisions and evaluate their effectiveness (JRC, 2013). Consequently, there is an urgent need to evaluate the applicability and cost-efficiency of alternative innovative technologies, such as uncrewed aerial vehicles (UAVs), commonly known as aerial drones, to target large pollution hotspots, obtain high temporal and spatial resolution, and generate consistent and comparable datasets across regions. UAV-based monitoring offers an opportunity to move from simple records of amounts, large-scale distribution and composition of litter, to record additional spatial information to better understand small-scale distribution, pollution sources, transport pathways, accumulation hotspots, and sinks at both beaches and coastal waters, while minimizing effort. Various studies have demonstrated the potential of UAVs for rapid litter assessment and mapping at beaches and surface waters, as reviewed in Kako et al. (2026). Still, the environmental requirements, limitations and cost-efficiency of UAVs as monitoring tools have received little attention, and a thorough discussion of these factors is essential for their effective implementation in monitoring programs.

Due to the variety of impacts that litter causes to marine species, their habitat (Kühn et al., 2015) and local economies (Newman et al., 2015), marine litter has been a priority for science and policy in the past decades. Global policies include the International Convention for the Prevention of Marine Pollution from Ships, 1973 (MARPOL 73/78) and its revised Annex V, the Regional Seas Programme, the Global Programme of Action for the Protection of the Marine Environment from Land-based

Activities (GPA) and the Global Partnership on Marine Litter (GPML), the Agenda 2030 and the Sustainable Development Goals (SDG), and the IMO Action Plan to Address Marine Plastic Litter from Ships (IMO) (Ryan, 2015). These initiatives act on voluntary or legally-binding basis to monitor and avoid marine litter pollution at beaches and sea. Most recently, the International Plastic Treaty (UNEP, 2025) shall regulate plastic production and its entire life-cycle on a legally binding basis with the aim to reduce marine litter and its impacts to the environment. While it is a promising step, negotiations over the past three years have not yet reached consensus. In the meantime, high impact and low effort litter reduction measures are required.

Coastal sites are areas where management measures could have the strongest impact, since they would target plastics and litter at-source before they enter the marine environment. To appropriately address macrolitter pollution and efficiently use public funding, management measures should be informed by research. These can be classified into preventative, mitigating, removal and behavior-changing measures (Chen, 2015). Few studies have revised existing management measures to reduce plastic pollution (Löhr et al., 2017; Agamuthu et al., 2019; Williams and Rangel-Buitrago, 2019; Schmaltz et al., 2020; Winterstetter et al., 2021) and even fewer have discussed their cost-efficiency and effectiveness (Willis et al., 2018; Urbina et al., 2020; Bellou et al., 2021; Nikiema and Asiedu, 2022). Therefore, more research is needed to critically evaluate measures effectiveness to reduce litter in the long-term, under different geographical contexts, considering factors like level of tourism, material consumption, socio-economic conditions, availability of infrastructure, and policy implementation, which influence their success.

Hotspots of pollution (i.e., accumulation areas) such as beaches and estuaries, during specific events, can serve as interesting case studies to assess the effectiveness of measures over a reduced space and time. Coastal festivals attract a large number of visitors over a short period and thus are subject to high waste generation (Gomes et al., 2007; Mateu-Sbert et al., 2013; Abdulredha et al., 2018). Due to their closeness to the sea, festivals can be emission points of litter if appropriate waste management practices are not implemented. For example, the reduction of single-use plastic tableware is currently sought in Europe after the implementation of the EU Single-Use Plastic Directive (EU/2019/904), and while studies have assessed the potential of new bio-based materials to replace SUPs (Carina et al., 2021; Rosenboom et al., 2022; Yap et al., 2023), fewer studies have critically evaluated their implementation effectiveness in regards to disposal and infrastructural requirements, public awareness and acceptance (Filho et al., 2022), or environmental impact (Van Roijen and Miller, 2022; Bouma et al., 2024). These aspects are crucial to avoid the introduction of new polluting materials. Since SUPs are aimed to be reduced worldwide, more research is needed to evaluate alternative materials, with special focus on geographical regions with highest pressure where waste management infrastructure is still largely lacking (Löhr et al., 2017).

Policy implementation and enforcement, and the lack of infrastructure are, in fact, common problems hindering waste management and the reduction of litter, especially in low- and middle-income countries (LMICs). Beach and tourism ecolabels, also known as awards or certifications, provide a "quality symbol" to recognize sustainable efforts in the tourism sector (Botero, 2019) and have often been suggested as tools to promote the sustainable management of beaches (Zielinski and Botero, 2015; Botero, 2019). However, ecolabel effectiveness specifically regarding beach litter reduction has not been well studied. Given the growth of coastal tourism, population growth at the coastal zone, and the increasing waste generation, it becomes relevant to assess mitigation measures involving the private sector, particularly in countries with weak policy enforcement, where ecolabels could serve to raise public awareness, bring litter management to the political agenda, and reduce public expenditure.

Against this background, this thesis addresses the problem of plastic pollution from an integrated view of the coastal interface, focusing on the land-based source tourism and recreation, and single-use plastics as the major polluting items affecting coasts worldwide, thereby contributing to the plastic pollution research assessing innovative monitoring technologies, transport pathways and critically evaluating management measures across different geographical regions.

1.1. Aim and objectives

The aim of this thesis is to quantify and characterize macrolitter pollution at touristic coastal sites using innovative monitoring methods, identify litter transport pathways from land to sea, and evaluate the effectiveness of management measures to reduce macrolitter in different geographical regions. The following objectives were raised:

1. To quantify beach macrolitter abundance using modified survey methods to address highly polluted beaches, and to identify predominant litter items and main pollution sources (Paper I).
2. To evaluate the applicability, transferability and cost-efficiency of aerial drones for long-term beach macrolitter monitoring, and to determine environmental and technological factors influencing item detection on sandy beaches (Paper II).
3. To estimate macrolitter emissions from coastal festivals and to analyze transport pathways and accumulation patterns within an estuarine system (Paper III).
4. To critically evaluate mitigation measures for macrolitter reduction at touristic coastal sites, assessing their effectiveness in targeting predominant litter items, and develop recommendations for improvement (Papers IV and V).

1.2. Novelty of the research

This thesis moves beyond conventional plastic pollution assessments towards innovative monitoring technologies and the critical evaluation of mitigation measures, therefore encompassing the plastic pollution problem from land-to-sea in a holistic manner. A variety of methods for macrolitter pollution monitoring were used to quantify abundances and identify sources and transport pathways in different geographical regions, and management measures were critically evaluated in terms of their applicability and effectiveness.

The first cross-country beach macrolitter survey was conducted along the southern Mediterranean coast (Morocco, Tunisia and Egypt), where monitoring data was lacking. Detailed item categorization enabled pollution source identification with local experts. The UNEP/IOC 100 m transect method was adapted into a faster 10 m transect approach, increasing efficiency at highly polluted beaches while maintaining broad spatial coverage and low survey time.

A UAV-based study for beach macrolitter monitoring was among the first studies to test consumer-grade drones for detection of meso- (1–25 mm) and macrolitter (> 25 mm) on sandy beaches. A cost-efficiency analysis, considering the cost and effort (time) required for the implementation of drones for long-term monitoring was assessed, where aspects of accuracy, reproducibility, flexibility and quality were evaluated by three experts. For the thesis, an updated analysis was conducted supported by recent literature on drone technology and image analyses advances.

A novel application of a high resolution (20 m) physical hydrodynamic model coupled with a Lagrangian particle tracking was used to simulate plastic transport in complex estuarine systems, considering artificial structures and vegetation which influence litter retention. Land-to-estuary emissions (i.e., emission scenarios) from coastal festivals were estimated using different methods to sample floating litter at the Warnow estuary (details in section 2.4) and extrapolated to other 50 events taking place at the Baltic Sea based on number of visitors. Estuary-to-sea transport was assessed with a Lagrangian particle tracking to assess retention and transport potential of virtual particles. The results showed estuaries can act as litter sinks, revealing the need to consider plastic retention in rivers and estuaries to improve emission estimations of plastic into the open ocean.

Two mitigation measures implemented at touristic coasts were critically evaluated: replacing single-use plastics (SUPs) with bio-based, biodegradable and compostable alternatives at coastal festivals, and beach and tourism ecolabels to reduce common litter items at beaches. These studies are some of the first to provide a comprehensive evaluation of measures to reduce plastic pollution, encompassing revision of policies and regulations, assessment of social perception and awareness, experiments on material disintegration in real environments, evaluation of effort (time and costs) and effectiveness from a stakeholder perspective, as well as implementation challenges across different geographical regions.

Finally, research was conducted in regions with distinct socio-economic contexts—the southern Baltic (Europe), southern Mediterranean (North Africa) and the Chilean (South America) coast. Litter abundances, predominant litter items, pathways and sources were compared between the regions, discussing the transferability of monitoring methods and mitigation measures and highlighting remaining research gaps.

1.3. Scientific and applied significance of the results

The thesis explored new methods for monitoring at beaches, assessed macrolitter abundances, pollution sources, and transport pathways at different regions, and evaluated the applicability and effectiveness of mitigation measures from a global perspective.

Cross-country monitoring along the southern Mediterranean coast (North Africa) closed knowledge gaps on macrolitter abundance and distribution. The adapted method can be applied by local researchers and the experiences were used to delineate a long-term beach macrolitter monitoring plan for the region. Results showed higher pollution on urban and touristic beaches, mainly from shoreline activities and poor waste management. The data can guide practitioners to implement measures targeting these pollution sources, meet the Mediterranean threshold values establish by IMAP, and assess whether southern Mediterranean countries require region-specific thresholds.

The UAV study demonstrated the potential of consumer-grade drones for beach litter detection. Tests in recovery experiments and transects highlighted strengths and weaknesses of mapping and classification, offering guidance for future development. Due to relatively clean Baltic beaches with smaller litter items, drones were not considered for long-term monitoring there. However, the methodological results and cost-efficiency analysis are transferable, and the updated assessment provides new perspectives considering recent image analyses and technological advances, suggesting that aerial drones share similar cost-efficiency as the OSPAR method, and thus can be considered at highly polluted sites around the world to detect pollution hotspots and complement current methods.

The contribution of coastal festivals as sources of plastic pollution was assessed for the Baltic Sea, using the *Hanse Sail* festival (Rostock, Germany) as a case study, with results extrapolated to 50 Baltic coastal festivals. Very low land-to-estuary emissions were observed. The high resolution (20 m) physical hydrodynamic model coupled with a Lagrangian particle tracking gave insights into estuary-to-sea transport and accumulation, revealing negligible transport and high accumulation in reed belts, usually excluded from surveys. The study highlighted the need for further research in estuary transport dynamics to improve plastic emission estimations from land to the sea, and the need to address aspects like particle size, shape and buoyancy, as well as processes like windage, sinking and remobilization, which are key to determine particle deposition and resuspension.

The tourism and recreation source were addressed through the critical evaluation of mitigation measures to address single-use plastics. The study on replacing single-use plastic tableware with bio-based, biodegradable or compostable alternatives, in Rostock (Germany), Klaipeda (Lithuania), Hammamet (Tunisia) and La Serena (Chile), showed that none of the cities had adequate infrastructure to handle these materials, highlighting a mismatch with policy goals. Public knowledge of item disintegration and correct disposal was also limited. Results indicate that poorly managed alternatives can still contribute to litter. The study on beach and tourism ecolabel for beach litter reduction revealed that ecolabels are currently ineffective, with only two addressing over 50% of effective litter reduction measures. Our recommendations include adapting ecolabels to local contexts, integrating effective measures, aligning litter thresholds with international policy and emphasizing ecosystem protection. A list of ecolabels as well as mapped beaches and hotels with beach access (with and without ecolabels) was made available in Zenodo for future studies.

1.4. Scientific approval

The results of this study were presented at 6 international conferences.

- Escobar-Sánchez, G., Robbe, E., Baccar-Chaabane, A., Gatel Rebours, M., Schernewski, G. Mitigation measures for macroplastics in coastal zones: a critical assessment of biodegradable materials. LITTORAL Conference, Costa da Caparica, 12-16 Sept 2022 (in person).
- Haseler, M., Escobar-Sánchez, G. Monitoring and mitigation measures. TouMaLi Conference Marrakesh, Morocco, November 8-9th, 2023 (in person).
- Escobar-Sánchez, G., Weischedel, J., Robbe, E., Haseler, M., El Fels, L., Ben Abdallah, L., Hassan, G., M´hiri, F., Hense, P., Schernewski, G. Can Ecolabels effectively help reducing beach litter in touristic sites? Green Destinations Conference, Tallinn, Estonia, October 9-10th, 2023 (in person).
- Escobar-Sánchez, G., Robbe, E., Baccar-Chaabane, A., Gatel Rebours, M., Schernewski, G. Replacing Single Use Plastics (SUPs) for biodegradable and compostable materials: a benefit for the environment or greenwashing? SPLACH Conference, Santiago de Chile, January 10th – 12th, 2024 (in person).
- Escobar-Sánchez, G., de Ramos, B., Piehl, S., Haseler, M., Lange, X., Schernewski, G. Emission, transport and fate of floating plastics in estuaries: an emission budget and high-resolution model study. MICRO 2024 – Plastic

pollution from Macro to Nano, Lanzarote, Spain, September 23rd – 27th, 2024 (in person).

- Escobar-Sánchez, G., de Ramos, B., Piehl, S., Haseler, M., Lange, X., Schernewski, G. Emission, transport and fate of floating macroplastics in estuaries: an emission budget. EGU Conference Vienna, Austria, April 27th – May 2nd, 2025 (in person).

2

Materials and methods

This thesis explores the macrolitter and plastic pollution problem from an integrated view of the coastal interface (land to sea), and addresses three research gaps: 1) new methods for monitoring, 2) identification of sources of pollution and transport pathways, and 3) critical evaluation of mitigation measures in regards to applicability and effectiveness at different geographical regions. Figure 1 shows the research gaps addressed, the methods used and the relationships between each section.

2.1. Study area

This thesis examines macrolitter pollution at three coastal regions subject to high tourism pressure: the southern Baltic, the southern Mediterranean and the Chilean Pacific (Fig. 2). These sites were selected to represent distinct environmental and socio-economic contexts and management frameworks. Although the regions were not investigated to the same extent, the study aimed to provide a global perspective on the problematic allowing cross-regional comparisons on the state of plastic pollution and management possibilities. The southern Baltic region was included to represent a European region, in a semi-enclosed sea, with relatively moderate plastic pollution levels and advanced waste management and policy frameworks. The southern Mediterranean region represented a North African region, in a semi-enclosed sea, with rela-

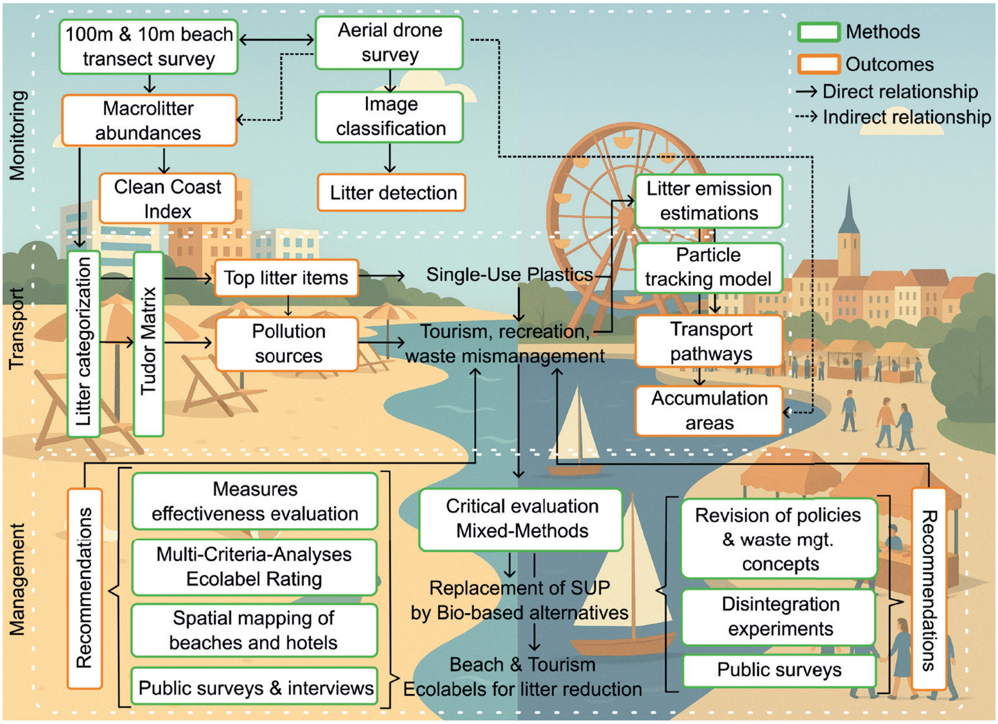


Figure 1. Concept of the thesis showing the three research gaps covered (Monitoring, Transport, and Management), methods used and how outcomes relate with other topics. Direct relationships indicate aspects that were addressed in the thesis, while indirect relationships indicate potential implementation of the method to other aspects. Own creation, the background images were created with *ChatGPT*.

tively high pollution levels and a poor waste management and policy infrastructure. Finally, the Chilean Pacific coast was included to represent a South American region, in an open ocean, with relatively moderate plastic pollution levels, and recently implemented waste management and policy frameworks.

The PhD was carried out in frame of the *TouMaLi (Tourism Marine Litter)* project, which aimed to develop and implement "sustainable waste management systems in the tourism sector of North Africa for the protection of marine ecosystems" and the *COP (Circular Ocean-bound Plastic)* project in the southern Baltic, which provided an opportunity to investigate pollution patterns in tourism-driven coastal areas. The PhD was carried out at *Klaipeda University* in collaboration with the *Leibniz Institute for Baltic Sea Research Warnemünde*, which facilitated access to data and infrastructure.

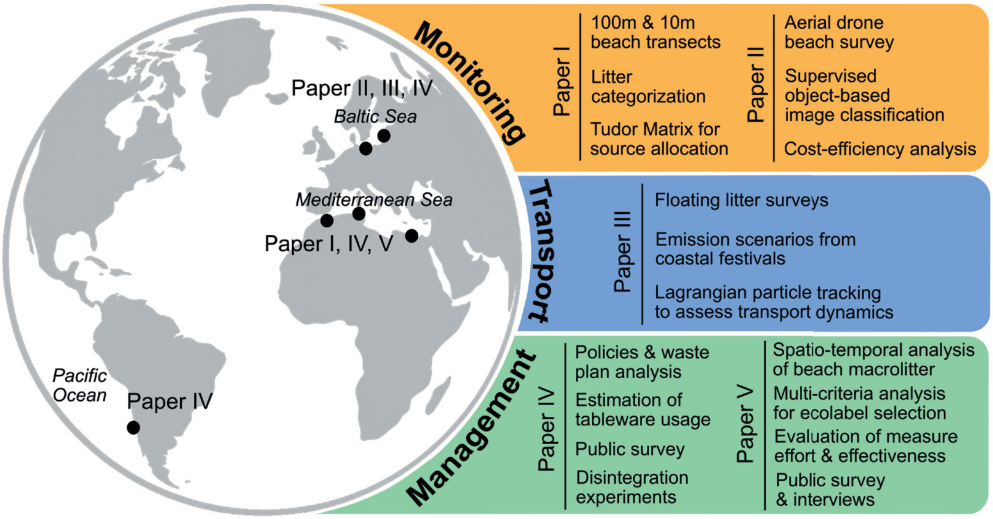


Figure 2. Conceptual scheme of the three research gaps covered in this thesis (Monitoring, Transport dynamics and Management), methodologies used at each paper and the study areas covered.

2.1.1. Southern Mediterranean Coast

The Mediterranean Sea is a semi-enclosed system with a surface water inflow from the Atlantic Ocean through the Strait of Gibraltar, which circulates along the coasts of North Africa, Asia and Europe before exiting back into the Atlantic. The water flow is further influenced by mesoscale eddies (Millot and Taupier-Letage, 2005), which can lead to the retention and onshore accumulation of floating litter, but also redistribution offshore, as it has been suggested with the "transboundary" effect (Liubartseva et al., 2018). Salinity in the Mediterranean Sea is 36–39.5 PSU, with highest values at the Levantine basin (GRID Arendal, 2013). The Mediterranean Sea has a microtidal regime with tidal range below 0.2 m (Poulos, 2020), except for the Gulf of Gabes where tidal ranges can reach up to 1 m (Sammari et al., 2006). Rivers with highest flow rate in the Mediterranean Sea are the Rhone, Po, Ebro and Nile. The Nile River is the longest river in the world (GRID Arendal, 2013; EEA, 2015), estimated to transport over 730 tonnes of plastic every year (Lebreton et al. 2017), however, nowadays its flow is restricted by various dams.

The Mediterranean Sea is bordered by 18 countries from southern Europe, North Africa and Asia, with a population of ca. 520 million people; over a third living on the coast and 61% living on the southern and eastern shores (UNEP, 2020) (Fig. 3A).

It attracts almost a third of global international tourists (Plan Bleu, 2022). Morocco, Tunisia, and Egypt have large coastal populations (Fig. 3A) and are the countries in Africa with the highest influx of national and international tourists, receiving over 38 million visits in 2023 (Statista, 2024).

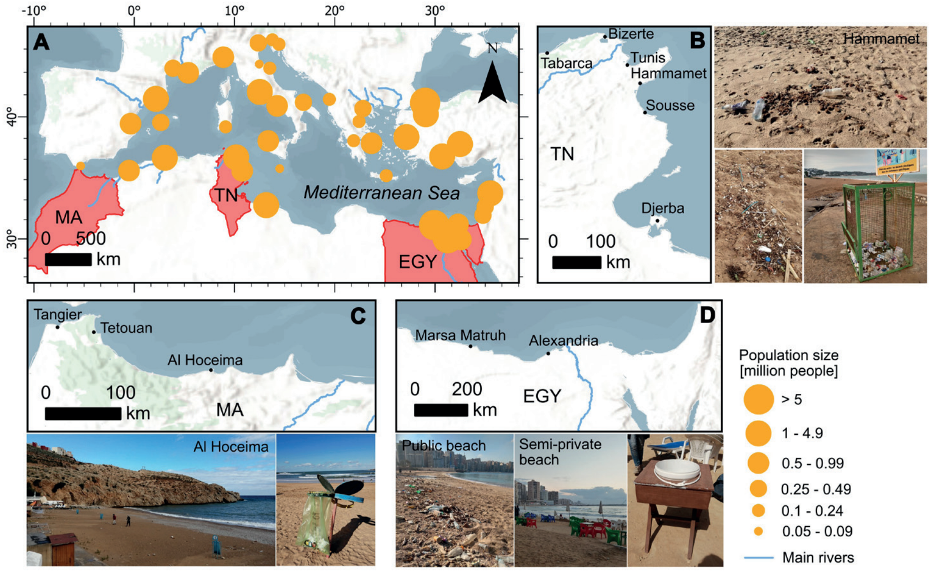


Figure 3. A - The southern Mediterranean coast showing largest cities and main rivers, and study areas B – Tunisia (TN), with close ups to litter pollution at Hammamet beach and waste bin for plastic bottles; C – Morocco (MA), with close ups to Al Hoceima semi-urban beach and waste bin, D – Egypt (EGY), with close ups to a public versus semi-private beach in Alexandria and waste bins used at private hotel beaches. Basemap: ESRI, TomTom, FAO, NOAA, USGS. Sources shapefiles: Population - ArcGIS (2025), Rivers – GRDC (2025).

The Mediterranean Sea is one of the most polluted seas in the world (Cózar et al., 2015), with an estimated total leakage of 0.57 million tonnes of plastics per year (WWF, 2019a). The northern Mediterranean coastline has been widely studied (Vlachogianni, 2019; Vlachogianni et al., 2020), however there is a lack of long-term litter data and uneven research coverage for the southern region. According to this data, mean beach litter abundance is 961 ± 3664 items per 100m (range: 8–47,361 items per 100m) (UNEP, 2023). Plastic and polystyrene items (2.5–50 cm) are the most common litter found, followed by cigarette butts and plastic caps and lids, accounting for 60% of the total litter. The main sources of pollution are land-based, including household waste mismanagement, run-off from waste dumps, tourism, run-off from rivers, as well as leisure boats and ship-generated waste (UNEP/MAP, 2012).

Morocco, Tunisia and Egypt are among the Mediterranean countries with lowest municipal waste generation (200–300 kg per capita per year in contrast to an average of 400 kg per capita per year) with 8–13% corresponding to plastic waste (average 12%) (World Bank, 2025). However, the three countries are among the top 20 countries worldwide for mismanaged plastic (Jambeck et al., 2015), and among the countries in Africa with highest plastic waste generation (Akan et al., 2021), having lower recycling rates (4–12%) than other Mediterranean countries (World Bank, 2025). Due to this, it is estimated that between 0.07 and 0.78 million tonnes of plastic enter the oceans annually from these countries (Jambeck et al., 2015, using 2025 projections).

This region experiences a tense political environment, which has affected the waste management system (Chaabane et al., 2019; Chaabane, 2020), and hindered the implementation of policies and measures to reduce litter. Policies regulating litter pollution in the southern Mediterranean include the Barcelona Convention which provides a framework to assess, control and reduce marine pollution, and set environmental targets (UNEP/MAP, 2012). The Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast (IMAP) includes marine litter as ecological objective 10 and adopted a litter threshold value (130 items per 100m). Only 16% of beaches in the Mediterranean achieved a Good Environmental Status (GES) (UNEP, 2023). The contributing countries that align to the IMAP are mainly European, and there is a lack of policies for the southern Mediterranean Sea (UNEP, 2023). The Regional Plan on Marine Litter Management in the Mediterranean (MLRP) was adopted in 2013, and it is the first legally binding instrument among all Regional Seas Conventions, requiring European, North African and Middle Eastern countries to take specific actions to reduce litter (UNEP, 2020). In addition, the *Littoral Sans Plastique* aims to reduce plastic leakage from land- and sea-based sources at national level in Tunisia and Morocco, through circular economy, plastic recycling value chains and stakeholder involvement (World Bank, 2022). However, the implementation of measures in the region to achieve plastic litter reduction is still a challenge.

The focus area is Hammamet (Fig. 3B), a small city in Tunisia with 83,000 inhabitants (personal communication, Hammamet municipality, November 2021), located in the highly touristic region of Nabeul. In 2024, it attracted ca. 2.5 million visitors (African Manager, 2024). The *International Festival Yasmine Hammamet* is among the most popular carnivals in the Nabeul region, which gathered over 40,000 people in 2025 (RTCI, 2025). Along the coastline, there is several holiday resorts, restaurants, cafés and takeaway stalls. Waste segregation at-source is not effective, and most waste is landfilled or dumped (Chaabane, 2020). The study areas count with different waste management measures at the beach, reflected in Figure 3 (B, C, D), which include the placement of bins during high season, regular cleaning, and bins for plastic containers (e.g., from the *Eco-Lef* recycling program).

2.1.2. Southern Baltic Coast

The Baltic Sea is a semi-enclosed brackish system with a surface water inflow from the North Sea through the Danish Strait, flowing in a counter-clockwise motion along the coastline back out into the North Sea. The system is further influenced by circulation patterns and eddies (Elken and Matthäus, 2008), which can influence the transport and retention of litter (Christensen et al., 2023; Pärn et al., 2023; Hariri et al., 2025). The Baltic Sea is a brackish water system with 0–2 PSU in the northern basins, 7–8 PSU at the Baltic Proper and 15–19 PSU at the Sound, and has a low water turnover of 25–35 years (HELCOM, 2023). Being a microtidal system, tidal ranges are below 0.2 m, except for the Kattegat region which is influenced by tides from the North Sea (Medvedev et al., 2016; HELCOM, 2023). Rivers with highest flow rate include the Neva, Vistula, Daugava, Nemunas and Oder (HELCOM, 2018) (Fig. 4A).

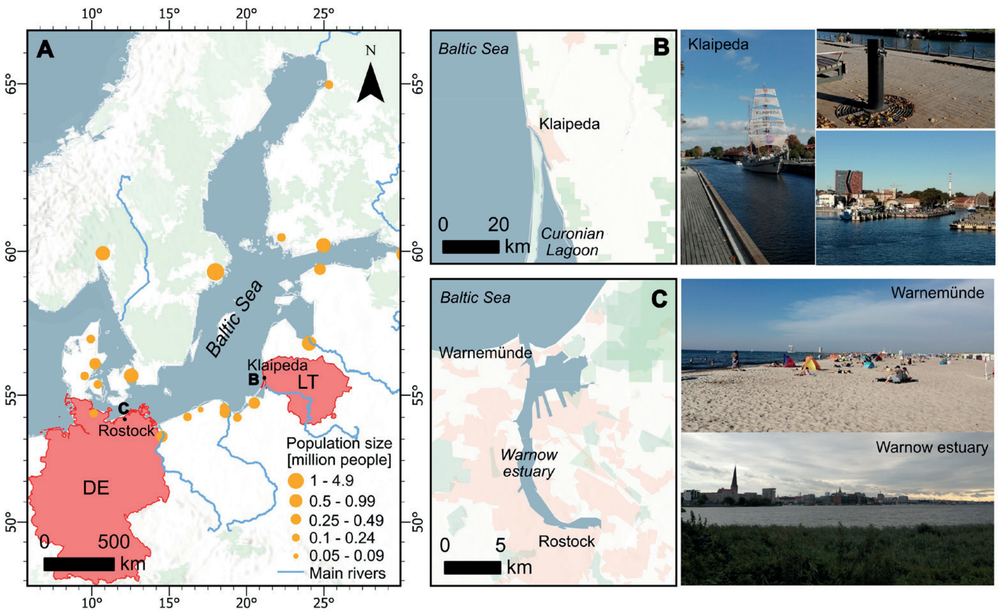


Figure 4. A – The southern Baltic Sea showing largest cities and main rivers around the Baltic, and the study areas: B – Klaipeda in Lithuania (LT) with close ups to the Dane river crossing Klaipeda, and a water refill station; and C – Rostock in Germany (DE), with close ups to Warnemünde beach and the Warnow estuary from the reed belt area. Basemap: ESRI, TomTom, FAO, NOAA, USGS. Sources shapefiles: Population - ArcGIS (2025), Rivers – HELCOM (2025b).

The Baltic Sea has a population of 90 million people and 15 major coastal cities (Fig. 4A). Coastal tourism is highly important in the region, receiving 80 million recreational visits per year, and an associated value of 27.5 million Euros annually (Czajkowski et al., 2024). Focusing in the southern Baltic Sea, Germany, Poland and Lithuania are the countries with highest coastal tourism (Eurostat, 2024). Tourism and recreation are the predominant sources of beach macrolitter (Schernewski et al., 2017). Beach litter abundance is highest at the coasts of Finland, Latvia and Lithuania (HELCOM, 2025a). HELCOM established a threshold value for beach litter at 20 items per 100 m; however, 11 out of 16 basins exceed this level. Plastic packaging waste generation in the southern Baltic Sea countries ranged between 26–41 kg per capita per year in 2023, with Germany, Denmark and Lithuania among the highest generators (Eurostat, 2023a). In contrast, plastic recycling rate was 28–59% in 2023 (Eurostat, 2023b). As a consequence, plastic accounted for 32–93% of the total beach litter (HELCOM, 2023).

The region has a well-established policy framework for integrated coastal zone management. The Marine Strategy Framework Directive (MSFD) is a legal framework for the protection of the European marine waters, identifying the necessary measures to achieve or maintain a Good Environmental Status (GES) in all European seas. Descriptor 10 refers to marine litter and the identification of trend amounts, accumulation sites, composition, spatial distribution and sources of litter pollution (JRC, 2011). The Baltic Sea Action Plan established that by 2030, the amount of marine litter should not cause harm to wildlife and humans at the Baltic Sea (HELCOM, 2021) and the Regional Action Plan for Marine Litter in the Baltic Sea establishes specific actions to achieve this goal (HELCOM, 2019). Other relevant EU policies include the Waste Framework Directive (EU/2008/98/EC), Water Framework Directive (EU/2000/60/EC), the Strategy for Plastics in a Circular Economy (EC, 2018) and the Single-Use Plastics Directive (EU/2019/904), requiring countries to implement measures for plastic waste reduction and management. Extensive research is available on the abundances, sources (Schernewski et al., 2017; Haseler et al., 2018; Kataržytė et al., 2020; Gyraite et al., 2023) and physical transport pathways of litter (Schernewski et al., 2017, 2021). However, new technologies for macrolitter monitoring are discussed within the MSFD and need to be evaluated. Moreover, there is also a need to further assess the role of estuaries as sources or sinks of pollution in the Baltic region, to determine and refine plastic emission budgets.

Focus areas are Klaipeda (Lithuania) (Fig. 4B) and Rostock (Germany) (Fig. 4C). Klaipeda, Lithuania‘s major coastal city, has 156,745 inhabitants. The coastal zone is highly touristic and received 946,427 visitors in 2022 (Official Statistics Portal Lithuania, 2022). Klaipeda has underground bring-points for separate waste collection of plastic, paper, aluminum, glass and organic waste (EEA, 2022), however, Lithuania‘s plastic recycling rates are low (1.9% from at-source collection and 17.5% from post-collection sorting in 2020) (KRATC, 2023). Rostock is a highly touristic destination with 210,795 inhabitants, which received 698,517 visits and 130 cruise ships having 419,000 passengers in 2023. Rostock generated 47,755 tonnes of municipal solid waste in 2023, of which 12% is plastic packaging (Hansestadt Rostock, 2024).

Hanse Sail, *Warnemünde Week* and *Klaipeda Sea Festival* are the most important coastal festivals at both cities. Both locations are sites with a high number of restaurants, cafés and takeaway stalls at the water border. However, both sites count with well-established waste management plans to reduce littering from events, which were driven by the EU Single-Use Plastics Directive (AbfS §2-3, 2023; Strandsatzung, §8, 2021, KRATC, 2023, 2024).

The Warnow estuary is a microtidal estuary which can be regarded as a representative estuary for the southern Baltic Sea. It has an area of 12 km^2, mean depth of 5.6 m, a catchment area of 3,280 km^2, an average water exchange time of 30 days, and a strong salinity gradient with 5 PSU at the river entrance and up to 18 PSU at the mouth. The strong salinity gradient and wind play the main role in reversing estuarine circulation (Lange et al., 2020). The Warnow estuary is surrounded by various land-uses and economic activities (e.g., residential, industrial, recreational and natural areas), which contribute to plastic emissions into the estuarine environment.

2.1.3. Chilean Pacific Coast

Chile, located in South America, is a long and thin country with a coastline of 6,435 km, bordered by Peru and Bolivia in the north, the Andes Mountains and Argentina on the east and the Pacific Ocean on the west (Gobierno de Chile, 2025) (Fig. 5A). The oceanography of the region is characterized by the Humboldt Current, which moves northward along the continental coast and offshore at the equator, transporting floating litter along the shoreline (Onink et al., 2021) or offshore (van Gennip et al., 2019; van Sebille et al., 2019; Chenillat et al., 2021). Wind-driven coastal upwelling may prevent litter from reaching the coast (Pereiro et al., 2019). Salinity varies between 33.8–35.2 PSU with lowest salinity in the south and Patagonian fjords (Dávila et al., 2002; Silva et al., 2009).

The Chilean Pacific coast is subject to varied tidal regimes, with microtidal regimes in the north and central regions and macrotidal regimes in the south (from latitude 42°S approximately) (SHOA, 2025). Rivers with highest flow rate are located in the south and include Puelo, Toltén, Bío-Bío and Aysén (INE, 2024a). However, most rivers along the country are relatively short, with lengths between 25–440 km (INE, 2024), and have been observed to transport high quantities of litter (Rech et al., 2014).

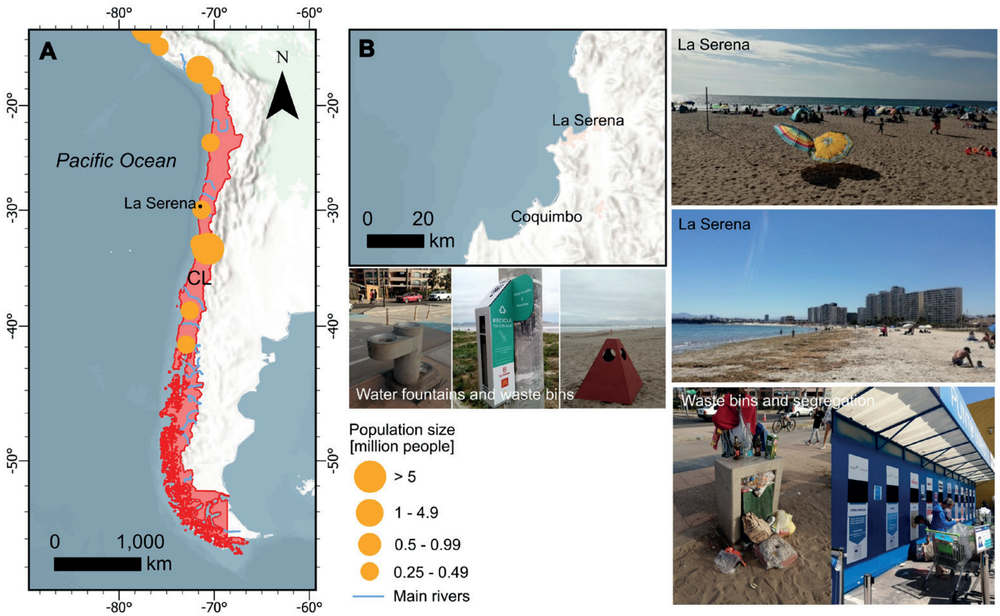


Figure 5. A – The Pacific coast of Chile (CL) showing largest cities and main rivers, and B – the study area in La Serena city, with close ups of the urban beach, waste bins and waste segregation practices. Basemap: ESRI, TomTom, FAO, NOAA, USGS. Sources shapefiles: Population - ArcGIS (2025), Rivers – GRDC (2025).

Chile has over 18 million inhabitants (INE, 2024b) with the majority of the population located in coastal cities, since the country is, on average, only 180 km wide (Fig. 5A). Tourism is an important industry of international and national value, receiving over 5 million international arrivals (SERNATUR, 2025a) and registering over 61 million inland travels in 2024 (SERNATUR, 2025b). Chile is the country in South America generating the highest amount of plastic waste with 74 kg per capita per year. However, waste management infrastructure lags behind, with 30% of plastic waste generated being mismanaged (Earth Action, 2024). Majority of waste is disposed in landfills or dumpsites (MMA, 2024) and plastic recycling rate is only 8%, highly centralized in the capital region (ASIPLA, 2022).

Beach macrolitter monitoring has been carried out since 2008 through *Científicos de la Basura* (CDLB), a citizen science network expanding along the East Pacific, where a nationwide monitoring is carried out every four years (De Veer et al., 2023). Their survey method uses 9 m^2 quadrats from the water line to the back of the beach and a simple litter categorization into six classes: plastic, cigarette butts, paper, glass, metal and wood (Bravo et al., 2009). However, this simplified categorization limits source allocation. Mean litter abundance was 1.5 ± 4.57 items per m^2 in 2020, with the main polluting materials being plastics and cigarette butts (De Veer et al., 2023). In 2024, mean litter abundance was reported at ca. 0.6 items per m^2, a significant decrease observed nationwide in comparison to previous campaigns (CDLB, 2025). No litter threshold has been established in the country yet.

The focus area is La Serena, located in northern Chile (Fig. 5B). The La Serena-Coquimbo conurbation has a total of 543,044 inhabitants (BCN, 2025a,b). The *Festival de La Serena* used to be one of the major festivals in the region, receiving ca. 25,000 visitors (Municipalidad de La Serena, 2019). The region is highly touristic and received 557,643 visitors in 2024 (INE, 2025). Beaches are highly urbanized with residential buildings, restaurants, bars and takeaway food stalls during the summer. Municipal solid waste generated in the conurbation was ca. 233,000 tonnes in 2022. Majority of the waste is dumped or landfilled (SUBDERE, 2024). Collection points (*Puntos limpios*) for plastics and other materials are placed in different areas of the city (MMA, 2025), however, usage by the population remains low due to long distances (UNAB, 2022).

2.2. Adapted macrolitter survey method for highly polluted beaches

Sandy beaches of the Mediterranean coastline of Morocco, Tunisia and Egypt (Fig. 6A) were investigated to assess macrolitter pollution (> 2.5 cm), between 2021 and 2023. The sandy beaches comprised touristic, urban, semi-urban and semi-rural, following the definitions in Table 1. A total of 37 surveys were carried out (7 in Egypt, 14 in Morocco and 15 in Tunisia), following the 100 m beach transect method (UNEP/IOC, 2009) (Fig. 6A).

The aim of this first cross-country survey was to assess the state of macrolitter pollution at the southern Mediterranean beaches before establishing a long-term monitoring. Therefore, a large spatial coverage along each coastline was prioritized. Due to high pollution levels, an adapted method using 10 m transects was tested to allow coverage of more sites under time constraints and thereby reduce sampling fatigue. For this, transects were first measured and georeferenced using a GPS device, to enable consistent sampling at the same location in the future. The number of transects varied, based on the time required for sampling, and was between 2–10 transects per beach, placed either adjacent to each other (Egypt and Tunisia) or spatially apart (Morocco) (Fig. 6B). To assess the small-scale variability of macrolitter abundance (items per m^2) in several 10 m transects of close proximity (adjacent and separated) at each beach survey, a coefficient of variation (CV) was calculated across two, three, four and five transects, where σ is the standard deviation and μ is the mean macrolitter abundance (items per m^2).

$$CV = \left(\frac{\sigma}{\mu}\right) * 100$$

In addition, it was assessed how frequently the top 25 item categories (representing > 80% of the total pollution) were counted within five 10 m transects, to gain an insight into their distribution. In this way, the minimum number of transects needed at highly polluted beaches could be established to find the majority of polluting items (for more details, see Paper I).

All litter above 2.5 cm was collected by a team of 5–10 people (Fig. 6C). Cigarette butts were initially excluded in the first monitoring campaign in Tunisia (2021). Surveys were primarily carried out during off-season (except Tunisia 2022 that was carried out in June). The litter collected was categorized using the Joint list of Litter (Fleet et al., 2021). If the surveyed area was less than 100 m, then the results were extrapolated.

The Clean Coast Index (CCI) was used to evaluate the level of cleanliness at beaches. The CCI is based on the number of items per area, multiplied by a coefficient (K = 20), where CCI values of 0–2: very clean beaches, 2–5: clean, 5–10: moderately clean, 10–20: dirty, and > 20 extremely dirty (Alkalay et al., 2007). Further details are described in Paper I.

$$CCI = \frac{Total\ litter\ items}{Total\ sampled\ area} * K$$

Figure 6. A - Study area and sites of beach macrolitter monitoring. For a description of each beach, refer to the supplementary material in Paper I. B – Beach macrolitter surveys using adapted 10m transects. The transects were joined next to each other (Tunisia and Egypt), or separated by a distance of 10–150 m (Morocco), depending on the length of the beach. C - Survey procedure, including systematic litter collection, litter counting and categorization. The Sand Rake method is not presented in the thesis (adapted from Paper I).

Table 1. Description of beach classification per use type.

Beach use type	Description	Reference
Touristic beaches	heavily used by national and international tourists, unlike urban beaches which are mainly frequented by locals	Haseler et al. 2025
Urban beaches	located in densely populated areas with public services and accommodations, accessible by both public and private transport	Semeoshenkova et al., (2017)
Semi-urban beaches	located near urban centers or coastal towns, with moderate tourist presence and accessible by public and private transport	Semeoshenkova et al., (2017)
Semi-rural beaches	adjacent to villages, with limited services and accommodations, and primarily accessed via private transport	Semeoshenkova et al., (2017)

2.2.1. Tudor matrix scoring technique

Macrolitter items were classified using the Joint list of Litter (Fleet et al., 2021) and categorized as single-use plastics (SUP) following the EU Single-Use Plastic Directive (2019/904). The potential sources of litter pollution were determined using the "Tudor matrix scoring technique" system E, as recommended in Veiga et al., (2016) following the method by (Tudor and Williams, 2006). The Tudor matrix assesses the likelihood that a litter item may originate from more than one source. Litter sources were classified into eight groups according to Vlachogianni, (2019) and Vlachogianni et al., (2018): 1) shoreline, including poor waste management practices, tourism, and recreational activities, 2) fisheries and aquaculture, 3) shipping, 4) fly-tipping, 5) sanitary and sewage related, 6) medical related, 7) agriculture, and 8) non-sourced. Local experts assigned scores to each of the top 25 items, to indicate the likelihood of an item coming from a potential source of pollution, as: not considered/impossible (0), very unlikely (0.25), unlikely (1), possible (2), likely (4), and very likely (16). The median of the scores was calculated and converted to a percentage estimation. For more details, see Paper I.

2.3. Aerial drones for beach macrolitter monitoring

A low-cost quadcopter *DJI Phantom 4 Pro V2.0* with an integrated RGB CMOS camera of 20 Megapixels was used to test an UAV-based approach for meso- (1–25mm) and macrolitter (> 25 mm) monitoring. Two mapping apps were used: *Drone-*

Deploy v.3.13.1 and *Pix4D Capture* v.4.5.0, which enabled the creation of ortomosaics from the obtained photos, at a specific flight altitude and field of view (FOV). The methodology for image acquisition and analysis followed five main steps (Fig. 7A). Recovery experiments were carried out using real litter items (14–57 items) from the most common item categories at Baltic beaches (Schernewski et al., 2017), having different colors, shapes and sizes (1–30 cm) on a previously cleaned area of 50 m^2 (Fig. 7B, photo 1). The experiment was carried out at four beaches of the southern Baltic Sea (Klaipeda in Lithuania; Warnemünde, Ahrenshoop and Stoltera in Germany), having different background substrates. Three different flight altitudes (10, 15, and 18 m) were tested, based on Ground Sampling Distance (GSD) to obtain spatial resolutions of 2.7, 4.1, and 4.9 mm, respectively, to detect litter in the meso (5–25 mm) and macro (>25 mm) scale. Different weather conditions were tested to evaluate its influence in litter detection. To assess litter detection accuracy, beach transects of 100 m (with an unknown number and type of litter) were mapped at each site from the water line to the back of the beach at a flight height of 10 m (Fig. 7B, photo 2). After mapping, two people collected the items seen by naked eye and classified them according to the OSPAR list of items (OSPAR, 2010). For more details, see Paper II.

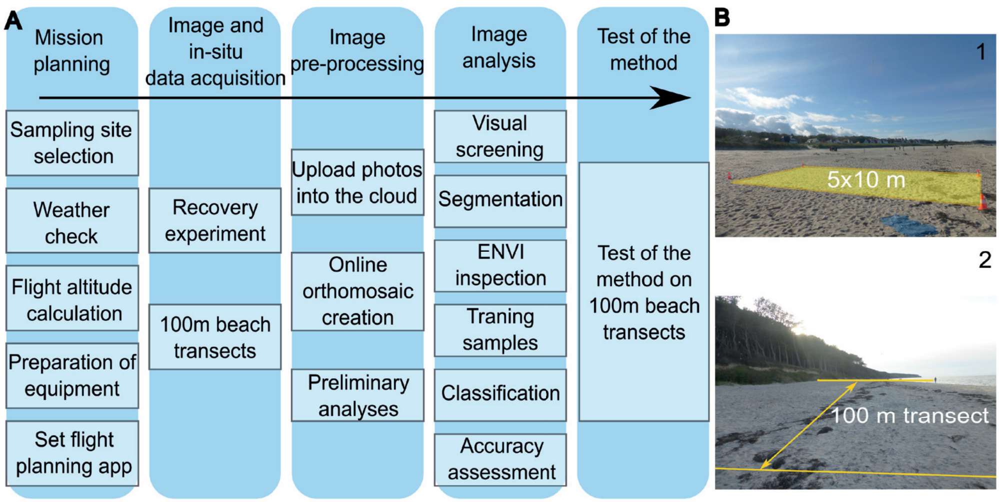


Figure 7. A – Workflow for drone-based monitoring and object-based supervised classification based on five main steps, each with separate single steps to follow. B – set up for the recovery experiment (1) and 100 m beach transects (2) (adapted from Paper II).

2.3.1. Image analysis of litter items at beaches

For each site, three orthomosaics (one for each flight height) of recovery experiments and one orthomosaic of a 100 m beach transect were produced, having spatial resolutions of 2.7 – 8 mm/px, based on flight height and mapping app used. *ArcGIS* v.10.5 was used to carry out supervised object-based classification. *ENVI* 5.3 was used to inspect the spectral signatures of different objects in the image by taking 10–20 samples per orthomosaic, to define the number of classes for classification. Image classification followed the standard procedure of object-based supervised classification, including segmentation, the selection of training samples, classification and accuracy assessment (Fig. 7A). The training samples taken at each recovery experiment were used for classification of the recovery experiment sites and 100 m beach transects, using 4 and 6 classes. Three supervised classification algorithms were used: Maximum Likelihood (ML), Random Forest (RF) and Support Vector Machine (SVM). Accuracy of the classification was assessed using a set of 500 validation points created in an "equalized stratified random" manner, i.e., distributed within each class. A confusion matrix revealed the accuracy of each algorithm, based on commission and omission errors for each class, total accuracy and kappa value of agreement, with a value of 0 indicating no better than random, > 0 better than random and < 0 worse than random (Cohen, 1960) (Table 2). For more details, see Paper II.

Table 2. Definitions of accuracy concepts used within a confusion matrix for the assessment of algorithm performance (taken from text of Paper II).

Accuracy concept	Definition
Total accuracy (TA)	Percentage of correctly classified validation pixels and measures the accuracy of the classified image
Producer´s accuracy (PA) – also known as Recall	Indicates the proportion of true positives in relation to true positives and false negatives in the **model classification**. It is also a measure of omission error
User´s accuracy (UA) – also known as Precision	Indicates the proportion of true positives in relation to true positives and false positives in comparison to the **reference data**. It is also a measure of commission error
Cohen´s Kappa value	Overall assessment of accuracy of the classification in respect to randomness, with a value of 0 indicating no better than random, >0 better than random and <0 worse than random (Cohen, 1960)

2.3.2. Cost-efficiency analysis

Cost-efficiency of aerial drone surveys was compared to the OSPAR method (2010), considering a long-term monitoring of 100 m beach transects (or 1 km beach transects for items > 50 cm) carried out at four beaches, four times a year, by a minimum of two persons. The estimations of costs, time and staff were based on own experiences in the Baltic Sea region and established protocols from JRC (2013) and UBA (German Environmental Agency), as well as current market values. The costs of both methods were calculated considering implementation costs (equipment, software and testing period for both methods, 6 months for the UAV-method and 3 months for the OSPAR method) and annual running costs. The latter includes field/lab working time (travel, survey and analysis) and office working time (planning, organization and reporting). The total monitoring costs for UAVs for beaches were classified as: 5 (very low) < 15,000 €; 4 (low) < 30,000 €; 3 (moderate) < 45,000 €; 2(high) < 90,000 € and 1 (very high) > 90,000 €.

In addition, efficiency was evaluated based on four criteria: accuracy, reproducibility, flexibility and quality, described in Table 3, for each survey method; scored by three experts as: 1 (very low), 2 (low), 3 (moderate), 4 (high) and 5 (very high). The efficiency score was the average of all evaluations. Finally, cost-efficiency was obtained by the multiplication of the cost and efficiency scores, classified as < 5 (very low), < 10 (low), < 15 (moderate), < 20 (high), and > 20 (very high). For more details, see Paper II.

Table 3. Cost-efficiency concepts (taken from text from Paper II).

Concept	Definition
Accuracy	Number of items found by each method in comparison to the real number of items (i.e., ground truth data)
Reproducibility	Likelihood of a method, when applied by different persons, equipment and software, derive the same result
Flexibility	Extent to which the method is dependent or not on external influences (weather, permissions, drone functioning)
Quality	Type and quality of data acquired by each method (i.e., type and number of items, type of material, and spatial distribution) and the conclusions that can be derived from it

2.4. Assessment of emissions, pathways and sinks of litter pollution

2.4.1. Assessment land-to-estuary litter emissions from coastal festivals

Sampling of floating macrolitter was carried out at the Warnow estuary (Rostock, Germany) to assess land-to-estuary emissions of litter from the *Hanse Sail* festival in 2017, 2018, 2019 and 2023. The sampling methods and sampling frequency varied, and included 300 µm plankton nets deployed with sticks (2017), collection from canoes with volunteers (2018), landing nets of 5 mm mesh size to remove litter near the harbour wall (2019), and on-site visual observations during the festival with collection of floating litter by boat (2023). For full description of each methodology, refer to Paper III. The sampling of 2018 was the most comprehensive, therefore it is the focus here. The survey covered the entire frontline of the *Hanse Sail* festival waterfront. Items collected were weighted and classified using the OSPAR list of litter (OSPAR, 2010). In addition, reed belts around the Warnow estuary were inspected and litter was collected on foot and by a small boat, at an area of 1 m width from the waterline and total length of the reed, covering a total of 5 km. Complementary data for other sites were obtained from a local nature protection NGO *NABU* (Naturschutzbund Deutschland). The proportion of floating litter found at the estuary in contrast to the total amount of waste generated at the *Hanse Sail* festival revealed the land-to-estuary litter emission contribution (%). The total emission was extrapolated to other 50 major coastal festivals, based on total visitor numbers, considering two waste management scenarios. Further details are described in Paper III.

2.4.2. Particle tracking model for the assessment of litter retention

To assess litter retention and transport potential for estuary-to-sea emission, a high resolution (20 m) physical hydrodynamic model of the Warnow estuary coupled with an offline Lagrangian particle tracking model were used. The hydrodynamic model was developed by the Physics department at the Leibniz Institute for Baltic Sea Research (IOW) and is based on the General Estuarine Transport Model (GETM) (Burchard and Bolding, 2002; Klingbeil and Burchard, 2013) with the General Ocean Turbulence Model (GOTM) (Umlauf and Burchard, 2005). Meteorological forcing was calculated from the German Weather Service Local Model (DWD-LM). The model represents local bathymetry, estuarine circulation and currents, as well as harbour infrastructure, and was provided at a temporal resolution of 5 minutes and 1 hour for 10 days for the month of August 2009 and 2010. The model was validated using observed data on sea level, bottom water temperature and bottom salinity. For further details, refer to Lange et al., (2020).

The years 2009 and 2010 were chosen because of contrasting weather conditions. The offline Lagrangian particle tracking approach was used based on the *Ocean Parcels* v2.0 framework (Delandmeter and Van Sebille, 2019). The model uses virtual particles having no particular characteristics, assumed to be passively transported in the upper 50 cm of the surface water layer, and thus windage (i.e., wind driven transport for items above the water layer) was not considered. Aspects like particle size, density or shape were also not considered, and are still aspects that need to be further studied in Lagrangian particle tracking research. Particles emitted into the system were trapped upon reaching cells representing reeds or beaches along the Warnow estuary, using a probabilistic factor of 0.7 (i.e., particles had a 70% probability of being trapped per encounter and time step). The remobilization effect at reed belts or beaches at the Warnow estuary is not fully investigated; therefore, the model adopted a simplification that does not consider remobilization of previously trapped particles. These assumptions regarding trapping factor and lack of remobilization were supported by field observations and reed belt sampling, which showed a high accumulation of fragmented plastic pieces and the presence of biofouled items (Newland, 2025; Gatel Rebours, 2023; and own observation), which indicated that particles reaching these environments remain trapped over time.

2.5. Critical evaluation of mitigation measures at touristic coastal sites

Macrolitter surveys from the southern Mediterranean coast (Paper I) and the southern Baltic coast, specifically Rostock, (Paper III) revealed a high predominance of plastic pollution, primarily single-use plastics (SUPs), and tourism and recreation as well as poor local waste management as the main contributors of litter. Here, two mitigation measures were selected and evaluated because they were currently discussed in policy, or already implemented but questioned for their effectiveness.

2.5.1. Replacement of Single-Use Plastics at coastal festivals

Coastal festivals are subject to high waste generation (Paper III), and due to their closeness to the sea, festivals can be emission points of litter if appropriate waste management practices are not implemented. In Paper IV, the replacement of single-use plastic tableware by bio-based, biodegradable and compostable materials was evaluated at four coastal festivals, taking place at three coastal regions: the *Hanse Sail* (Germany) and *Klaipeda Sea Festival* (Lithuania) in the southern Baltic, the *International Festival Yasmine Hammamet* (Tunisia) in the southern Mediterranean, and the *Festival de La Serena* (Chile) in the Chilean Pacific coast. The festivals were selected for their importance in each country and where accessible data was provided.

To evaluate the replacement of single-use plastic tableware by alternative materials, a holistic evaluation was sought, considering not only environmental aspects, but also policy, infrastructural and educational/cultural aspects. For this reason, a mixed-methods approach was used to construct a richer overall understanding. The methodology encompasses four main aspects: i) an analysis of policies and waste management for single-use plastics (SUPs) and alternative tableware materials, ii) a quantification of tableware usage in coastal festivals (Fig. 8), iii) an online public survey to assess the perception, awareness and acceptance of bio-based tableware and iv) disintegration experiments in coastal waters and at an industrial composting facility. Table 4 provides an overview of the studied alternative materials, with polystyrene (PS) used as negative control. These alternative materials have been implemented at the *Hanse Sail* event to replace conventional plastic tableware in Rostock (Germany), and thus it was considered as a case study.

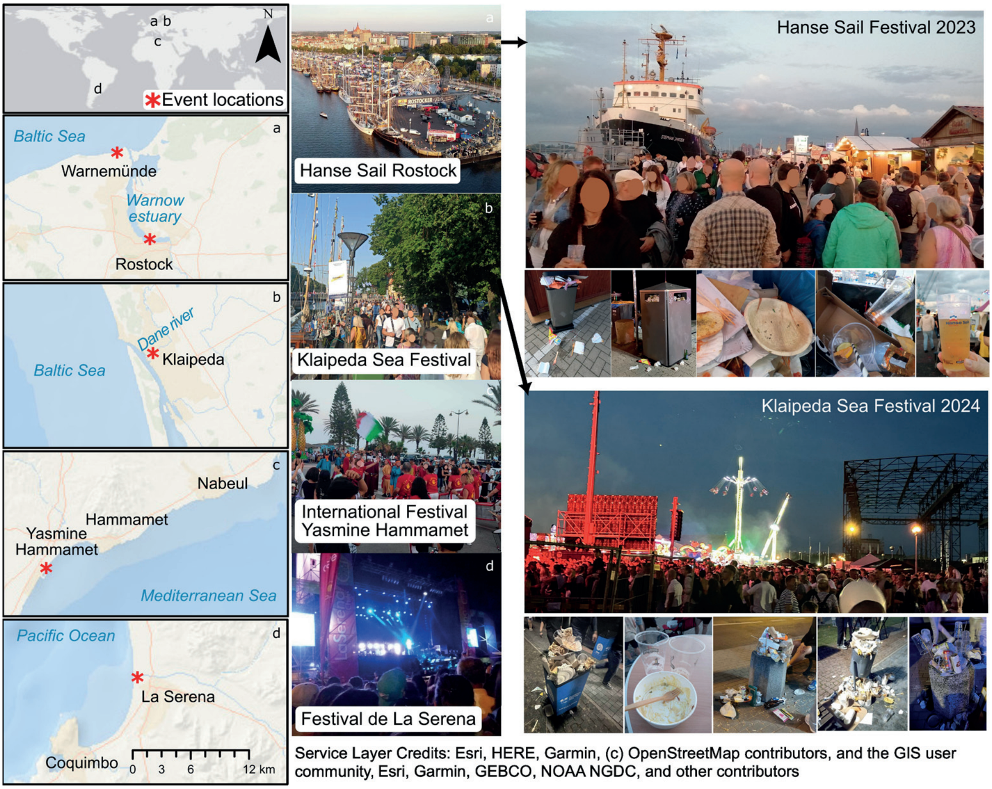
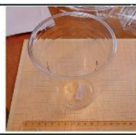
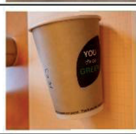


Figure 8. Study areas and event locations: a. *Hanse Sail* (Germany); b. *Klaipeda Sea Festival* (Lithuania); c. *International Festival Yasmine Hammamet* (Tunisia) and d. *Festival de La Serena* (Chile). On the right, close-up photos from *Hanse Sail* and *Klaipeda Sea festivals* with examples of litter-prone items. Photo courtesy of: Sylvain Riondet, Emna Jedidi, Paola Forni, Viktorija Sabaliauskaite, Jonas Gintaukas and Camila Escobar (taken from Paper IV).

Analysis of policies and waste management concepts

The policy documents were sourced from official government websites and complemented by the Chatham House (2025) database and local experts. It was assessed whether these policies 1) recommended the replacement of SUPs by bio-based, biodegradable or compostable items, and 2) outlined specific disposal and waste infrastructure requirements for their treatment. Concurrently, waste management plans were examined to identify the existing collection and treatment infrastructure at each site. The objectives outlined in the policies were compared to the existing infrastructure to identify discrepancies between SUP reduction goals and management. For details, see Paper IV.

Table 4. Characteristics of tableware materials used in the disintegration experiments. The materials represent those used to replace conventional plastic tableware at the coastal festival *Hanse Sail*, in Rostock (Germany), except for polystyrene (PS) used as negative control. Taken from Paper IV.

Material	Tableware items used	Label	Origin	Bio-based?
Recycled PS (rPS)		NA	Petroleum based Polysterene	No
Polylactic Acid (PLA)		Completely compostable	Synthesized from renewable source i.e. maize	Yes
Cardboard not coated (C)		Biodegradable and compostable	Cellulose	Yes
Cardboard coated with starch (CC)		100% Biodegradable	Cellulose and starch	Yes
Sugar cane bagasse not bleached (SC)		100% Compostable	Sugar cane pressed fibers	Yes
Sugar cane bagasse bleached (SCB)		100% Compostable	Sugar cane pressed fibers	Yes
Palm leaves (PL)		NA	Areca palm fruit sheath pressed	Yes
Wood (W)		NA	Birch wood pressed	Yes

Estimation of SUP and bio-based tableware usage at coastal festivals

The usage of tableware was estimated at *Hanse Sail* festival to give an insight for infrastructural needs for waste management. A sub-sample of stands (44 stands, 27% of the total) was randomly selected for an in-depth assessment on the number and type of items used during the busiest event hours: 12:00-13:00, 16:00-20:00 and 20:00-00:00, for a total of 11 hours. The number of buyers and the number and type of tableware obtained was counted over a period of 15 min per stall. Tableware was classified as reusable (i.e., returnable cups), recyclable with deposit (i.e., plastic bottles), disposable plastic, disposable bio-based, and other waste (i.e., aluminium foil, tissue paper). Tableware usage was extrapolated to other study areas, considering the estimated waste generated per visitor. For further details, see Paper IV.

Online survey to assess public perception, awareness and acceptance of tableware alternatives

An online survey was designed to assess the public perception, level of awareness and acceptance of six alternative tableware materials and was distributed in the four study areas: Rostock (Germany), Klaipeda (Lithuania), Hammamet (Tunisia) and La Serena (Chile). The surveyed people evaluated five criteria for each material: degradability, recyclability, ecological footprint, additives and/or harmful chemicals, and price/market costs (for definitions see Fig. 3 in Paper IV).

Main questions included:

- Are you willing to pay a higher price for alternatives to conventional (disposable) plastic tableware when buying food and drinks to go?
- What criterion do you think is most important when choosing plastic tableware and alternatives?
- How do you rate the degradability/ compostability/ mechanical recyclability/ energetic recyclability/ presence of additives and chemicals from the different materials? (each criterion was asked separately).
- In your knowledge, where should the materials be disposed of after use?

Further details are described in Paper IV.

Disintegration experiments of tableware in real environments

The disintegration of alternative tableware materials (Table 4) was tested at the Warnow estuary, a brackish estuarine system (Fig. 9a) and at an industrial composting facility (Fig. 9b). This allowed comparison between a coastal environment, where items may be littered during festivals (as observed in Schernewski et al., 2024) and a composting site, following disposal requirements according to policy recommendations. Total disintegration (%) was calculated as the difference in dry weight before and after the experiment. Disintegration rate (% d^{-1}) was calculated as the difference in dry weight before and after the experiment, over the number of exposure days for each treatment.

At the estuary, a sample of each material was placed on incubators with 2 mm mesh and exposed to estuarine waters, at two different depths and at three different sites for one year. ISO 22766 (2020) considers the disintegration of plastics in the marine environment over 3 years. In the absence of a standard establishing a disintegration threshold for brackish estuarine environments, in this study, items were considered "degradable" if > 90% of disintegration occurred over one year.

At the industrial composting site, three replicates of each tableware material were placed in a 5 litres PE/PP sack having a 5x10 mm mesh size, filled with organic waste. The samples were exposed to three treatments: 12-day thermophilic phase (T1), 24-day extended thermophilic phase (T2), and 12-day thermophilic phase followed by a prolonged maturation phase of 140 days (T3). Following EN 13432, ISO 17088 and the voluntary Compost Quality Assurance (BGK, 2024), items were considered "compostable" if they disintegrated by at least 90% within 12 weeks and left a remnant of < 20 mm. Although these standards are targeted for bio-plastics, in the absence of standards for non-plastic substituents, the same threshold was applied. Further details are described in Paper IV.

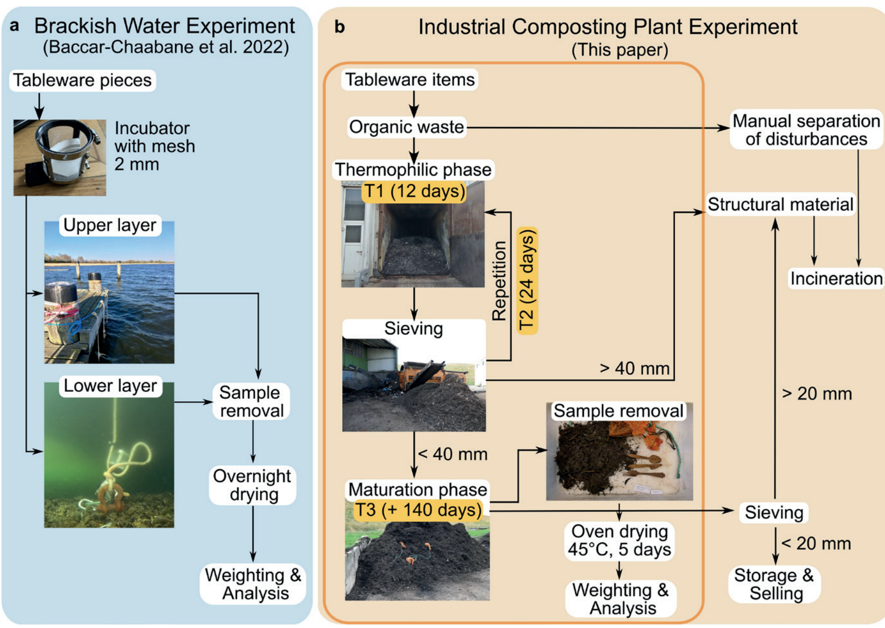


Figure 9. a - Experiment sites in brackish water at the Warnow estuary in the upper and lower water layers (Baccar Chaabane et al. 2022). b – Flowchart of the composting process at the industrial composting facility in Rostock, Germany. Outlined in orange the treatments tested: T1 – rotting phase in the chamber for 12 days, T2 – extended rotting phase for 24 days and T3 – rotting and maturation phase for a total of 152 days (taken from Paper IV).

2.5.2. Beach and tourism ecolabels for beach litter reduction

In Paper V, the potential of ecolabels to reduce beach litter and their suitability for implementation in the southern Mediterranean was assessed using the methodology in Fig. 10. The effectiveness of ecolabels to reduce litter needs to consider the existing state of pollution, the effort required for implementation, the effectiveness of measures for litter reduction and ecolabels suitability to be implemented per individual context. For this reason, a mixed-methods approach was applied, which comprised a i) global compilation and analysis of beach and tourism ecolabels to shortlist applicable ones for litter reduction at beaches, ii) an assessment of ecolabel effectiveness potential comparing ecolabel criteria with a list of litter-reduction measures, iii) an evaluation of the effectiveness of ecolabel implementation comparing litter pollution levels at beaches in North Africa with and without ecolabels, and iv) an identification of benefits and challenges of ecolabel implementation in North Africa, considering the perspectives of stakeholders and beachgoers from the region.

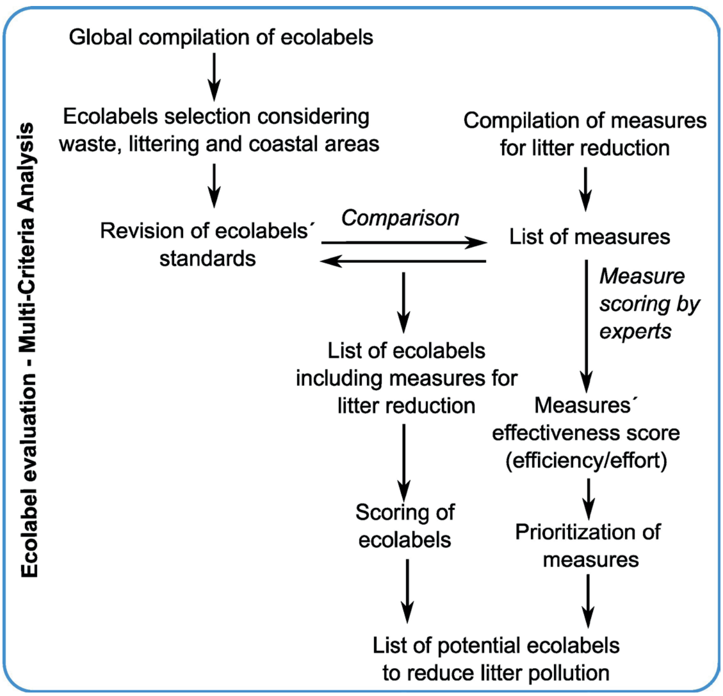


Figure 10. Methodology of the multi-criteria analysis (MCA) for the evaluation of ecolabels to assess their effectiveness and potential to reduce beach macrolitter. Taken from Paper V.

Ecolabel compilation and Multi-Criteria-Analysis

Beach and tourism ecolabels available globally were compiled up to February 2025, using the keywords “tourism ecolabel” and “tourism eco-certification”. Various spatial scales (international, regional, national) and tourism sectors (hotels, companies, destinations, beaches) were considered. A multi-criteria analysis (MCA), adapted from Zielinski and Botero (2015), was used to shortlist ecolabels including waste management criteria and applicable to the coastal zone. The MCA process involved a series of steps described in Fig. 10. Further details are described in Paper V. Ecolabel criteria were revised to extract data on 1) whether they considered beach and sea, 2) explicitly mention beach litter or general littering, 3) include waste management measures (e.g., solid waste, wastewater, or general waste reduction), 4) type of tourism sector targeted, 5) geographical scope, 6) alignment with global standards (e.g., ISO, GSTC), 7) validity period, and 8) associated costs (Paper V).

Litter reduction measures were compiled from different international frameworks, organizations and projects and grouped into eight categories (Appendix 1): 1) cleanups, 2) litter avoidance, 3) waste reduction, 4) alternatives, 5) management, policy and infrastructure, 6) monitoring, 7) stakeholder involvement, and 8) awareness and capacity building (Paper V). A total of 21 stakeholders evaluated each measure based on their perceived effectiveness and implementation effort (cost and time) to assign weights, and determine the measures considered most effective. Effectiveness was evaluated as the ratio between efficiency (impact) and effort required (cost and time) to implement the measure (Scholz, 1996). Measures were rated on a 0–4 Likert scale, with 0 = not at all efficient/effortful to 4 = highly efficient/effortful. The effectiveness score was the ratio of modes for efficiency and effort. Each ecolabel´s criteria were compared against the list of measures using a binary scoring system: 1 for compliance and 0 for non-compliance. Final scores indicate the ecolabel’s level of compliance with litter reduction measures (Paper V). Ecolabels addressing most of the effective measures in their criteria were considered the most effective for reducing beach litter.

Assessment of seasonal macrolitter pollution and mapping of ecolabeled sites

Macrolitter abundances obtained from beach litter surveys at Morocco, Tunisia and Egypt in Paper I (section 2.2) were complemented with literature to assess spatial and seasonal pollution patterns. Median values for beach macrolitter abundance (items per m^2) were calculated per beach type and season. Sandy beaches were mapped using *ArcGIS Pro* v3.3.5 and categorized following the definitions in Table 1. An additional beach type was included, “remote”, to characterize those beaches isolated from urban/village areas, lacking transport and accommodation infrastructure, and accessible only by private transport or by foot, which were not covered during our sampling but were however found on literature (Paper V). *Humanitarian OpenStreetMap* dataset (2025a, b, c) was used to extract hotels at a buffer zone of 300 m from the coastline and each site was validated via *Google Maps* to add missing entries. Only those hotels having direct beach access were included. Local tourism authorities and ecolabel websites served to identify ecolabeled beaches and hotels (*Plages Propres*, 2025a, *Blue Flag*, 2025, *Green Key*, 2025, *Green Globe*, 2025, *Green Star Hotel*, 2025, *Travelife*, 2025) to assess the proportion of ecolabeled versus non-ecolabeled sites (Paper V).

Stakeholder interviews and beachgoers surveys

Semi-structured opportunistic interviews were conducted to assess beach and hotel operations, waste management, and benefits and challenges of ecolabel implementation in Morocco, Tunisia and Egypt. Twelve beach managers were interviewed in total, however only three were interviewed regarding ecolabels (Paper V). Due to the low quantity of answers, the results here were only qualitatively summarized. Questions on ecolabels were:

1. Have you used tourism ecolabels? If not, do you think ecolabels could be useful to reduce beach litter in your region?
2. What was or what would be a motivation for you to implement an ecolabel (sustainable development, marketing, image, tourist demand, etc.)?
3. What are for you the challenges of implementing ecolabels?

A beachgoers survey was also conducted to assess public perception on litter, beach wrack, preferences on litter reduction measures, ecolabels and ecosystem services (Robbe et al. unpublished). In Paper V, only the results related to litter and ecolabels are presented. Questions included:

1. Would you prefer to visit a beach with an environmental label over a beach without one?
2. Which environmental labels for tourism and beaches have you heard of?
3. Which waste reduction measures at beaches would you personally accept? Which ones do you think are most effective?

Further details and the full list of questions are available in the supplementary material of Paper V.

3

Results and discussion

3.1. Macrolitter at beaches in the southern Mediterranean coast

Beach macrolitter surveys aimed to address the gap of research in the southern Mediterranean coast, to assess level of pollution, identify top polluting items and allocate sources of pollution. A total of 37 surveys were carried out in three countries (Morocco, Tunisia and Egypt). Given the high pollution levels in the region, an adaptation of the 100 m transect method was explored using 10 m transects, to test whether these shorter transects could reliably capture predominant litter items and approximate litter densities while reducing survey effort. The mean number of 10 m transects per site was five. Considering the two different methods used (adjacent transects and separate transects with a distance of 10–150 m in between), the results were similar. Mean coefficient of variance (CV) was ca. 18–28%, with higher CV with more adjacent transects or more distance between separated transects. Still, the relatively moderate CV and thus small variability of macrolitter abundance between transects, suggests that a survey using 10 m transects for highly polluted beaches could be an appropriate approach to decrease survey effort. In terms of frequency of the top litter items, all the top 25 litter item categories were found within 30m. This demonstrated that 10 m transects are sufficient to represent the litter characteristics of a beach with less effort (Paper I).

Considering all surveys, 71,391 macrolitter items (> 25 mm) were collected over a total surveyed area of 62,020 m^2. Plastics were the most common material found (80.5%), which is in accordance with the pollution observed at other sites (Addamo et al., 2017; Heinrich Böll Stiftung, 2019; Nachite et al., 2019). Abundances of litter per area were 0.22–13.69 items per m^2. Abundances extrapolated to 100 m, ranged from 436–24,270 macrolitter items (mean 5032 ± 4919 items per 100 m; median 3312). A total of 25 litter item categories were responsible for 81.9% of the macrolitter pollution overall, while 10 litter item categories contributed to 59.3% of total macrolitter. Single-use plastic items accounted for 45% of the total (32,131 items), with cigarette butts (20.9%, 6709 items), crisp packets/sweet wrappers (16.3%, 5212 items), plastic caps/lid drinks (15.6%, 4993) and small plastic bags e.g., freezer bags and pieces (13.9%, 4454 items) being the most common (Paper I). The predominant 10 items found at the southern Mediterranean coast were similar to what has been observed at other Mediterranean beaches (Vlachogianni et al., 2018), and the proportion of SUPs was comparable to what is found at European beaches (43%) (European Commission, 2019; Vlachogianni et al., 2020). The Clean Coast Index (CCI) was calculated for each beach to assess cleanliness levels. Most beaches were classified as extremely dirty (48.6%) or dirty (29.7%). The share of extremely dirty and dirty beaches is higher than what has been observed at regions of the world (Paper I). For example, in Chile, only 14–25% of beaches were considered dirty and none as extremely dirty (Rangel-Buitrago et al., 2019, 2020).

Pollution levels varied by beach type. Urban beaches (17) showed the highest pollution levels, with 0.34–13.69 items per m^2 (1,022–24,270 items per 100m, extrapolated). Touristic beaches (6) also showed high levels of pollution, with 0.41–3.20 items per m^2 (1,226–15,351 items per 100 m, extrapolated). In contrast, semi-rural and semi-urban beaches showed lowest pollution levels. Macrolitter abundance at semi-urban beaches (6) was 0.40–1.98 litter items per m^2 (1,352–6,680 items per 100 m, extrapolated) while at semi-rural beaches (8) was 0.22–1.69 items per m^2 (436–5,558 items per 100m, extrapolated) (Fig. 11) (Paper I). The higher level of pollution at touristic and urban beaches could be related to their use (Table 1) and the level of infrastructure, as it has been observed at other sites, like in Italy (Poeta et al., 2016), Kenya (Okuku et al., 2020) and Brazil (de Ramos et al., 2021). While long-term beach litter monitoring mostly address semi-urban and rural beaches, it has become important to address touristic and urban beaches to assess the effect of mitigation measures over time. For this, more detailed analyses need to be carried out, which were not part of this study. For example, the level of infrastructure, distance to tourist accommodations, number of parking lots and type of beach access are some of the factors that can be evaluated through Generalized Additive Mixed Models (GAMM) to assess the responsible variables influencing spatio-temporal variability of macrolitter pollution (De Veer et al., 2023). However, the influence of these parameters on litter abundance cannot be accurately assessed based on a one-time survey, thus repeated surveys are required.

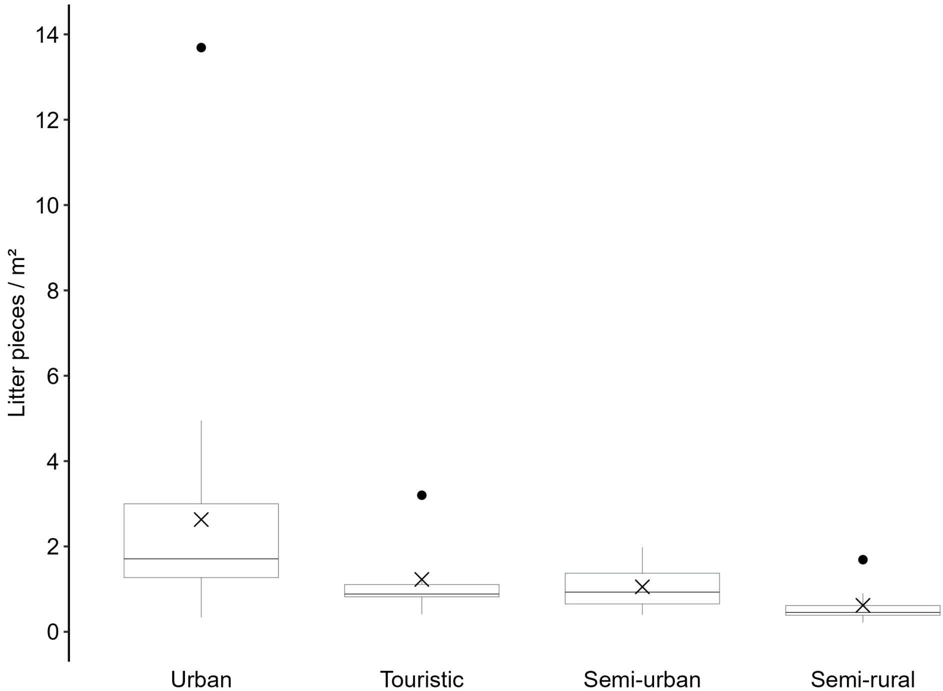


Figure 11. Macrolitter pollution in litter items per m^2 per beach type. Mean value is indicated by the “X”. Error bars reveal minimum and maximum, dots exhibit outliers (taken from Paper I).

In terms of pollution levels per country, high levels of macrolitter abundance were observed at all three sites. In Morocco, macrolitter abundance was 0.29–3.00 items per m^2, (1,304–5,558 items per 100 m, extrapolated) with a median of 0.52 items per m^2 and 39.7% being SUPs (8044 items) (Table 5). Comparing with results obtained at other studies, our results were on average 4–13 times higher (Nachite et al., 2019; Ministère de la Transition Energétique et du Développement Durable, 2022). Macrolitter abundance in Tunisia in 2021 was 0.41–13.69 items per m^2 (1022–12,325 items per 100 m, extrapolated) with a median of 1.20 items per m^2, and 46.5% being SUPs (8234 items) (Table 5). Litter abundances found at our study in Monastir (Tunisia) in autumn 2021, were nearly 8 times higher than what had been previously observed for the same beach (Dhiab Rym et al., 2022). In Egypt, macrolitter abundance was 0.80–4.95 items per m^2 (1,964–24,270 items per 100 m, extrapolated) with a median of 2.38 items per m^2, and 51.1% being SUPs (11,123 items) (Table 5). A study estimating beach pollution in Alexandria (Egypt) showed plastic pollution 3 times higher than our estimated results, attributed to the long pause in beach cleaning during the COVID-19 pandemic (Hassan et al., 2022). The overall higher pollution observed at Tunisian and Egyptian beaches, in comparison to Moroccan sites, is likely attributed to an accumulation of litter due to the pause in beach cleaning during the pandemic (Paper I).

Table 5. Top ten litter item categories found in the macrolitter surveys in total numbers, percentage and cumulative percentage. Note that no cigarette butts were surveyed in Tunisia 2021. Data from the survey in Tunisia 2022 is available in Paper I. Single-use plastic item categories are shown in grey (adapted from Paper I).

	Tunisia 2021	Egypt 2022	Morocco 2023
1	Plastic pieces 2.5 cm > < 50 cm 2546/14.4%	Cigarette butts and filters 3662/16.8%	Plastic pieces 2.5 cm > < 50 cm 2720/13.4%
2	Plastic caps/lids drinks 1802/10.2%/ 24.6%	Plastic pieces 2.5 cm > < 50 cm 2766/12.7%/29.5%	Cigarette butts and filters 2350/11.6%/25.0%
3	Crisp packets/sweet wrappers 1674/9.5%/34.0%	Small plastic bags, incl. pieces 1873/8.6%/38.1%	Crisp packets/sweet wrappers 1299/6.4%/31.5%
4	Shopping Bags incl. pieces 1311/7.4%/41.4%	Crisp packets/sweet wrappers 1487/6.8%/45.0%	Plastic caps/lids drinks 1158/5.7%/37.2%
5	Small plastic bags, incl. pieces 1022/5.8%/47.2%	Industrial packaging, plastic sheeting 1282/5.9%/50.9%	Polystyrene pieces 2.5 cm > < 50 cm 853/4.2%/41.4%
6	Slack/Coal 657/3.7%/50.9%	Plastic caps/lids drinks 962/4.4%/55.3%	Foam sponge / foamed plastic items 801/4.0%/45.3%
7	Polystyrene pieces 2.5 cm > < 50 cm 629/3.6%/54.2%	Straws and stirrers 816/3.7%/59.0%	Small plastic bags, incl. pieces 797/3.9%/49.3%
8	Cotton bud sticks 616/3.5%/57.9%	Food contaimers incl. fast food containers 758/3.5%/62.5%	Food waste (galley waste) 796/3.9%/53.3%
9	Paper fragments 611/3.5%/61.4%	Food waste (galley waste) 720/3.3%/65.8%	Carpet plastic string 748/3.7%/56.9%
10	String and cord (diameter less than 1 cm) 505/2.9%/64.3%	String and cord (diameter less than 1 cm) 653/3.0%/68.8%	Lolly sticks 740/3.7%/60.6%

Litter source allocation was done for the top 25 litter item categories. Land-based sources were predominant in the region, with 58.2–68.8% of the litter attributed to "shoreline, including poor waste management practices, tourism, and recreational activities" (Fig. 12). This source was relevant at all beach types, also observed by other studies in the same countries (Alshawafi et al., 2017; Nachite et al., 2019; Mghili et al., 2020) and in other Mediterranean sites (UNEP/MAP, 2015; Vlachogianni et al., 2018). In contrast, sea-based sources were less predominant (6.9–11.9%) (Paper I). Transboundary litter has been suggested as a problem in the Mediterranean, where litter is transported from and to different countries (Liubartseva et al., 2018). Thus, although litter is classified as land-based, it is possible that it comes from a different country (Paper I).

River transport is not fully accounted in this source allocation (Paper I). At least 11 (temporary) rivers flow in North Africa during rainy season or specific periods, each releasing 2–200 tonnes of plastic annually (Lebreton et al., 2017). The Nile River, which flows through Egypt, is considered the largest contributor of plastic litter into the Mediterranean Sea, with estimates that go from 200–2,000 tonnes (Lebreton et al., 2017), 6,772 tonnes (Liubartseva et al., 2018), and up to 7,043 tonnes per year (Schmidt et al., 2017). However, such estimations do not consider the retention of litter along the riverbeds and river vegetation or by dams, which has been observed in other studies (Boucher and Billard, 2020; van Emmerik et al., 2022). The influence of these processes on litter retention are further discussed in section 3.3.

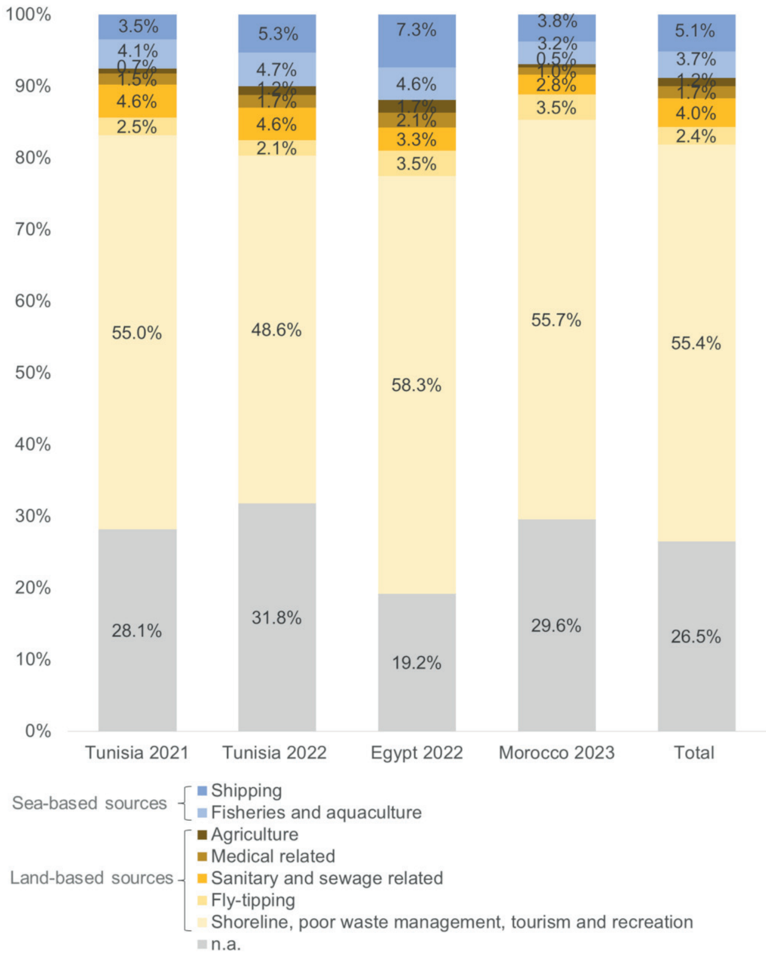


Figure 12. Macrolitter source allocation for the different macrolitter survey campaigns and in total (taken from Paper I).

3.2. New methods for beach macrolitter monitoring: Aerial drones

Considering the effort required to monitor highly polluted sites, here aerial drones were tested to assess whether they could serve as a tool to speed up beach macrolitter monitoring. For this, aerial drone surveys and image analyses using supervised object-based classification with three different algorithms (ML – Maximum Likelihood, RF – Random Forests and SVM – Support Vector Machine) were carried out. These methodological tests were conducted in the southern Baltic Sea. While it was intended to further test the methodology at highly polluted beaches, this was not carried out due to legal restrictions.

RGB images are not the best for image classification based on spectral signatures, and the combination with other sensors is recommended (Tasseron et al., 2021; Pérez-García et al., 2024). However, this option was not available at the time of the study; thus, a simplified approach using the visible RGB range was assessed. Preliminary image analyses to assess the spectral profile from different objects present at the beach was carried out to define the number of classes for classification. Here algae, vegetation, shells, stones, sand and litter, revealed that natural objects had clear and consistent spectral profiles, which could be distinguished from other classes. In contrast, litter objects presented no consistent spectral profile, due to the high variety of colors they can be encountered in (Paper II).

Recovery experiments were aimed at training the samples for supervised object-based classification at 100 m beach transects. Image classification within recovery sites with four classes (litter, vegetation/algae, stones/shells, sand) showed Total Accuracies (TA) of 36–90% for ML, 54–73% for RF and 44–75% for SVM, depending on flight height and site. Producer´s accuracy (PA) for litter, specifically, was 45–100% for ML, 67–95% for RF and 61–100% for SVM. User´s Accuracy (UA) for litter was lower for all algorithms; 18–88% for ML, 8–39% for RF and 14–75% for SVM with four classes (Paper II). Kappa values were > 0.60 in most cases, indicating that classification was better than random (Fig. 13). In contrast, classification of the recovery areas with six classes, revealed lower accuracy values for all algorithms and sites, with kappa values of < 0.60 (closer to random) (Fig. 14). These results showed that litter > 2.5 cm was the minimum size detectable; smaller items were detected but were often misclassified (Paper II). Other studies also showed limitations detecting small items, where sizes < 4 cm were most misclassified (Martin et al., 2018). The misclassification from our analysis is attributed to the fact that it relies on pixel color, which is influenced by object color, weather, light conditions, and background substrate (Martin et al., 2018). Moreover, the selection of training samples is also based on the judgement of the analyst, increasing error chances and misclassifications. No clear differences were observed in regards to algorithm performance to detect litter items (Fig. 13 and 14). Moreover, the overall classification accuracy was highest for images taken at 10m flight altitudes. Higher TAs were also seen at images taken at 15 m or 18 m; however, this was mainly due to higher accuracies in classes other than litter (Paper II). The classification of 100 m beach transects (with unknown number and type of litter items, images taken at 10 m flight height for German sites and 15 m for Klaipeda), showed lower accuracies, with kappa values of 0.23–0.54 for classification with four classes, and 0.11–0.64 with six classes, indicated a rather random classification with different algorithms where none could show a good performance in all cases (Fig. 15) (Paper II).

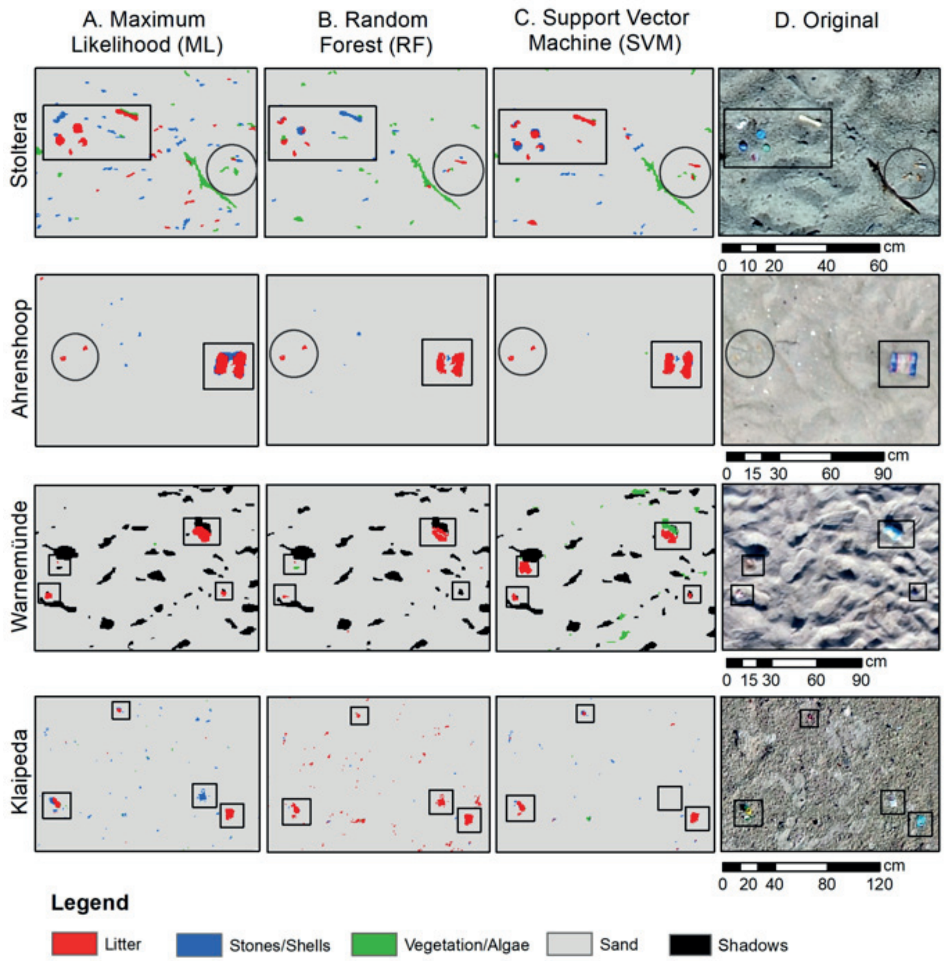


Figure 13. Comparison of supervised object-based classification with four classes with algorithms ML, RF, and SVM on aerial images at 10 m at sites Stoltera (Germany), Ahrenshoop (Germany), Warnemünde (Germany) and Klaipeda (Lithuania). Each close-up image shows litter objects on the recovery site (D) and their classification result (A–C), such as litter objects of different sizes (square) and cigarette butts (1–2.5 cm) (circle). Taken from Paper II.

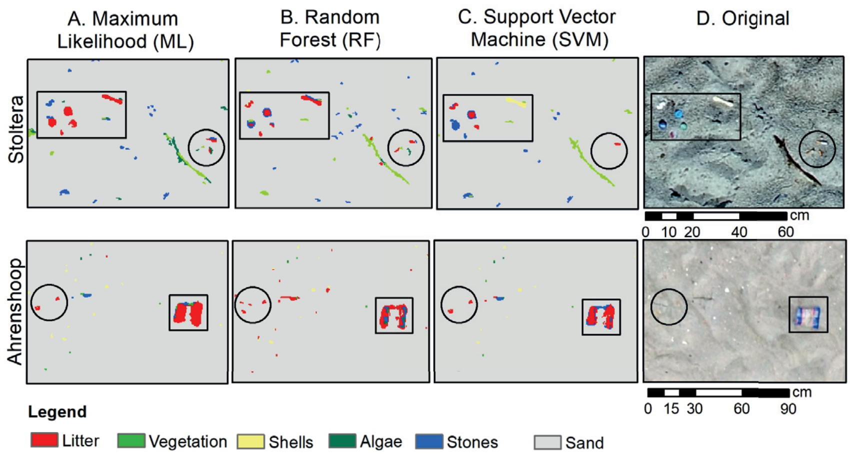


Figure 14. Comparison of supervised object-based classification with six classes with algorithms ML, RF, and SVM on aerial images at 10 m at sites Stoltera and Ahrenshoop. Each close-up image shows the distribution of litter objects on the recovery site (D) and their classification result (A–C), such as litter objects of different sizes (square) and cigarette butts (1–2.5 cm) (circle). Taken from Paper II.

Supervised object-based classification, as the one used here, was not suitable for detecting and classifying litter from drone imagery. Limitations included: 1) RGB images based on pixel color, which is highly influenced by weather, light conditions, item color/shades, and background substrate; therefore, training samples cannot be transferred to other sites (since at such small scale, pixel color varies greatly) (Paper II). These aspects have also been observed at a study assessing the suitability of spectral bands in the VIS and NIR range (Pérez-García et al., 2024). 2) Segmentation used low segment sizes to include small items, however, this led to one item having several segments and litter "objects" could not be counted as such, since the number would be overestimated, and 3) classification cannot provide a distinction of litter type, but rather only detection of litter and their distribution, which in our study presented high level of misclassification at 100 m beach transects (Kappa values of 0.11–0. 64) (Fig. 15) (Paper II). For these reasons, this type of image analysis is not sufficiently accurate or time-efficient to detect and classify litter for monitoring purposes.

Other image analysis methods, such as multispectral or hyperspectral sensors, may improve the detection of litter to allow estimations of abundance and distribution, as well as the identification of material composition (Levin et al., 2006; Acuña-Ruz et al., 2018; Garaba et al., 2018; Tasseron et al., 2021, 2022; Pérez-García et al., 2024). However, one of various challenge is the detection of litter partially buried or hidden by dunes or vegetation

(Kataoka et al., 2018). Multispectral drone cameras have demonstrated the potential to detect litter at beaches (Gonçalves and Andriolo, 2022) and half-buried plastic bags (Oberski et al., 2025), and hyperspectral cameras have even shown the potential to detect and classify plastics by polymer type (Balsi et al., 2021, 2025). These sensors can enable the detection of litter at dunes or vegetation, but also floating on coastal waters (Tasseron et al., 2021, 2022).

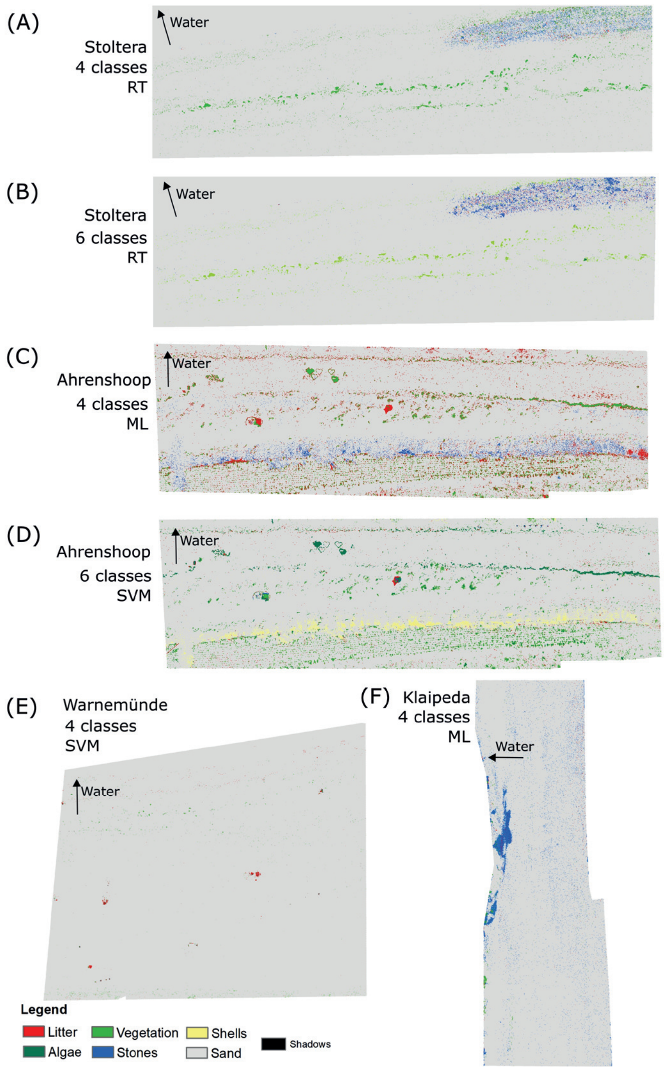


Figure 15. Object-based supervised classification of 100 m beach transects taken at 10 m flight height. Only the results with best total accuracy (TA), producer's accuracy for litter (PA) and kappa value of agreement with 4 and 6 classes are shown for each site: Stoltera (A,B), Ahrenshoop (C,D), Warnemünde (E) and Klaipeda (F). Taken from Paper II.

Another challenge is the classification of litter by material and item type to identify predominant litter items, to derive sources of pollution and define appropriate management measures. While the majority of remote sensing studies have relied on traditional methods like manual screening, various studies have demonstrated the potential of deep learning approaches, specifically convolutional neural networks (CNN), enabling litter detection with accuracies of 80–90% (Kako et al., 2026). Litter classification by type is also conducted, however, the accuracy achieved is lower than with binary detection (litter/non-litter) (Pinto et al., 2021; Pfeiffer et al., 2023). For this reason, newer approaches are using already annotated image databases, like *Google Image Database* (Google, 2025) or *ImageNet* (Deng et al. 2009) which contain images of items in a new state, but also *TrashNET* (Aral et al. 2008) or *SODA* (Pisani and Seychell, 2024) which contain images of weathered items as found in the real environment, and social media images (Pan et al., 2024). A study using social media images in Japan for the detection of plastic PET bottles in rivers achieved a F-score of 0.9 (Pan et al., 2024), while a study aiming at the automatic detection of litter at beaches using *Google Images* and *TrashNET* achieved accuracies of 87% (Nazerdeylami et al., 2021). Most recently, a study showed the potential of using deep learning and 5G communication network for real-time litter detection and classification at beaches, achieving an accuracy of 95–98% for different litter types (Duangsuwan and Prapruetdee, 2024). These new approaches using annotated image databases for litter detection and classification could make drone monitoring highly reproducible, decreasing chances of human error, due to surveyor experience, weather or light conditions, which have been estimated at ± 15% for litter detection with volunteers (Schernewski et al., 2017). Nevertheless, limitations may be encountered for local litter items that are not widely found, and for which the necessary training data will need to be collected to train the models (Kako et al., 2026).

Monitoring approaches need to be carried out long-term to provide sound data on spatio-temporal patterns, and therefore, assessing their cost-efficiency (in terms of effort and costs required for implementation) is highly important. Cost-efficiency of aerial drones (UAV) and the OSPAR method was compared, considering 100 m and 1 km beach transects. For details on the terminology and updated calculation, refer to Appendix 2.

Results showed that the UAV monitoring method for 100 m and 1 km transects involved higher initial costs and ca. two times higher costs and time effort for field work and analysis than the OSPAR method (Table 6). Higher investment costs were mainly attributed to the license software required to analyze the imagery. If open-source software was used, these costs would be reduced to only 3,000 €. Costs for the testing period of implementation were higher for the UAV method, estimated as 30,000 € for the 100 m and 1 km transect monitoring vs. 15,000 € for the OSPAR method. Office costs were the same for both methods. Annual running field costs were lower for the UAV method at 100 m beach transects (1,800 € vs. 2,400 € for the OSPAR), but higher once spatial extension increased to 1 km (2,400 € vs. 1,800 € for the OSPAR method). Annual running costs for data analysis were considerably higher for UAV than for the OSPAR method (4,800 € vs. 2,400 € for 100 m and 9,600 € vs. 1,200 € for 1 km). The overall cost-efficiency score for beach litter monitoring was 9–12 (low to moderate) for the UAV method vs. 16–18 (high) for the OSPAR method (Table 6) (Paper II).

Table 6. Cost-efficiency analysis for UAV and spatial-OSPAR for beach litter monitoring methods. The values are based on our experience taking into account the MSFD guidelines (JRC, 2013) and federal state authority staff salaries (37.5 € per hour), for a monitoring of four beaches, four times a year. In bold are shown the scores for cost and efficiency, giving the cost-efficiency score. Taken from Paper II. Updated calculations are in Appendix 2.

Costs	Description	Items > 2.5 cm 100 m monitoring		Items > 50 cm 1 km monitoring	
		UAV	OSPAR	UAV	OSPAR
Investment and initial test for implementation[a]	Costs of equipment, software, methodological tests in the field, training for field work and analysis	48,000 €	15,100 €	48,000 €	15,100 €
Annual office costs[b]	Orders, selection of sites, drone permissions and licenses, reporting, annual replacement costs for materials	10,000 €	10,000 €	10,000 €	10,000 €
Annual field/lab costs[b]	Travel to site, survey, analysis of data	10,600 €	5,800 €	16,000 €	4,000 €
Annual running costs		20,600 €	15,800 €	26,000 €	14,000 €
Total annual costs[c]		36,600 €	20,833 €	42,000 €	19,033 €
Person hours/year		1,296	768	1,440	720
Cost score		**3**	**4**	**3**	**4**
	<u>Efficiency</u>				
Accuracy		3	4	5	5
Reproducibility		5	3	5	5
Flexibility		1	4	2	4
Quality		3	5	4	4
Efficiency score		**3.0**	**4.0**	**4.0**	**4.5**
Cost - Efficiency		**9 (Low)**	**16 (High)**	**12 (Moderate)**	**18 (High)**

[a] One-time investment to be done every 3 years, considering a drone lifetime of 3 years and renewal of training
[b] Considers brutto salary for a federal state authority in Germany (37.50 € per hour, in 2020)
[c] Considers a third of the investment and initial costs added to the annual running costs.

At the time this study was developed, the *DJI Phantom 4 V2* drone used was still relatively new, but has now been replaced by at least four new versions (*Phantom 4 Advanced, RTK, RTK SE and Multispectral*) (DJI, 2025). Like this, technology has advanced at a very fast pace, with improved camera qualities, sensors and battery life, which improve resolution and decrease the time and costs required for mapping. Considering the new technology and the increased access provided by artificial intelligence (AI) to speed up data processing and image analysis, our cost estimations can be updated (Appendix 2). Costs for software and data analysis can be reduced from 18,000 € (due to software license) to 2,600 €, and annual replacement costs can be reduced from 4000 € to 1400 € (Appendix 2). The time for analysis is highly related to the method used. We consider 6 months of data training, which could be allocated for image annotation and training algorithms. Once this is achieved, the time for image analysis could be decreased from the estimated 8 h for image manual screening per beach, to approximately 2–4 h per beach with deep learning approaches with already trained algorithms, depending on image resolution and item size to be detected. Like this, time for analysis could be reduced by 75% than our previous calculation (Appendix 2). In this sense, the total annual costs can be highly reduced leading to total annual costs of ca. 25,300 € for the monitoring of macrolitter items (> 2.5 cm) at 100 m transects and ca. 27,000 € for the monitoring of items > 50 cm at 1 km transects; being within the same cost score of the OSPAR methods (Appendix 2).

Our assessment of efficiency of UAVs can also be updated using literature as reference. Accuracy of the classification for litter items > 2.5 cm could be increased to 4 (considering an accuracy of 95–98%, as obtained by Duangsuwan and Prapruetdee (2024). Quality of the data could be increased to 4, considering the newest approaches for litter classification by type (Nazerdeylami et al., 2021; Pan et al., 2024) and material (Balsi et al., 2021, 2025) previously discussed. Reproducibility of the method can be further ensured by using suggested drone settings (Escobar-Sánchez et al., 2022; Andriolo et al., 2023). Here, a guideline considering different coastal compartments has been created to achieve harmonization (Isobe et al., 2024). Flexibility is, however, still the main limitation for establishing drones as monitoring tools and, therefore, remains with a value of 1 (Appendix 2). Legal permissions are required to fly drones at most places, with strict regulations at the European Union (EU 2018/1139, EU 2019/947, EU/2019/945), establishing no-fly zones at areas of high urban density or nature protected areas (EU 2019/947) which are often sites of research interest. At several other countries, such as those in North Africa, the use of drones is strictly prohibited or only allowed with a government permit which is not always granted (Dronemade, 2025). Drone pilot licenses are also required to operate all types of aerial drones (EU 2019/947). Limitations may increase in the future, considering aspects of data privacy and complex political atmosphere in different countries. Considering these aspects, efficiency can be increased to 3.50 for monitoring of both > 2.5 cm at 100 m transects and > 50 cm items at 1 km transects. Overall, the cost-efficiency of aerial drones increases to 14 (moderate) (Appendix 2), suggesting that drone technology and deep learning approaches could be a suitable option to speed up monitoring and can be further explored.

In conclusion, several benefits can be derived from using aerial drones for litter monitoring. First, sampling efforts and the fatigue aspect, often encountered with volunteers, can be reduced if automatic detection is carried out. Second, beach maps obtained with drone imagery can assess spatial distribution of litter on a beach and provide estimations of litter density at different areas (dunes, tide lines, river banks) (Gonçalves et al., 2020; Andriolo et al., 2023; Ayana et al., 2025). Third, drone imagery can cover areas of high pollution or after tsunamis or storms (Murphy, 2015) or social events, speeding survey time to assess pollution levels and design removal or mitigation measures. Aerial drones could also serve to complement risk map analysis, addressing accumulation areas of pollution near waterbodies (Kalonde et al., 2025), for which management measures can then be implemented. In this way, measures can target the areas with highest pressure, where they will be more impactful. Fourth, drones can also serve to access and survey rocky coasts, remote or fragile sites (Castellanos-Galindo et al., 2019; Fallati et al., 2019; Sousa-Guedes et al., 2025), often not considered during regular monitoring. Finally, the data obtained can be used to build a database over time, that allows detailed analysis of the influence of different factors on litter distribution (weather, geomorphology, infrastructure, etc) for spatio-temporal analysis, as done for satellite imagery (Kataoka et al., 2018; Kako et al., 2026).

3.3. Emissions, pathways and sinks of litter pollution in the Warnow estuary, Germany

3.3.1 Land-to-estuary emission estimation

Land-to-estuary litter emissions during the *Hanse Sail* festival were estimated through sampling of floating litter items in the Warnow estuary using different methods which took place before, during and after the event (Paper III). Here we focus on the results from 2018 (Fig. 16). During this sampling, a total of 1333 floating items were found in the waterfront of the harbour, with over 90% classified as macrolitter, and with 85% being plastic (ca. 1143 items), mainly PE (37%) and PP (41%). Here, 21% were cigarette butts, 54% were SUP tableware or packaging and 27% was plastic confetti. The spatial coverage of the sampling allowed to assess the spatial distribution of floating litter, which showed a higher concentration of items (798 items) along the harbour wall, in front of the *Hanse Sail* festival (Fig. 16). Considering the entire area of the city harbour (1.4 km^2), the pollution of macrolitter was ca. 950 items per km^2 (810 items per km^2 for plastic only) (Paper III).

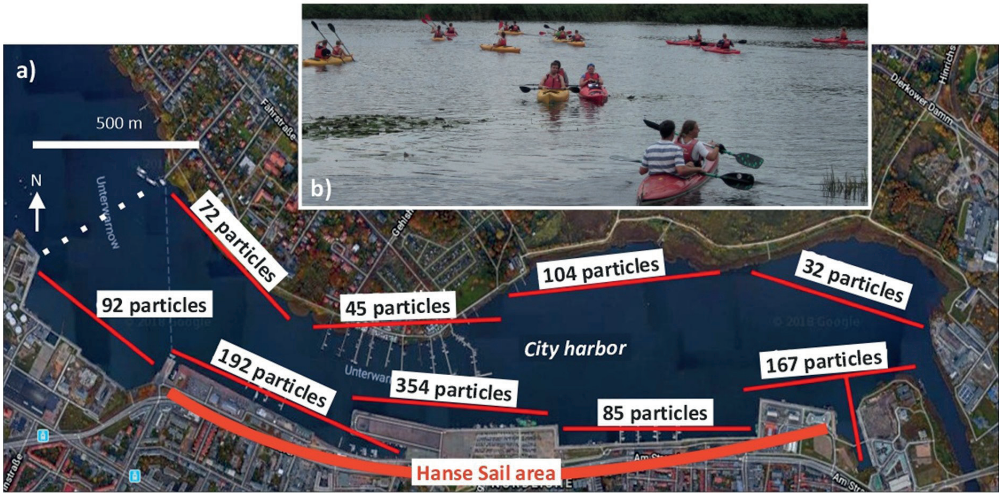


Figure 16. a) Floating litter items found on the water surface in different parts of the city harbor in Rostock after the *Hanse Sail* 2018 (Appendix B from Paper III). The thick red line indicates the 2.2 km extent of the *Hanse Sail* activities along the south coast; the dotted white line indicates the boundary of the city harbor (map: *Google Maps*). b) Photo taken during the sampling activity. Taken from Paper III.

Litter emissions from land into the estuary were calculated considering the results from the sampling of floating litter and assuming that *Hanse Sail* had 1 million visitors (500,000 visitors for 2023). The following assumptions were considered: 1) the survey covered only 50% of the total area, 2) 10% of the litter had left the surveyed area before the survey, 3) small items, such as cigarette butts were not found, since they are only temporarily buoyant, and 4) 25% of the litter found was already in the water before the *Hanse Sail* event. Based on this, litter emissions from land into the estuary were estimated at 3 items per 1000 visitors, or 3000 items in total. Using the data from 2019 (1492 items) and similar assumptions, emissions were estimated at 3.7 items per 1000 visitors or 3700 items in total. Considering the data obtained during the 2023 survey, which covered the reed belt and harbour area finding only 19 items, the litter emissions from land into the estuary were estimated at 0.24 items per 1000 visitors, or 120 items in total. Various uncertainties can be introduced during the sampling of litter at rivers or estuaries, related to the area covered during sampling, observation time, sampling frequency and recovery rate related to the characteristics of litter (Vriend et al., 2025). Despite the different methods considered in our study, the limited data basis led to an estimated uncertainty of ±100% and require further sampling to assess the spatial distribution of litter. Further methodological limitations are described in Paper III.

The strong decrease in litter in the water surface between 2018 and 2023 was attributed to the "Sustainability Concept" designed for the *Hanse Sail* event, which decreased visitor density next to the water border and implemented deposit systems for cups, mandatory use of degradable and compostable tableware, optimized waste bins distribution, frequent waste collection and ground cleaning/sweeping overnight (Hanse Sail, 2024). Considering the 50 tonnes of waste collected during the *Hanse Sail* event, it was estimated that 100 g of waste were generated per visitor. Considering the 12.1 kg of floating litter collected in the harbor area during 2018, and assuming a total waste generation of ca. 60 tonnes, about 0.02% of all waste (in weight) produced during the event ends in the harbor water (land-to-estuary emission) (Paper III). Since the waste from events is collected mixed, the 60 tonnes represent all waste materials (also non-plastic and non-consumer waste), thus waste data providing proportions per material (especially plastic) could provide better estimations. Nevertheless, estimations of litter items from weight-based estimations still present several weaknesses (Smith and Turrell, 2021) and more research is needed to improve these results.

3.3.2 Extrapolation of coastal festival emissions using two waste management scenarios

Litter emissions from over 50 sailing and coastal festivals (11 largest) were estimated to assess the potential transport of litter towards the Baltic Sea, considering two waste management scenarios: 1) an improved waste management system (litter emissions of 0.24 items per 1000 persons, based on *Hanse Sail* 2023) and 2) before improved waste measures (3 items per 1000 visitors, based on *Hanse Sail* 2018) (Table 7). It was assumed that ca. 85% of the litter was plastics (as observed in 2018). Considering the worst scenario (scenario 2), litter emissions from land into the estuary per event remain below 12,000 items, and about 56,000 items considering the 50 festivals around the Baltic Sea. With an improved waste management scenario (scenario 1), the Baltic wide litter emissions reach about 4500 items (Table 7). It is important to consider, however, that we assume similar festival characteristics as the *Hanse Sail* for other Baltic coastal festivals, and the level of uncertainty in emission estimation is high (± 300%), thus more event-related data is needed to improve estimations. Further methodological limitations are described in Paper III.

Table 7. Estimated Baltic-wide annual macro-litter emissions resulting from harbor and sailing festivals. The most recent visitor numbers, mainly for 2023, were used. Scenario 1 assumes an emission of 0.24 litter items per 1000 visitors based on calculations for *Hanse Sail* 2023. Scenario 2 is based on an emission of 3 litter items per 1000 visitors as calculated for *Hanse Sail* 2018. Taken from Paper III.

Festival	City	Country	Visitors	Days	Emission scenarios	
					Scenario 1	Scenario 2
Hanse Sail Rostock	Rostock	Germany	500,000	4	120	1500
Warnemünde Week	Rostock	Germany	650,000	9	156	1950
Travemünde Week	Travemünde	Germany	500,000	10	120	1500
Kiel Week	Kiel	Germany	3,800,000	9	912	11,400
River Harbour Festival	Turku	Finland	550,000	3	132	1650
Baltic Herring Market	Helsinki	Finland	80,000	7	19	240
Maritime Festival	Kotka	Finland	200,000	4	48	600
Maritime days	Tallinn	Estonia	130,000	4	31	390
Klaipeda Sea Festival	Klaipeda	Lithuania	500,000	3	120	1500
Baltic Sail	Gdansk	Poland	3,700,000	4	888	11,100
Tall Ships Races	Szczecin	Poland	2,000,000	4	480	6000
Total of smaller events			6,000,000		1440	18,000
		Sum	**18,610,000**		**4466**	**55,830**

3.3.3 Particle transport and retention simulations for the assessment of estuary-to-sea emission

To assess particle transport and retention potential, a total of 3000 particles were used as input for the Lagrangian particle tracking model, assessing their transport during 10 days in August 2009 and 2010 (Fig. 17A). The model results showed that during the simulation of 2009 (August 6th to 9th, 2009), wind speeds of 4 m/s (gentle breeze) from easterly direction caused the transport of particles towards the west, accumulating at reed belts 3 km away from the harbor. At the end of the festival, 42% of particles remained in the waterfront of the harbour, while 58% were further transported into other sections of the Warnow estuary. Six days after the festival, 28% of the particles were trapped in the reed belt area in front of the harbour, while 72% were trapped in the lower Warnow estuary section (Paper III). The trapping in the reed belts could be observed on site, however quantification of the litter trapped was limited due to inaccessibility (Fig. 17B).

Comparing with model results for the simulation of 2010 (August 5th to 8th, 2010), northwesterly winds scattered particles towards the south, causing an accumulation of litter along the quay walls and hard walls which do not allow particle trapping (Fig. 17). Changing wind directions after the festival caused the transport of particles up to 7 km northward from the event location where particles were trapped along reed belts and small beaches of the Warnow estuary. 88% of the particles remained trapped in the harbour, while 12% were further transported into other sections. Six days after the festival, 17% of all emitted particles were trapped in reed belt areas in front of the harbour, 76% were trapped in the lower Warnow estuary section, and 6% in northern parts of the estuary. The majority of particles were trapped within 7 km away from the festival area, and only 0.4% reached the opening to the Baltic Sea (11 km) (Fig. 17B). This long-distance transport is unusual, as it was demonstrated by data collected by *NABU* close to the Warnow opening. Here, tableware waste (which could be attributed to the *Hanse Sail*) was low (13–31 particles, a share of 0.25–0.28% from the total) (Paper III).

The high retention and trapping potential observed for the Warnow estuary is expected to occur similarly for other microtidal estuaries of the Baltic Sea. The tidal ranges below 0.2 m play an insignificant role in the movement of water and litter landward or seaward. Instead, wind and salinity play more important roles in transport, which can shift estuarine circulation under storms (Lange et al., 2020). The geomorphology of the estuary and predominant wind direction also determine trapping. The Warnow estuary has predominant west to north-west winds (Lange et al., 2020), thus if particles are emitted at the *Hanse Sail* location, the majority will be transported towards the reed belt areas in the east of the city harbour (Fig. 17A). In case of northern winds, water transport from the sea to the land may occur, further retaining litter inland. In the case of storm events and changing wind direction e.g., south dominated (as it was observed for the 2010 simulation), water transport from the river to the sea occurs, causing a flushing effect of litter into northern sections of the estuary (Fig. 17B). However, the presence of storms in the German Baltic Sea are more common in winter and autumn (BSH, 2025), which does not coincide with the time the *Hanse Sail* takes place. To confirm this, a recent study using the same hydrodynamic and Lagrangian model approach for the Warnow estuary simulated litter emissions every 12 hours and assessed their transport during different seasons over an entire year, finding total annual retention of 91.0% in winter and 98.2% in autumn, in contrast to 97.4% in summer and 93.3% in spring. The distance travelled by the particles was shortest in the summer, with 70% remaining within 400 m away from the emission point (Ramos et al. in review), thus further supporting our findings of high retention, regardless of season.

Macrotidal systems have shown to highly influence transport dynamics causing remobilization. Schreyers et al., (2024) estimated the net plastic transport over full tidal cycles at the Saigon River in Vietnam and found out that the net plastic transport was only 20–33% of the total plastic transport. This high litter retention potential has also been observed at the Loire estuary in France, where bottles with GPS trackers had a travel time in water that did not exceed 4 days before stranded, and for items that were remobilized, they were stranded again after a median of 3 days. The tracked bottles spent 2 months in water and travelled up to 100 km, without any of them reaching the ocean (Ledieu et al., 2022).

In addition to wind, salinity also influences the transport dynamics at estuaries and salinity gradients can act as barriers of litter and accumulation areas (Le et al., 2024, 2025). This was observed in Río de la Plata, Argentina (Acha et al., 2003), the fjords of Patagonia in Chile (Hinojosa et al., 2011) and between the coastal and offshore waters of the German Bight, North Sea (Gutow et al., 2018). Based on this, it can be expected that all estuary systems retain litter over time and depending on tidal cycles or storms, a release of litter may occur.

Besides the complex interactions regarding estuarine circulation, near-surface transport, harbour infrastructure, shoreline morphometry and presence of vegetation, revealed in Paper III, the need for more research addressing aspects like particle buoyancy (determined by item size, shape and density), or windage, sinking and remobilization were highlighted. These aspects are still open questions in several particle tracking simulations. Particle size and shape for macroplastics have not been fully explored, but it is suggested that these aspects play less of a role than buoyancy (Van Utenhove, 2019). Particle buoyancy will determine its position in the water column, where processes like windage, sinking and vertical remobilization occur. Windage has shown to increase the travel velocity of items, leading to faster beaching (Van Utenhove, 2019). The same process has also been observed at the field. Schreyers et al., (2024) observed that soft and neutrally buoyant items experienced lower net transport rates (10–16%) than rigid, highly buoyant items (30–38%). This can already suggest the role of windage in item transport. Similarly, Tramoy et al., (2020) and Ledieu et al., (2022) used GPS trackers inside bottles which were either half-submerged (vertically) and floating (horizontally), observing that those floating horizontally were more subject to windage and thus faster transport rates and shorter travel distances. For higher dense particles reaching the riverbed, bottom shear stress and other bottom currents may remobilize it (Van Utenhove, 2019). These aspects need to be further explored to be able to refine litter emissions and plastic budget at rivers and estuaries.

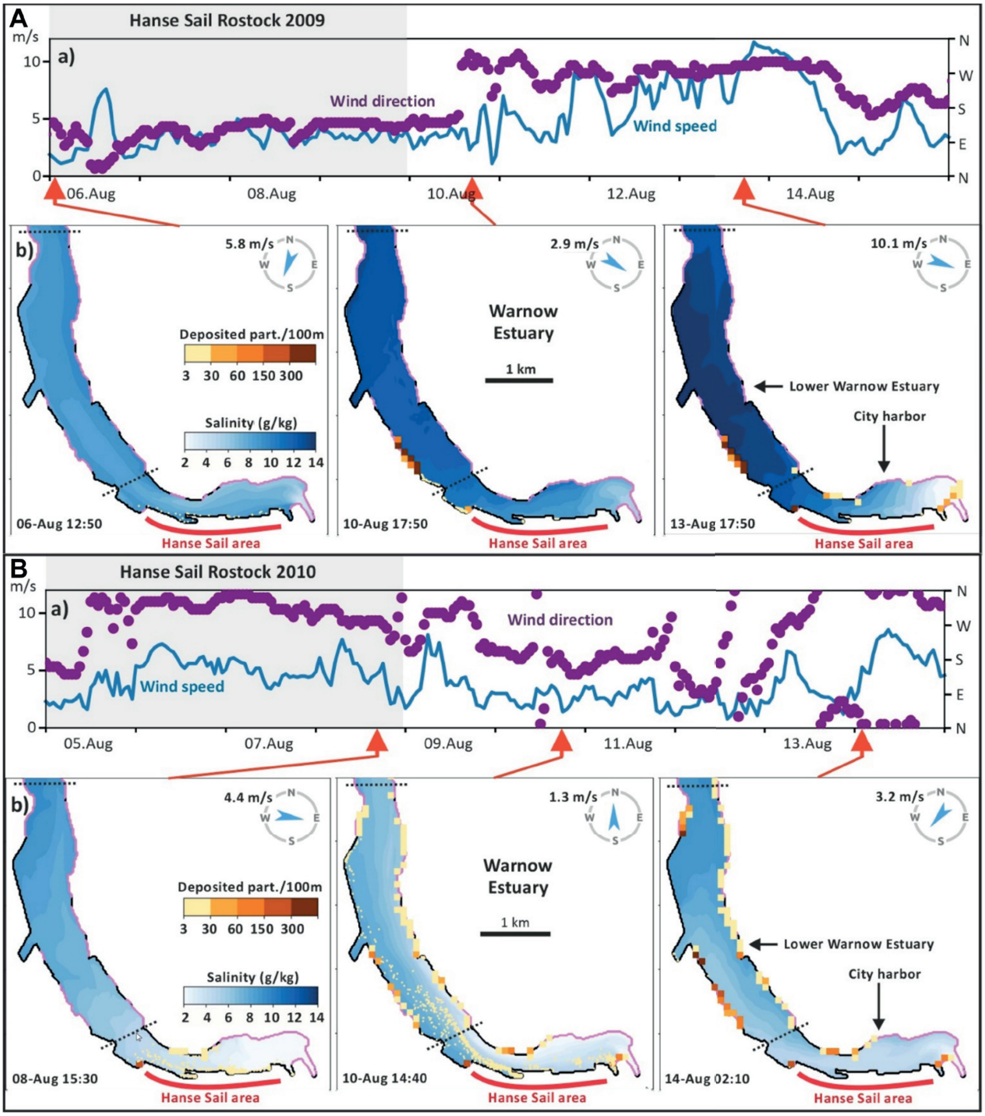


Figure 17. a) Wind speed and direction during *Hanse Sail* 2009 (A) and 2010 (B). The red arrows indicate the date and time of figure series. b) The model simulation of floating macro-litter and the litter deposition along the shoreline for three dates. Purple coastlines indicate reed belts or beaches; black colors indicate hard wall structures; the dashed line indicates the boundary of the city harbor. The model simulation movie shows the dynamic transport behavior in detail (Supplementary Material in Paper III). Adapted from Paper III.

3.3.4 Estimation of estuary-to-sea emissions from coastal festivals

Previous riverine litter emission estimations used parameters like population density of the river catchment, level of municipal waste mismanagement (Lebreton et al., 2017; Schmidt et al., 2017), as well as human development index (Mai et al., 2020) and the level of waste management infrastructure (González-Fernández et al., 2021) to assess leakage of litter into the rivers. Thus, longest rivers having larger drainage basins and subject to high level of population were assumed to lead to higher emission.

González-Fernández et al., (2021) considered leakage from all drainage basin outlets and estimated 307–925 million macrolitter items released annually from rivers in Europe. For the Baltic Sea, a total mean of 85.4 million items (40–100 million items) and for the Warnow estuary a mean of ca. 124,000–366,000 litter items were estimated to be released annually. These estimations ignored the distance from the waste source to the river, the type of surface and item mobilization effect, as well as flow rate, geomorphology and topography which could determine transport and retention of litter at land and river (Meijer et al., 2021; Mellink et al., 2024). Newer studies considering these aspects estimated an annual riverine litter emission for the Baltic Sea of 196.5 tonnes of litter (ca. 25–98 million items, considering the majority is plastic and a weight of 2–8 g per plastic item) and ca. 2.8 tonnes of litter from the Warnow river and smaller streams, ca. 350,000 items to 1.4 million items per year (Meijer et al., 2021).

Considering the range between both estimates and the worst (and most likely current) waste management scenario for Baltic coastal festivals leading to 56,000 items (Table 7), harbor and sailing festivals contribute to 0.05–0.22% of the total annual river inputs into the Baltic Sea. It is important to take into account that our study only considered the small-scale emission from a particular event “coastal festival”, and many other emission sources contribute to river and estuarine litter emission budgets, whereby more comprehensive analyses taking place over an entire year would lead to more reliable results to account for the effect of storms (Vriend et al., 2020, 2025). For this small-scale emission study, uncertainty might have been introduced by not effectively sampling the emitted litter in the harbour area and assuming similar emission quantities based on visitor estimates for the rest of the 50 coastal festivals. Less so in the transport dynamics. Aspects like weather (stormy wind speeds, changing wind directions, and hydrodynamics), were considered within the hydrodynamic model. Thus, while the quantities of litter emitted in the Warnow estuary may be uncertain by a factor of 3 (Paper III), the physical transport behavior of the particles remain the same. Sensitivity analyses carried out at the same estuary with the same model infrastructure at another study, showed that both particle retention rate as well as accumulation areas do not change using 1000 or 10,000 particles (Ramos et al. in review), and thus a change in 1 or 2 orders of magnitude in particle emissions may lead to very similar results in terms of retention rate and accumulation areas.

The overall results from Paper III suggest that estuaries act as sinks of litter, which has also been supported by previous studies (Vermeiren et al., 2016; Krelling et al., 2017; Okuku et al., 2022; van Emmerik et al., 2022). Considering that these ecosystems cover 88% of the global coastline (Dürr et al., 2011), and that their role in litter emissions is highly neglected, it is likely that litter emissions from rivers or estuaries are highly overestimated. This relatively low transport of litter towards the sea and high retention in inland waters, suggests these have become accumulation zones, highlighting the need to assess the impact of litter in the riverine ecosystem and prioritize the implementation of measures at land-based sources. One of the measures, specifically targeting litter from coastal festivals, is analyzed in the next section.

3.4. Management of macrolitter: a critical evaluation of measures

3.4.1. Replacing Single Use Plastics with Bio-based tableware at coastal festivals

Single-use plastics are a common problematic item at beaches worldwide (Hardesty et al., 2021). In contrast to Paper III which calculated litter emissions from coastal festivals, Paper IV aimed to calculate tableware usage to assess the waste management infrastructure required for disposal and handling of bio-based, biodegradable and compostable materials.

Tableware usage at coastal festivals was quantified based on item usage per person from *Hanse Sail* festival in 2023 (1.91 items per person). The item-based estimation was translated to weight-based, with 2–8 g for SUP items and 4–29 g for bio-based items, based on manufacturer details (Supplementary material in Paper IV). For *Hanse Sail*, the extrapolation of items per person revealed a total of 1.8 tonnes of tableware waste generated during the event, which represented 9% of the total waste generation (21 tonnes). From the waste generated, 16% was SUP, 42% was bio-based tableware and 43% was other waste (e.g., tissues). For details on the calculations, refer to Paper IV. The context at *Hanse Sail* was considered an “Improved Waste Management” scenario, which led to 3.6 g of tableware generated per visitor. In contrast, a “Business-as-Usual” (BAU) scenario assumed all tableware was SUPs, hence 67% SUP and 33% other waste. The results were extrapolated to the other festivals, revealing that study areas would need to manage 0.13–3.00 tonnes of SUP tableware in a BAU scenario, or 0.01–0.50 tonnes of SUP tableware and 0.04–1.30 tonnes of bio-based tableware in an Improved Waste Management scenario (Table 8). While the quantities at some festivals are rather low in terms of weight, item-based estimations are still high, and if not managed appropriately, the generated tableware could be littered, highlighting the need for management measures at each site.

Table 8. Estimation of SUP and alternative tableware generation in coastal festivals in the different study areas based on a Business-As-Usual scenario considering only SUP usage and an Improved Waste Management scenario considering 16% SUP and 42% alternative materials. Taken from Paper IV.

Event and Location	**Event duration**	**Number of visitors**	**Total waste collected during event**	**Total number of SUP tableware items used (Business as Usual, SUP)**	**Total number of SUP tableware (Improved Waste Management, 16% SUP)**	**Total number of Bio-based tableware (Improved Waste Management, 42% Bio-based)**
Hanse Sail (Rostock)	4 days	500,000 (2023)	21 tonnes[a]	2.6 tonnes (325,500 – 1.3 million items)	0.5 tonnes (62,500 – 250,000 items)	1.3 tonnes (45,000 – 325,000 items)
Klaipeda Sea Festival (Klaipeda)	3 days	ca. 500,000 (2023)	20 – 30 tonnes (mean = 25 tonnes)[b]	3.0 tonnes (375,000 – 1.5 million items)	0.3 tonnes (37,500 – 150,000 items)	0.9 tonnes (31,000 – 225,000 items)
Festival de La Serena (La Serena)	2 days	25,000 (2019)	No data	0.13 tonnes (15,000 – 65,000 items)	0.01 tonnes (1,250 –5,000 items)	0.04 tonnes (1,400 – 10,000 items)
International Festival Yasmine Hammamet (Hammamet)	4 days	ca. 30,000 (2019)	No data	0.16 tonnes (20,000 – 78,000 items)	0.02 tonnes (2,500 – 10,000 items)	0.05 tonnes (1,700 – 12,500 items)

References
[a] Stadtentsorgung Rostock, 2024 (personal communication)
[b] Ecoservice, 2023

The policy analysis carried out at the four study areas (described in detail in Paper IV) revealed that despite the existence of policy instruments aiming to reduce plastic waste at all sites (Fig. 18), the regulation of bio-based materials and specifically tableware is still in early stages, and there is a lack of policy translation towards waste management infrastructure. At Rostock (Germany), despite having two regulatory policies that require the usage of biodegradable and compostable tableware (AbfS §2-3, 2023; Strandsatzung, §8, 2021), waste from coastal festivals is collected mixed and incinerated. In Klaipeda (Lithuania), the national solid waste management plan (KRATC, 2023) implements an Extended Producer Responsibility (EPR) scheme with the separate collection of organic waste, however segregation at source remains low, thus incineration and landfilling predominate. In La Serena (Chile), the law on single-use plastics (Ley 21.368, 2021) requires the usage of "certified compostable plastic alternatives" however, recycling is highly centralized at the capital city and no industrial composting site is available, thus festival waste cannot be segregated and treated properly. In Hammamet (Tunisia), the policy implementation at municipal level is low and no facility exists for the treatment of organic waste, thus it is landfilled (Paper IV).

This discrepancy between policies and waste infrastructure indicates a risk of policies (especially in Rostock, Germany and La Serena, Chile) not solving the reliance of SUPs but instead promoting the creation of new materials that cannot be properly managed and thus becoming new polluting items. Although policies addressing bio-based plastics (the closer examples to the management of bio-based materials, or "non-plastic substitutes"), highlight the need for appropriate labelling to specify material of origin, type of treatment or disposal requirements, none of the items used in this study had this information. Finally, the fact that bio-based tableware is still aimed for single-use does not align with the requirements to prioritize reuse, and "only use biodegradable options where the reduction, reuse or recycling of plastics in not possible" as highlighted in COM 2022/682, or in the International Plastics Treaty (INC 5.2) (Paper IV).

Whether these items end up as long-lasting litter in the environment will depend on mainly three factors: 1) the available waste management systems to prevent these items from being accidently or intentionally littered, 2) people´s behavior, which could determine intentional littering or appropriate disposal, and 3) the material´s disintegrating capacities. Disintegration potential of the six tableware materials was assessed in two real environments, a brackish estuarine environment and an industrial composting site (Paper IV). At the estuarine environment, only sugar cane, cardboard and palm leaves disintegrated after one year, with disintegration rates of 0.1–0.7% d^{-1} (Fig. 19) and final disintegration of 32–100% (for separate values per material, refer to Paper IV), which was within the requirements set in ISO 22766. Wood and polylactic acid (PLA) experienced virtually no disintegration after one year. While this study was limited to only one

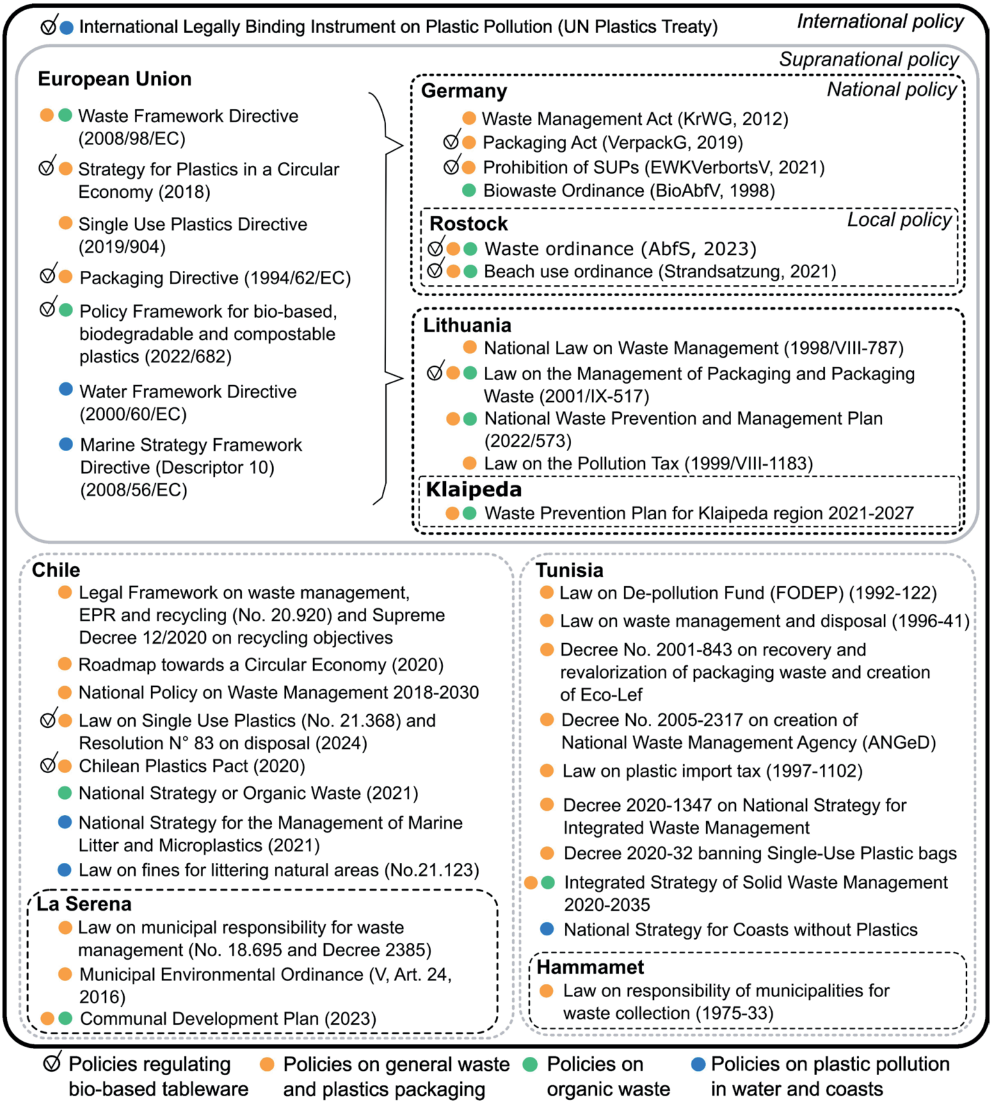


Figure 18. International, supranational, regional and local policy instruments on general waste, plastic waste, organic waste and bio-based tableware. For details on each policy instrument, please refer to the references in Paper IV. Taken from Paper IV.

year and a second year of exposure (as set by ISO 22766) may increase disintegration, the slow disintegration rate is already concerning. Few studies have tested disintegration of bio-based tableware or other materials in aquatic environments; the majority focuses on bio-plastics, such as PLA (Zhang et al., 2017; Rudnik, 2019; Folino et al., 2020). In our study, PLA was one of two materials not disintegrating. A study identified sunlight conditions are a contributing factor to PLA disintegration (Beltrán-Sanahuja et al., 2020). This was, however, not observed in our study. Further research is needed to assess the effects of salinity, pH, sunlight, temperature and oxygen availability in aquatic environments leading to disintegration of bio-based materials. In spite of this, the negligible disintegration of PLA and wood in estuarine water suggests that if these items are littered into coastal waters, they may persist as pollutants for a long time.

Conversely, in the industrial composting site, the opposite was observed. Four out of six materials were labelled as compostable; however, PLA was the only material achieving disintegration (as per EN 13432) with rates of 0.6–7.7% d^{-1} (Fig. 19) and final disintegration of 91–92%, leaving only a powder residue after 12 days (Paper IV). All other materials experienced remarkably lower disintegration and did not meet conditions to be labelled as compostable. Materials that do not disintegrate within the 12-day thermophilic phase (55–65°C) may pose a problem in home composting systems operating at lower temperatures. Moreover, at most industrial composting sites, organic waste has a rotting window of 2–4 weeks, and an extension is usually not economically viable. Regardless of whether tableware in coastal festivals is segregated at source and composted, as recommended by policy regulations, problems of insufficient disintegration arise, thus, most if not all materials are incinerated or sent to landfill (Paper IV). This also suggests that conditions for degradability established in standards like EN 13432 or ISO 17088 need to be revised to accurately reflect real environmental conditions, as also suggested by Haider et al., (2019). Due to a lack of studies assessing the disintegration of bio-based materials in industrial compost, studies carried out in other real environments were considered. A 90% degradation of PLA was observed after 36 days in anaerobic digestion (Hegde et al., 2019) and 85% after 70 days in sludge (Yagi et al., 2013), which was similar to what we observed in industrial compost. Food bowls made of a hybrid fiber of sugar cane bagasse and bamboo achieved 52% disintegration after 60 days in soil (Liu et al., 2020), and plates made of tapioca starch and sugar cane bagasse reached 56% disintegration in soil after 2 weeks (Wahid et al., 2019). In our study, sugar cane bagasse (un-/bleached) (labelled as 100% compostable) fully disintegrated in the brackish estuarine water, however total disintegration in the industrial composting site was negligible (0–12.1%). Similarly, plates made of tapioca starch and oil palm fiber exhibited 61% disintegration in soil after 2 weeks (Wahid et al., 2019), which was opposite to what we observed for tableware made of areca palm sheath, which fully disintegrated in brackish water, but only reached 1–32% total disintegration in the industrial composting site. Low degradability has been observed for cardboard due to high lignin content (Venelampi et al., 2003), however, no studies were found on the degradation of cardboard tableware (un-/coated) in the environment. Clearly, more research is needed to assess the parameters defining degradability of these materials in real environments.

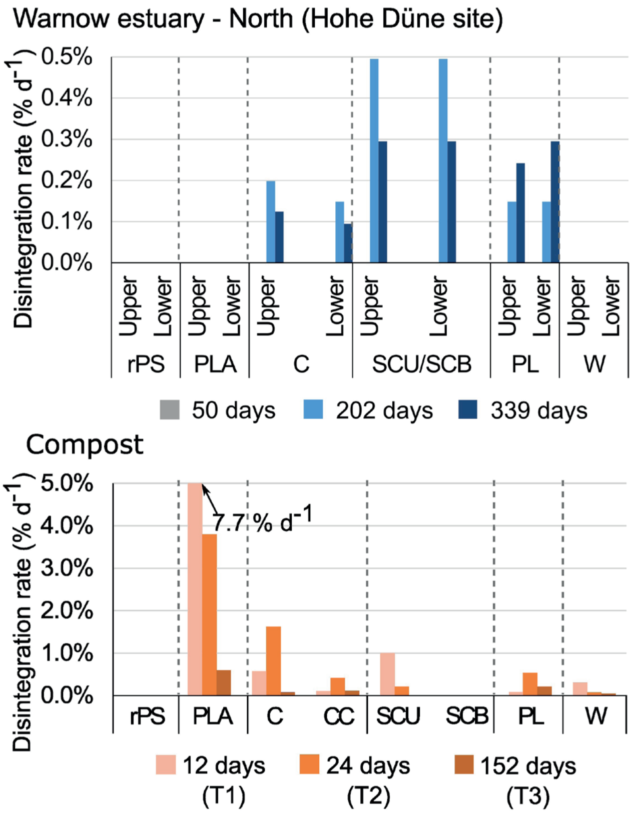


Figure 19. Disintegration rate for the different materials, namely recycled polystyrene (rPS), polylactic acid (PLA), cardboard (C), cardboard coated with starch (CC), sugar cane bagasse unbleached (SCU), sugar cane bagasse (SC), palm leaves (PL) and wood (W), presented as the difference in weight before and after experiment period (% d−1) in a brackish estuary system (here Hohe Düne, for other sites see Baccar Chaabane et al. 2022) and in compost. Taken from Paper IV.

Assessing public´s awareness on the environmental impact (positive or negative) and disposal of alternative materials is highly relevant for the selection of an appropriate material to replace SUPs and avoid littering behavior. Here, we evaluated the acceptance, perception and awareness of bio-based tableware materials with a public survey obtaining a total of 369 responses. While the representation of the four study sites was not even (see Supplementary Material in Paper IV), here a general insight is provided. The main outcome of the survey was that while there is a high acceptance to use alternative materials to SUPs (73–83% of respondents are willing to pay for an alternative material, preferring reusable PP), knowledge of the material characteristics, environmental impact and disposal requirements is low (Paper IV), which has also been observed at other studies (Ansink et al., 2022).

Public´s perception regarding degradability, compostability, mechanical and energetic recyclability, the presence of additives and harmful chemicals, and ecological footprint (for specific definitions of each concept, refer to Paper IV) was overall more negative towards (reusable) PP, PS and PLA than sugar cane, palm leaves, cardboard and wood (Fig. 20). The positive perception of degradability for sugar cane, palm leaves and cardboard were aligned with the results from the disintegration experiments in water, except for wood. In contrast, PLA was perceived negatively for compostability but was in fact the only material that disintegrated by > 90% (Paper IV).

Ecological footprint was rated as the most important criterion for selection of an alternative material for SUP (Paper IV) and was perceived negatively for reusable PP, PS and PLA and positively for non-plastic materials (Fig. 20). Majority of life-cycle assessment (LCA) studies have been conducted on bio-plastics (Genovesi et al., 2022; Rosenboom et al., 2022; Van Roijen and Miller, 2022). A study assessing palm leaves tableware suggested high ecological footprint related to transport and energy required for production (Korbelyiova et al., 2021). Thus, public perception may not be aligned with reality regarding ecological footprint of non-plastic substitutes, however there is a need for more studies evaluating other materials. In general, the biased perception in favor of bio-based non-plastic alternatives and against PLA does not align with disintegration results in the estuarine environment nor industrial compost, and neither with the potential environmental impact of materials shown in other studies (Geueke et al., 2018; BEUC, 2021; Bouma et al., 2024).

The assessment on awareness of disposal for each material revealed that, regardless of geographical region, economic prosperity, educational access and the country´s environmental performance, the majority of respondents do not know how to properly dispose alternative tableware materials (Paper IV). Around 59% of respondents think PLA should be disposed in the plastic bin, while 10–17% assigned alternative materials to residual waste, and 3–12% recognizes not to know where to dispose them (Fig. 21). At sites where segregate disposal is not available (e.g., Hammamet, Tunisia) a higher proportion of “I do not know” answers were observed. On the contrary, in Rostock (Germany) where waste segregation is widely implemented, a higher proportion of materials were assigned to residual waste (Paper IV). This could be due to the public knowledge in the country that dirty materials cannot be recycled and that the majority of waste is not segregated during coastal festivals (personal observation), being deposited in the residual waste. In this sense, despite the willingness to use different alternatives, the absence of packaging information, lack of infrastructure to handle the materials and lack of education regarding correct disposal can potentially increase littering (Haider et al., 2019; Filho et al., 2021).

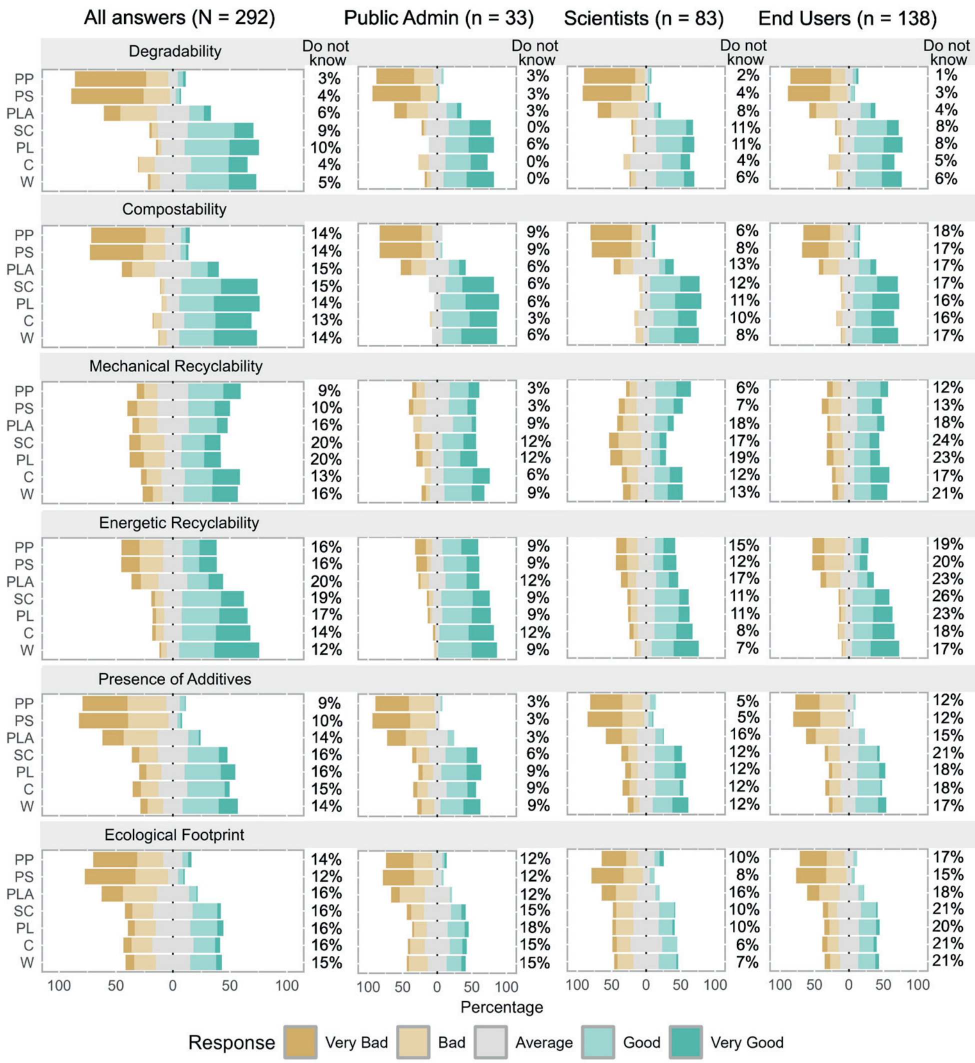


Figure 20. Perception on degradability, compostability, mechanical and energetic recyclability, presence of additives and ecological footprint of alternative materials to replace SUP tableware, namely reusable Polypropylene (PP), Polystyrene (PS), Polylactic Acid (PLA), sugar cane bagasse (SC), palm leaves (PL), cardboard (C) and wood (W), considering all answers (N = 292) and per stakeholder group. Results from the test survey not included, since definitions of the criteria were adapted. Survey results separated per study area, available in the Supplementary data S8 of Paper IV. Taken from Paper IV.

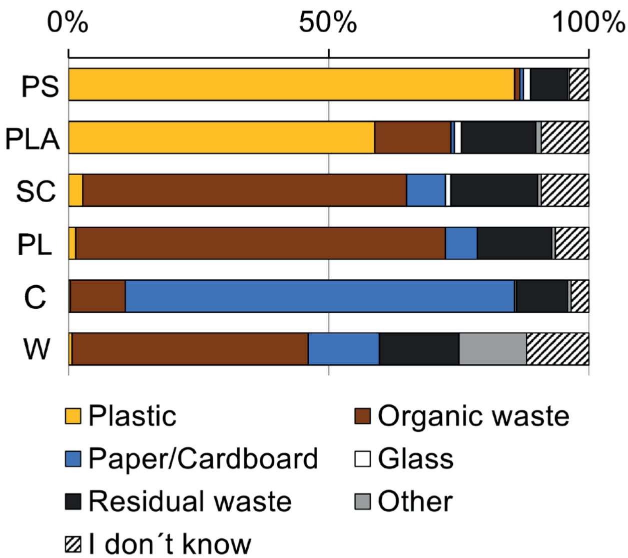


Figure 21. Awareness on the correct disposal requirement for the alternative materials to replace SUP tableware (n = 294), namely polystyrene (PS), Polylactide Acid (PLA), sugar cane bagasse (SC), palm leaves (PL), cardboard (C) and wood (W). Survey results separated per stakeholder group and study area in Supplementary data S9 and S10 of Paper IV. Taken from Paper IV.

3.4.2. Beach and tourism ecolabels: can they effectively help to reduce beach litter?

In the aim to address beach litter pollution from the tourism and recreation sector, ecolabels were evaluated to assess their effectiveness to reduce litter. A total of 142 active tourism ecolabels were collected, 92 addressing waste management, and 30 ecolabels address coastal litter and waste. Of these, six ecolabels did not provide access to their criteria, leaving 24 for analysis (Paper V). Eleven ecolabels were evaluated at our site-specific context, while others were reviewed for global context (Fig. 22).

Concurrently, a total of 43 measures for beach litter reduction were compiled (Appendix 1). Most effective ecolabels were considered those considering not a high number of measures, but primarily more effective ones, thus stakeholders rated measures based on their perceived measure efficiency and effort to reduce beach litter (Paper V). Measures perceived as **most efficient** were "elimination of single-use plastics (ID 18) and non-recyclable items (ID 21), development of seasonal waste management plans (ID 30), and prohibition of waste dumping and littering in public places, including beaches (ID 31)" (Paper V). Measures rated as **least effortful** were: "handing out pocket ashtrays to reduce cigarette butt littering (ID 6), providing waste bins in public areas (ID 7), reducing unnecessary packaging (ID 20), involving decision-makers and society in environmental management (ID 36), and providing tourists with guidance on minimizing waste (ID 42)" (Paper V). In this sense, the most **effective** (efficiency-to-effort ratio) measures were: "providing waste bins in public areas (ID 7), increasing the use of reusable items (ID 16), eliminating single-use plastics (ID 18), and prohibiting the dumping of waste in public places (ID 31)" (Paper V) (Appendix 1).

While the prioritization of measures with stakeholders is a novel approach, the 21 stakeholders participating were mainly from European background and from the environmental sector. In this sense, future research should aim to include a larger stakeholder group with diverse professional and cultural backgrounds. Moreover, some solutions may target more than one litter item size or type, and may be applicable in more than one area (e.g., tourism sector, or at city level), making some measures more effective than others, which may not be reflected from the stakeholder rating. Weighting could be adjusted to include these aspects, however here more research is needed to assess effectiveness of measure implementation over time. The list of measures and methodology used here intended to use stakeholder knowledge and experience to assess effectiveness, which allows for adaptation based on each context and transferability.

The 24 shortlisted ecolabels were compared against the list of compiled litter reduction measures (Appendix 1) using a scoring chart to assess level of compliance, i.e., quantity of litter reduction measures included in their awarding criteria (Appendix 3) (Paper V). Ecolabels included only 7–53% of the list of 43 litter-reduction measures. Only *Blue Flag* (53%) and *EarthCheck* Destination (51%) exceeded 50% (Table 9) (Paper V). A high number of measures included in ecolabels criteria is not a direct indication of effectiveness, but rather the inclusion of more effective measures. Yet only 3–6 ecolabels included most effective measures as rated by stakeholders (Appendix 3), with most emphasizing measures requiring systemic policy or infrastructural changes or public education, such as recycling, appropriate wastewater and waste disposal, beach cleaning or awareness-raising campaigns; instead of simple and low-effort practices that the HORECA sector can implement (Paper V). For instance, preventive low-effort measures with high impact (e.g., distributing pocket ashtrays, deposit-refund systems, providing guidance to customers on minimizing waste or reducing/eliminating/replacing non-recyclable and single-use plastics) were the least included (Appendix 3) (Paper V). In practice, ecolabel´s criteria can be applied laxly, with awards granted without full compliance, thus even fewer measures could be implemented.

	Beaches													Destinations					Accomodations						
	Bandera azul ecológica	Bandera ecoplayas	Blue Flag	ISO 13009	IRAM 42100	NMX-AA-120-SCFI-2006	NTE INEN 2631	NTS-TS-001-2	Seaside Award - England	Seaside Award - Northern Ireland	Seaside Award - Wales	Green Destinations - Quality Coast Award	White Flag	Green Destinations Award	Green Destinations Certified	Istanbul Environment Friendly City Award	NTS-TS-001-1	EarthCheck (destinations)	Earth Check Certified (companies)	Certified Sea Turtle Friendly	NMX-AA-171-SCFI-2014	Pacific Sustainable Tourism Label	Seychelles Sustainable Tourism Label	Stoke (surf)	
Accomodations													X						X	X	X	X	X	X	**9**
Beaches	X	X	X	X	X	X	X	X	X	X	X	X	X												**14**
Campsites																			X						**2**
Businesses																			X						**3**
Conference Centres																			X						**2**
Marinas			X										X						X						**7**
Tour operators																			X	X				X	**4**
Restaurants																			X						**2**
Amusement Parks																			X						**2**
Golf Courses																			X						**2**
Attractions																			X						**2**
Destinations													X	X	X	X	X	X				X		X	**9**
Activities																			X						**2**
Transport																			X						**2**
Tourism Boats			X										X						X						**5**
	1	**1**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**5**	**1**	**1**	**1**	**1**	**1**	**13**	**2**	**1**	**2**	**1**	**3**	

Figure 22. Shortlisted ecolabels addressing the management of waste or litter at coasts or sea, including ecolabels for beaches, destinations and accommodations. On the left are the tourism sectors covered by each ecolabel. In grey are the relevant sectors for addressing the problem of beach litter. Taken from paper V.

Ideally, a combination of both short- and long-term measures are needed to address litter pollution (Löhr et al., 2017). Surveys to beachgoers aimed to assess the acceptance to mitigation measures for beach litter reduction, as well as their awareness of ecolabels and influence in beach selection. The survey results (215 responses) revealed that 78% of beachgoers accept both awareness raising campaigns and fines for littering, while 67–68% accept plastic alternatives or deposits for reusable containers. Least accepted measures were smoking bans (49%) and single-use plastics bans (59%) (Fig. 23). Beachgoers considered fines for littering and awareness campaigns as most effective, which was contradicting to the most effective measures rated by stakeholders (Appendix 3) (Paper V). This reflects public preference for short-term, visible measures, and resistance to stricter, long-term policies, which has also been observed at other sites (Grilli et al., 2022).

Table 9. Level of compliance of ecolabels to measures for beach litter reduction. The extent of compliance with weights takes into consideration the most effective measures to reduce beach litter, based on the stakeholders´ evaluation. Ecolabels with highest compliance for each sector are indicated in bold. Taken from Paper V.

Sector	Ecolabel	Number of criteria	Level of compliance	Level of compliance with weights
Beaches	Bandera Azul Ecológica	18	37%	35%
	Bandera Ecoplayas	12	15%	15%
	Blue Flag for beaches	**33**	**54%**	**53%**
	ISO 13009	56	10%	7%
	IRAM 42100	42	24%	21%
	NMX-AA-120-SCFI-2006	**7**[a]	**44%**	**44%**
	NTE INEN 2631	14[c]	34%	28%
	NTS-TS-001-2	62	32%	29%
	Seaside Award – England	25	22%	24%
	Seaside Award – Northern Ireland	24	22%	25%
	Seaside Award – Wales	24	24%	25%
	Green Destinations – Quality Coast Award	84[d]	29%	26%
	White Flag	5	17%	10%
Destinations	Green Destinations – Green Destination Award	84[d]	29%	37%
	Green Destinations – Green Destination Certified	84[d]	29%	37%
	EarthCheck Destination	**114**	**49%**	**51%**
	Istanbul Environment Friendly City Award	55	24%	24%
	NTS-TS-001-1	**116**	**39%**	**47%**
Accommodations	**Certified Sea Turtle Friendly Tourism**	**291**	**41%**	**44%**
	EarthCheck Certified for companies	80	31%	29%
	NMX-AA-171-SCFI-2014	**9**[b]	**41%**	**47%**
	Pacific Sustainable Tourism Standard	**61**	**38%**	**42%**
	Seychelles Sustainable Tourism Label	109	15%	12%
	Stoke Surf	38	31%	30%

[a, b] with many subsections
[c] for gold level
[d] The same type of criteria applies to all ecolabel or award types. Which ecolabel is awarded depends on the number of criteria fulfilled, or the sector where the ecolabel should be implemented.

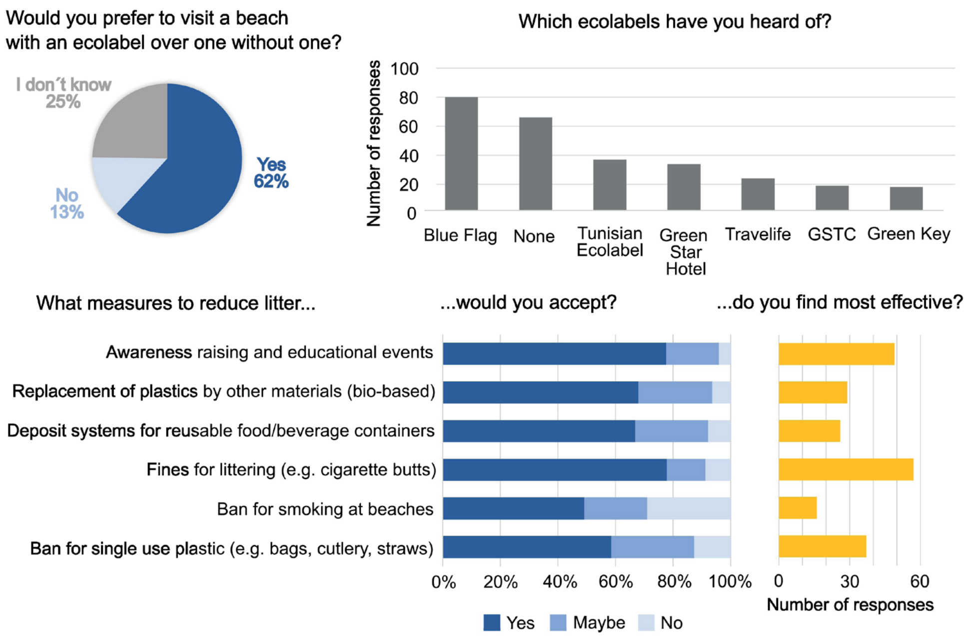


Figure 23. Survey results for beachgoers on the knowledge of ecolabels, and the acceptance and perceived effectiveness of measures to reduce beach litter. Taken from Paper V.

The data from beach macrolitter monitoring obtained in Paper I was complemented with literature data from 2015–2023 to assess seasonal and spatial pollution patterns. The Clean Coast Index (CCI) was calculated for high (spring and summer) and low (autumn and winter) seasons using median values of litter abundance for each beach. Cleanest beaches during both high and low season were present in Morocco (with some exceptions, Fig. 24a). In contrast Tunisia and Egypt, presented highly polluted beaches (moderate to extremely dirty levels) (Fig. 24, b-d). For Egypt, only data from the high season was available (Spring 2022) (Paper V).

Blue Flag is by far the largest ecolabel worldwide, with most certified sites located in Europe (Blue Flag, 2025). To our knowledge, there is so far no scientific evidence that confirms *Blue Flag*´s effectiveness to reduce beach litter over time. In Morocco, beaches are awarded the *Blue Flag* since 2006 (Mohammed VI Foundation, 2025). The *Plages Propres* programme implemented in 1999, supports beaches to qualify for *Blue Flag* (Plages Propres, 2025b). Nine *Blue Flag* and 29 *Plages Propres* beaches existed in 2024, spatially distributed regardless of beach type (Fig. 25). Morocco presented lowest litter abundances, which seems to align with *Blue Flag* implementation. Semi-urban and semi-rural beaches having the *Plages Propres* ecolabel showed similar pollution levels to touristic and urban beaches (Paper V). However, these were lower than semi-urban and semi-rural beaches in Tunisia, suggesting a possible ecolabel effect (Paper V). Still, it remains unclear whether improvements stem from ecolabels alone. Morocco´s *Plages Propres* program (Mohammed VI Foundation, 2025) and litter monitoring in place since 2016, possibly have raised public awareness of the litter and plastic pollution issue, leading to improved environmental behavior. In addition, stakeholders interviewed highlighted the "obligation" for municipalities to "keep beaches clean" which is mandated by the government (for details on interview results, refer to Paper V).

Beach ecolabels are not used in Tunisia and Egypt; therefore, analysis cannot be carried out. Instead, a revision on the litter reduction effect from other ecolabels was done for other sites in the world. In Costa Rica, the *Programa Bandera Azul Ecológica* (PBAE) in place since 1996 (CST, 2025), certified 140 beaches in 2025, majority in the Pacific coast (ICT, 2025), however citizen science campaigns have detected high pollution levels (0–8.47 items m^{-2}; mean 2.01 ± 3.27 items m^{-2}) (De Veer et al., 2023) which can be regarded as very clean to moderately clean as per CCI. In Mexico, the NMX-AA-120-SCFI-2006 ecolabel certified 27 beaches in 2024, majority at the Pacific coast (Gobierno de México, 2025). Here, litter abundance ranged 0.5–2 items m^{-2} (mean 1.04 ± 0.62 items m^{-2}) (De Veer et al., 2023), which could be regarded as very clean beaches as per CCI. The English Seaside Award, implemented since 1992, certified 144 beaches in 2025, with the majority located in the East of England, South East and South West regions (Keep Britain Tidy, 2025), which are sites that have shown moderate to high litter abundance over ca. 10 years (2005 and 2014) (Nelms et al., 2017). Data is lacking for other ecolabels to conduct analyses to assess their effectiveness (Paper V). In spite of the need for more research to assess the effect of beach and tourism ecolabels to reduce beach litter over time, the current evidence suggests that ecolabels only cause a temporary (high-season) reduction (Paper V).

Hotels with beach access are common at North African countries, hosting large numbers of tourists during the high season, thus hotel ecolabels were also evaluated. The results highlighted in Paper V, suggests that the few ecolabeled hotels in the study area (5–12% from total number of hotels with beach access) and the high pollution observed at touristic beaches (Fig. 24 and 25) have a minimal potential effect of ecolabeled hotels in litter reduction. In Tunisia, touristic beaches with ecolabeled hotels near Nabeul, Hammamet and Sousse, had moderate to dirty pollution levels as per CCI during both low and high seasons, and higher pollution levels than urban beaches, which may suggest challenges for beach management to counteract high tourist numbers and waste generated in high season (Fig. 24 and 25) (Paper V). Although hotels are required to clean their leased beaches (according to interview results), the hotel ecolabels implemented on site, such as *Travelife*, *Green Star Hotel*, *Green Key* and *Green Globe*, do not explicitly require beach litter management in their awarding criteria. It is possible that waste management practices extend beyond leased areas, however beach sections outside "hotel properties" are excluded (personal observation). As a result, the hotels can keep ecolabel status even if their waste impacts surrounding coastal areas (Paper V).

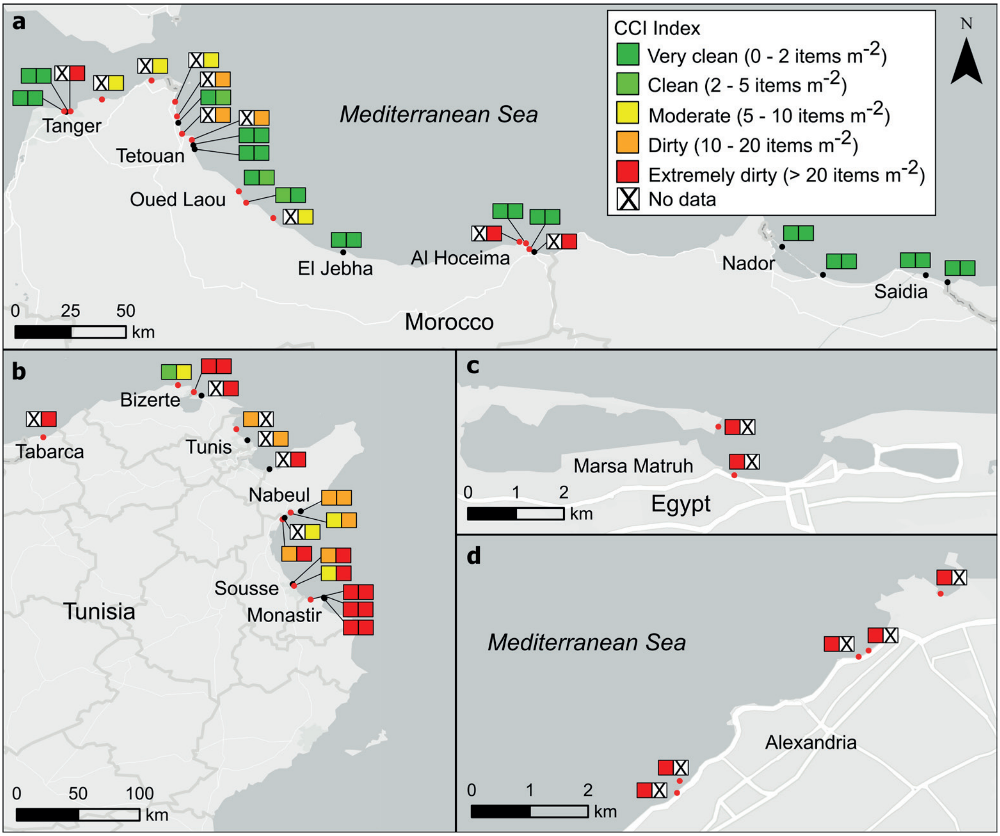


Figure 24. Pollution map based on the Clean Coast Index (CCI) for beaches at Morocco (a), Tunisia (b) and sites in Egypt, namely Marsa Matruh (c) and Alexandria (d). Points in red correspond to our beach macrolitter monitoring and points in black are complementary sites found in the literature. The first and second square represent CCI levels based on the median litter abundance for high and low seasons, respectively. In case no data was available, it was represented with an "X". For details on each value, refer to Supplementary data S7, from Paper V. Taken from Paper V.

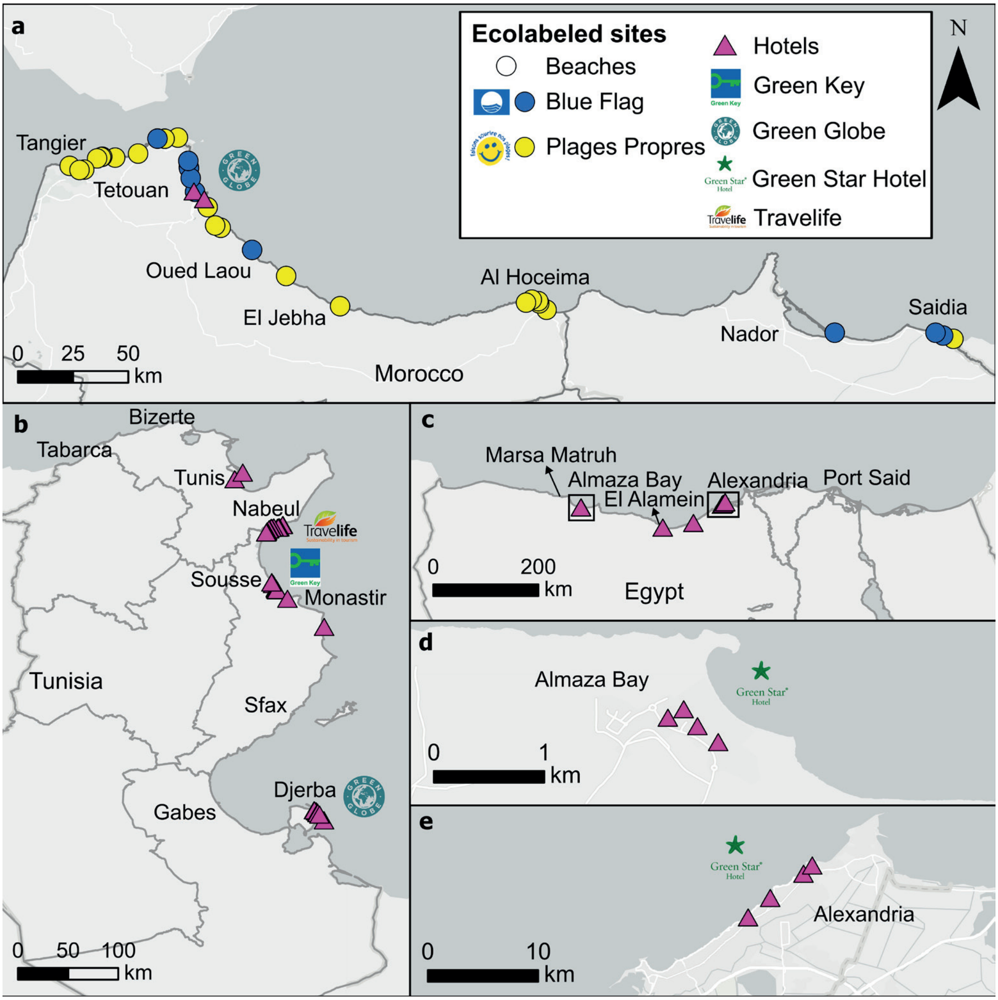


Figure 25. Ecolabeled beaches and hotels (with beach access) in Morocco (a), Tunisia (b) and Egypt (c) – Almaza Bay (d) and Alexandria (e). The ecolabeled sites were obtained from ecolabels´ websites (*Foundation Mohammed VI*, 2024; *Plages Propres*, 2025, *Green Key*, 2025, *Green Globe*, 2025, *Travelife*, 2025, *Green Star Hotel*, 2025). Taken from Paper V.

In terms of ecolabel implementation for the North African region, various challenges arise, including high costs for criteria fulfilment, maintaining beaches clean off-season, and in some cases high ecolabel costs (Appendix 4) (Paper V). In Morocco, acquiring the *Blue Flag* is free, but compliance with awarding criteria requires the implementation of costly infrastructure (e.g., recycling), still lacking regionally. Validity periods that are too long (2–3 years) may discourage participation due to the recurring effort and costs required for renewal, while validity periods that are too short (< 1 year) may lead to weaken commitment (Paper V). Finally, stakeholders view ecolabels as tools to boost tourism, however public´s awareness on ecolabels remains low. Surveys to beachgoers revealed that while 62% preferred ecolabeled beaches, only 36% knew *Blue Flag*, and 30% knew none (total responses: 264, multiple choice) (Fig. 23). In Morocco, 53% were unaware of it, despite widespread adoption (Paper V).

Municipalities in North Africa spend US$1,000–5,000 annually per beach for cleaning during high season (Paper V, La Presse, 2025). Urban beaches (comprising 10–20% of each country´s coastline) could benefit from ecolabel implementation by keeping beaches clean, if effective measures were enforced and litter reduction was secured long-term. Ecolabels implemented at touristic beaches (comprising 9–22% of each country´s coastline), often managed by hotels, present an opportunity to transfer beach cleaning costs to hotel operators. Yet ecolabeled hotels remain uncommon (5–12% from total number of hotels with beach access). Political instability can challenge waste management, as it was observed in the study by Chaabane (2020), thus low-effort measures targeting problematic items which remain affordable and administratively light are highly needed (Paper V). These challenges likely extend to other low-/middle-income countries too. Ecolabels could bring the problem of litter and plastic pollution into the political agenda and raise public awareness; however, their success will depend on enforcement mechanisms and available infrastructure in the region (Paper V).

The findings of Paper V show that ecolabels, as they are, are not effective for beach litter reduction. Ecolabels fail to target top litter items or most effective measures, emphasize management actions (e.g., cleaning) over outcomes (e.g., reducing litter pollution/specific items), lack thresholds for acceptable pollution levels and ignore seasonal variation, restricting their effect to short-term seasonal efforts (Paper V). In order for ecolabels to be effective tools for beach litter reduction, they should 1) integrate effective and site-specific litter reduction measures identified by local stakeholders, and informed by monitoring campaigns and source allocation analyses, to assess the effectiveness of management measures over time; 2) define thresholds for acceptable litter levels aligned with international legal frameworks (e.g., MSFD or Barcelona Convention), with monitoring across seasons to adapt measures based on effectiveness; and 3) combine short-term, low-effort actions implementable by the HORECA sector, with long-term policy measures such as banning single-use plastics or enforcing extended producer responsibility (Paper V). Ecolabels could also incorporate indices such as Integrated Beach Quality Index (IBQI) (Semeoshenkova et al., 2017) which integrate human health, ecosystem health and recreational aspects to assess the reduction of specific litter items, enabling evaluation of measure effectiveness across beaches and the wider HORECA sector (restaurants, cafés, hotels); and emphasize ecosystem preservation, setting tourist capacity limits and allow recovery periods, as suggested by Fraguell et al., (2016) (Paper V).

3.5. Global perspectives for macrolitter: Closing research gaps and addressing management needs

The relatively high macrolitter abundances observed at beaches in the southern Mediterranean (Paper I), the high litter retention potential for estuaries and rivers (Paper III) and the high pollution observed also in Chilean beaches at the Pacific in relation to other countries in Latin America (De Veer et al., 2023; Honorato-Zimmer et al., 2024) call for the implementation of measures prioritizing and targeting land-based sources. Single-use plastics and cigarette butts were the most common items observed at all sites, and pollution sources were mainly attributed to poor waste management and the tourism and recreation section. Research is highly important to guide decision making to select appropriate measures targeting top litter items and pollution sources (Williams and Rangel-Buitrago, 2019).

While there is a good baseline of research for high income countries, research gaps regarding detailed litter classification to identify top litter items and sources of pollution still exist for the Low- and Middle-Income Countries (LMICs), especially where long-term monitoring is lacking. A recent systematic literature study in the Latin America East Pacific, highlighted that the Central American Pacific coastline is highly understudied (Honorato-Zimmer et al., 2024). Similar research gaps also exist for the Indian Ocean coastline (Honorato-Zimmer et al., 2022) and the southern Mediterranean coastline (Vlachogianni et al., 2020; UNEP, 2023). Currently, long-term beach litter monitoring in the Mediterranean is only carried out in Europe, as required by the MSFD and the IMAP. Under both policies, a litter threshold was established to determine a Good Environmental Status (GES) for beaches. Litter thresholds are highly relevant to set a goal for managers; however, they require the establishment of long-term monitoring to gain sufficient spatio-temporal data for it to be representative of the region. In this sense, the beach litter threshold for the Mediterranean could be adapted to integrate the context of the southern Mediterranean countries once sufficient data is available. Beach litter thresholds are also highly needed in other regions, such as Latin America, however, here a higher temporal resolution of monitoring data and more detailed litter characterization is needed.

Establishing long-term monitoring in these regions is, however, challenging. Often, these are beaches with high pollution levels, limited infrastructure, and low monetary capacities to carry out long-term monitoring surveys as suggested by UNEP/IOC (2009). Therefore, they often rely on citizen science campaigns with simplified approaches carried out at a lower frequency (every four years nationwide) (De Veer et al., 2023). Adapted methods using shorter transects (Paper I) or aerial drones (Paper II) could serve to speed up surveys and minimize effort. The use of aerial drones for litter monitoring has increased rapidly since 2020, and while they could enable a fast screening of beaches to assess the presence/absence of litter, accumulation hotspots or even assess litter abundance and item categorization (Kako et al., 2026), their expansion for monitoring is often legally restricted, at the European Union (EU 2018/1139, EU 2019/947, EU/2019/945), and at other countries, like those in North Africa, where often the use of drones is strictly prohibited (Dronemade, 2025). These limitations may increase in the future, considering complex political atmosphere in different countries.

Using deep learning approaches for analyzing drone images, a faster image analysis could be achieved, however limitations regarding image annotation and the need for ground truth data should be considered (section 3.2). Here citizen science campaigns, like those already existing in Chile (CDLB, 2025), can complement and overcome these weaknesses, and at the same time address the need for social environmental education. Additional spatial data obtained with aerial drones can also aid to assess the impact of infrastructure or coastal oceanographic variables in litter abundance and distribution (De Ramos and da Costa, 2025), as well as detect accumulation hotpots at rocky shores along estuaries, rivers and reed belt vegetation which are often not included in litter monitoring. Overall, aerial drones will keep evolving in the future and become more cost-efficient with time (section 3.2), thus it is expected that they become a regular tool in litter and plastic monitoring at coastal zones. To enable harmonized sampling approaches, guidelines should be followed as the one developed by Isobe et al. (2024).

Using detailed litter categorization lists is highly needed, however it comes with the trade-off of time-effort and the detail required. The "Joint list of litter categories for marine macrolitter monitoring" combined litter categorization lists from UNEP, OSPAR, ICES and others, and includes six hierarchical levels that go from material type to specific litter type for use within the MSFD for the monitoring of European coasts and seas (Fleet et al., 2021). This list enables a harmonized and comprehensive litter categorization; however, the level of detail calls for a certain level of expertise and time effort.

Data harmonization is highly needed for cross-regional comparisons. Harmonized sampling protocols create a standardize process to achieve reliable, consistent and comparable data, while enabling a certain level of flexibility to address each individual contexts and research question. The harmonization of data could allow cross-region comparisons using transferable units and litter categorization, and could be entered to a central database. Databases are highly relevant to keep and manage data for spatio-temporal analyses, especially when it comes to assess the effectiveness of litter-reduction measures over time. EMODNET provides free access to harmonized datasets, however it is aimed for Europe (Molina Jack et al., 2019; Partescano et al., 2021). LITTERBASE only maps the results from publications globally, without access to the data. IMDOS (Integrated Marine Debris Observing System) advocates for the implementation of a coordinated and harmonized global network of marine debris observation at beaches, sea surface and seafloor, through remote sensing, drones, modelling and in-situ sampling (IMDOS, 2025). Ramos et al., (2022) made an evaluation of the existing databases for marine litter data in Brazil, finding out that many do not follow the FAIR principles. In Chile, the *Científicos de la Basura* (CDLB) citizen science initiative carries out beach litter monitoring in Chile and the Latin American East Pacific. While their results are published in reports on their website (CDLB, 2025), the data is not placed in a repository. In the view of a future International Plastic Treaty, central databases play an important role to assess regional and global trends of beach litter abundance and the reduction of predominant polluting items.

Global particle transport models have addressed main questions regarding the transport and accumulation of litter in the ocean gyres (Van Sebille et al., 2020; Onink et al., 2021), however, more research is needed to assess coastal processes and the complex estuary-ocean interaction. The results from Paper III and the discussion with most recent literature highlights the role of hydrodynamics and tidal cycles (or lack thereof) in micro- and macrotidal systems. While highly spatially resolved hydrodynamic models are available for the Northern Hemisphere, the Southern Hemisphere has to rely on the open-source hydrodynamic models such as HYCOM (2025) or NEMO (2025), which do not have a sufficient spatial resolution to represent coastal dynamics. Research and resources should be directed to provide the infrastructure needed to develop such physical hydrodynamic models at these sites, to understand local hydrodynamic factors playing a role in litter transport, as highlighted in Paper III. Alternatively, comprehensive analyses considering item mobilization, weather factors, distance from waste source to the river and geomorphology of the river or estuary, can overcome this technical constraint to assess litter emissions and transport as demonstrated by Meijer et al. (2021). Here, long-term monitoring for rivers and estuaries would be needed to assess spatio-temporal pollution patterns and accumulation zones over time (Vriend et al., 2020; Tasseron et al., 2024). Still, the understandings obtained from Paper III and its discussion already suggest that estuaries act as sinks of litter which may be subject to remobilization upon storms or tidal cycles, however retaining litter for long periods of time, up to decades (Tramoy et al., 2020a). Therefore, litter-reduction measures need to address these sites.

Bellou et al., (2021) made an analysis of innovative solutions available to target litter at different coastal and marine compartments, finding that majority of solutions have a high focus on monitoring; driven by the research community. A high number of measures were also aimed for cleaning, mainly at the ocean and coastal waters, which were mainly initiated by NGOs. These are, however, end-of-pipe measures that are highly costly and less effective than targeting litter at its source. Over 50% of the solutions were funded by the EU and scientific institutes (Bellou et al., 2021), i.e., they relied on public funds. This highlights the urgent need for preventative and mitigating measures that focus on pollution sources (mainly land-based) and involve industries to fund these. To achieve this, the urgent implementation of measures needs to be informed by long-term monitoring data, followed by an assessment of predominant litter items and pollution sources. It should also be coordinated with local stakeholders and adapted to each cultural and infrastructural context. According to Jambeck et al. (2015), 16 from the top 20 countries with mismanaged plastic waste are low- and middle-income countries (LMICs). Based on their estimations, litter inputs to the ocean may have increased by an order of magnitude by this year (2025) unless waste management infrastructure was improved. Cigarette butts and SUPs are predominant polluting items globally, and phasing away from these items is still a major challenge. While recycling has increased over the past years, the demand for recycled plastics, at least in Europe, is still very low (Plastics Europe, 2024). Top five largest companies (Coca-Cola Company, Pepsico, Nestlé, Danone and Altria) worldwide account for 24% of the total branded audit plastic, and 56 companies contributed over 50% of plastic pollution (Cowger et al., 2024). A shift towards Extended Producer Responsibility (EPR) schemes may help to keep the largest plastic polluters accountable. “Plastic Pacts” are examples of the transdisciplinary collaboration between researchers, policy makers and industry and may also be a possible route to address the industry (Ellen MacArthur Foundation, 2025).

Bans for plastic bags worldwide have been an example of measures taken by policy makers to address polluting items. So far, 91 countries have undertaken either a ban or a levy addressing plastic bags (Statista, 2024). However, the data from beach clean ups from Ocean Conservancy (2024) shows that plastic bags are still among the top 10 items most found at beaches. National policies put an Eco-Tax of 1.5% on the import of plastics in Morocco (Law No. 4/1994), and prohibit plastic bags > 0.025 mm in thickness in Morocco, Tunisia and Egypt (Law No. 202, Law No. 77-15, Law No. 96-41, Decree No. 97-1102) however they are still imported by irregular markets and are still found in use (personal observation). In Chile, plastic bags are banned since 2018, initiated by collective municipality action (Amenábar Cristi et al., 2019). However, bags are still allowed in small enterprises and farmer´s markets (personal observation). Due to the lack of detailed litter item categorization, it is not possible to assess whether plastic bags have decreased in abundance, however it has been claimed that after 6 years from implementation, a decrease of plastic bags has been observed at beaches (Urbina et al., 2020). Urbina et al. (2020) suggests that Chile needs a combination of top-down and bottom-up approaches to target plastic pollution, as it was done for the SUP bag ban. Moreover, a law prohibiting smoking at beaches, rivers and lakes was established in 2022 (Law 21.413), however cigarette butts are still among the litter items most found at Chilean beaches (CDLB, 2025). Cigarette butts are also a problem in the southern Mediterranean. A proposal in 2023 aimed to prohibit smoking at all public places in Morocco; however, cigarette littering still remains high (Mghili et al., 2023).

While local solutions are relevant, the infrastructure falls short considering the fast increase in plastic production. Bio-based, biodegradable and compostable materials have been claimed as alternatives for single-use plastics. However, as it was observed in section 3.4.1, their viability will depend on several factors related to available infrastructure to handle them, and their properties related to degradation potential in different environments. So far, majority of the studies assessing this latter aspect as carried out in the lab and more research is needed to assess degradation in real environments. Removal or remediation measures (i.e., clean-ups) at different coastal and marine compartments are some of the most common management measures implemented (Schmaltz et al., 2020; Winterstetter et al., 2021). However, these end-of-pipe measures can end up being less cost-effective over time than targeting litter at land-sources. However, Frantzi et al., (2021) highlighted that there is a need for more evidence of the benefits of prevention measures over remediation measures to lower public costs and direct resources to those. Willis et al., (2018) made an analysis of the effectiveness of various waste reduction measures in Australia, finding that outreach programs were the most effective, and even more so when combined with waste infrastructure. Most effective outreach programs involved awareness rising on recycling, littering prevention and illegal dumping, suggesting that councils could decrease litter along their coastlines by investing at least 8% from their budget.

However, low public funds and weak policy enforcement are often challenges in waste management at LMICs. For example, political and social challenges at the southern Mediterranean have been observed to cause an impact in economic growth and sustainable development (Colombo et al., 2010) as well as in waste management in North Africa (Chaabane, 2020). Ecolabels have been regarded as tools combining aspects that include beach cleaning, the implementation of waste reduction infrastructure and awareness raising for consumers (Botero, 2019), motivating the engagement of the private sector in beach management. However, Paper V revealed that ecolabels are not effective to reduce beach litter, because they still focus on management actions instead of clear outcomes, and do not ensure the implementation of most effective measures to target predominant litter items, and thus require improvements, as those discussed in section 3.4.2, to achieve an effect in long-term litter reduction.

An international agreement may be meaningless unless local, regional and national governance solutions also take place, fitting for each context (Cowan and Tiller, 2021). The negotiated International Plastics Treaty, involving researchers, policy makers and industry is an example of governance engaging all sectors from society to ensure a reduction in plastic production and a shift away from the current reliance on SUPs. In that way, clear targets for the reduction of plastic production and its management can be established and provide incentives, as well as a global fund for countries that lack infrastructure (Borrelle et al., 2017). However, unilateral agreements can take a very long time to be achieved. Thus, until then, researchers should focus on establishing long-term monitoring campaigns, generating the necessary harmonized data required for the design and delineation of thresholds and management measures, and assess the effectiveness of measures in terms of cost and effort to decrease litter abundances, predominant litter items and specific pollution sources over time.

4

Conclusions

1. In the southern Mediterranean beaches, previously understudied, results revealed high macrolitter levels observed at all three countries (Morocco, Tunisia and Egypt), with 30–49% classified as dirty or extremely dirty with the Clean Coast Index (CCI). Single use plastics comprised 40–51% of total litter items per country, and 58–69% of the litter was attributed to tourism, recreation and waste mismanagement were predominant pollution sources. A seasonal analysis showed high pollution levels during both high and low season (despite beach cleaning), however, more temporal data and long-term monitoring is required to provide conclusive results.
2. The adapted 10 m transect method for highly polluted beaches demonstrated to be sufficient to represent the litter characteristics of a beach with less effort, since the top 25 item categories were found within five 10 m transects, and these 25 item categories were responsible for 82% of the pollution. This method could enable faster analyses of top litter items and pollution sources, required to implement effective measures that target specific polluters.
3. Aerial drone experiments for litter detection showed best classifications for images at 10 m flight height and items > 2.5 cm. Accuracy of image classification for recovery experiments with four classes were high (total accuracies of 36–90%, kappa > 0.60), however decreased for classification with six classes and

for 100 m beach transects across all algorithms. Aerial drones are not suitable for Baltic beaches, however could serve to target highly polluted beaches as a fast-screening tool. The updated cost-efficiency analysis revealed that drones have a moderate cost-efficiency in comparison to high cost-efficiency from OSPAR method, and can be further explored as complementary tools for monitoring.

4. The particle tracking model at the Warnow estuary demonstrated a very high litter retention, with only 0.4% of particles reaching the estuary opening (ca. 11 km away from emission point) and existing into the Baltic Sea after a 10-day simulation under stormy conditions. Considering the litter emissions scenarios estimated for coastal festivals in the southern Baltic, sailing and harbour festivals contribute only to 0.05–0.22% of total annual river inputs into the Baltic Sea. However, the model shed light into several factors playing a role in litter transport in these complex systems, such as estuarine circulation, presence or absence of tidal cycles, wind speed and direction, storms, salinity gradients, harbour and shoreline morphometry and presence of vegetation, which cannot be easily transferable. Litter emission estimations from rivers need to be revised to consider litter retention.
5. Bio-based, biodegradable and compostable tableware are not solutions to reduce single-use plastics at coastal festivals. Waste management realities in the study areas showed a lack of infrastructure needed to compost these materials, despite policy ambitions to reduce single-use plastics and suggesting alternatives. The low disintegration rates in the industrial composting systems (0.6–7.7% d^{-1}), suggests that these alternative materials are either incinerated or landfilled. Public´s biased perception in favour of non-plastic substitutes and low knowledge and awareness on disposal needs, suggests that usage of these alternative materials also aimed for single use could increase littering behavior. In case these items are littered into the environment, their degradability cannot be guaranteed, as seen from the low disintegration rates in experiments at the brackish estuarine environment (0.1–0.7% d^{-1}), thus further contributing to pollution.
6. Beach and tourism ecolabels fail to target common litter items or most effective measures, making them insufficient as stand-alone solutions to reduce beach litter. Only 24 ecolabels addressed beach litter, and only two addressed over 50% of measures for litter-reduction. Ecolabels rather emphasized management actions (e.g., cleaning) over outcomes (e.g., reducing litter pollution/specific items), failed to target most effective measures and their effect is limited to seasonal efforts. More research is needed to assess the effect of beach ecolabels in litter reduction, considering long-term and seasonal data. The high pollution observed at touristic beaches in the southern Mediterranean having ecolabeled hotels (< 12% from total hotels with beach access) demonstrated a negligible effect in litter reduction.

5

Recommendations

1. A long-term monitoring for beach litter in the southern Mediterranean is highly needed and should be established to obtain more spatio-temporal data. For highly polluted beaches, an adapted method considering 3–5 transects of 10 m per beach, monitored at least once per season could allow to assess litter abundance trends during the year (and between low and high season), assess the effectiveness of litter reduction measures, and establish a litter threshold representative for the region in the long-term, once sufficient data has been gathered.
2. Aerial drones can serve to complement already existing litter monitoring approaches (at beaches and coastal waters). For cost-efficiency, aerial drone surveys should target highly polluted sites, with item sizes > 2.5 cm, using flight heights adjusted in accordance to the item size targeted. Image analyses can be carried out with deep learning approaches for litter detection and categorization, using already annotated image databases and complemented with ground truth data with e.g., citizen science. Guidelines for aerial drone surveys need to be considered, using standardized methodology to obtain harmonized data that allows cross-regional comparisons.
3. Coastal transport processes should be further explored. Highly resolved hydrodynamic models coupled with Lagrangian particle tracking can be useful

to assess transport pathways. Since physical hydrodynamic models are not available for most coastal sites, field experiments using GPS trackers or regular riverine litter sampling can enable to adjust emission budgets. Aspects like particle buoyancy, windage, sinking and remobilization need to be further explored, to assess particles sinking, deposition and resuspension. Litter retention at rivers or estuaries needs to be considered to refined plastic emission into the open sea and plastic budgets at different compartments.

4. To address the challenge of SUPs and litter pollution in coastal areas, it is crucial to strengthen waste management infrastructure, especially with regard to segregate collection and recycling in touristic sites. If new materials are introduced, such as bio-based, biodegradable and compostable materials, their potential impact to coastal environments needs to be assessed, and experiments assessing disintegration rates should be carried out in real environments. Policy goals need to align with local realities and should drive the improvement of waste infrastructure. Labelling information for correct disposal is highly needed and society must be educated to differentiate between the terms “bio-based”, “biodegradable”, “compostable”, and “eco-friendly” as well as on disposal needs.
5. Ecolabels need to be revised to integrate effective and site-specific litter reduction measures in their awarding criteria, addressing predominant litter items and sources of pollution. They also need to define thresholds for acceptable litter levels, and prioritize low-effort and direct actionable practices involving main polluters (e.g., HORECA sector). They could also incorporate beach quality indices to assess welfare and ecosystem status, and allow recovery periods from mass tourism.
6. No one measure fits all, thus measures to reduce single-use plastics, and macrolitter in general, need to be critically evaluated for each context, considering aspects of costs, effort and effectiveness. The problem of litter and plastic pollution is multi-actor and cross-sectoral and requires an integrated and holistic approach to select appropriate measures, integrating researchers, policy makers, industry and the general public.

6

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8

Summary in Lithuanian

ĮVADAS

Jūrų ir pakrančių tarša jūrą teršiančiomis šiukšlėmis, ypač plastiku, yra didėjanti pasaulinė problema (UNEP, 2019). Jūrą teršiančios šiukšlės apibrėžiamos kaip bet kokia patvari kieta medžiaga, tyčia ar atsitiktinai patekusi į jūros ir pakrančių aplinką (UNEP, 2005), ir apima plastiką, popierių, metalą, stiklą / keramiką, medieną, gumą ar tekstilę (Fleet ir kt., 2021). Plastikas yra problemiškiausias – jis sudaro iki 99 % į pakrantes, jūros paviršių ir dugną išplaunamų jūrą teršiančių šiukšlių (Galgani ir kt., 2015). Apie 40 % plastiko produkcijos skirta pakuotėms (Plastics Europe, 2023), o gyvavimo ciklas nuo pagaminimo iki utilizavimo trunka mažiau nei metus (Geyer ir kt., 2017). Bioplastikai dabar sudaro 0,5 % visos pasaulinės plastiko gamybos, o 45 % jų skirta pakuotėms (EEA, 2025). Kartu su cigarečių nuorūkomis vienkartiniai plastikiniai gaminiai yra labiausiai paplitusios paplūdimius teršiančios šiukšlės pasaulyje (Hardesty ir kt., 2021). Dėl plastiko patvarumo, per didelio naudojimo, išmetimo įpročių, kenksmingų priedų ir nesuderinamų atliekų tvarkymo sistemų, skirtų tvarkyti didėjantį plastiko atliekų kiekį, plastikas (ypač vienkartinis) yra viena pagrindinių pakrančių ir jūrų aplinką trešiančių medžiagų.

Į vandenynus patenkančių atliekų kiekis labai priklauso nuo pakrančių gyventojų skaičiaus ir netinkamo atliekų tvarkymo. Apskaičiuota, kad kasmet į vandenyną patenka 3,1–12,7 mln. tonų netinkamai tvarkomų plastiko atliekų iš netoliese gyvenančių pakrančių gyventojų (Jambeck ir kt., 2015; Lebreton ir Andrady, 2019), o iki 2060 m.

šis kiekis gali išaugti tris kartus (Lebreton ir Andrady, 2019). Atsižvelgiant į tai, kad 25 % pasaulio gyventojų gyvena 50 km spinduliu nuo pakrantės, kur populiacijos augimas yra spartesnis nei sausumoje (Cosby ir kt., 2024), šiukšlių kiekis greičiausiai didės. Anot Jambeck ir kt. (2015), 16 iš 20 šalių, kuriose plastiko atliekos tvarkomos netinkamai, yra mažas ir vidutines pajamas gaunančios šalys. Be geresnės atliekų tvarkymo infrastruktūros iki šių metų (2025 m.) į vandenyną išmestų šiukšlių kiekis gali labai padidėti. Sparčiai augant pakrančių gyventojų skaičiui Pietų pusrutulyje (Barragán ir de Andrés, 2015) pabrėžiama būtinybė tirti šią problemą Afrikoje, Azijoje ir Lotynų Amerikoje.

Turizmas, 2023 m. sudaręs 3,2 % pasaulinio BVP, yra svarbus pakrantės zonoje (WTTC, 2025). Turizmo ir poilsio sektoriai yra atsakingi už taršą šiukšlėmis ir yra jos veikiami. Tarptautinis ir vietinis turizmas kasmet pasaulyje sukuria 35 mln. tonų kietųjų atliekų (UNEP ir WTO, 2012). Atliekų, kurių daugeliu atvejų negalima tvarkyti turistinėse vietose (Wilson ir Verlis, 2017; Garcés-Ordóñez ir kt., 2020; Grelaud ir Ziveri, 2020). Viduržemio jūra pritraukia beveik trečdalį visų pasaulio turistų (Plan Bleu, 2022) ir yra viena labiausiai užterštų jūrų pasaulyje (Prevenios ir kt., 2017; Vlachogianni ir kt., 2020). Baltijos jūroje pagrindiniai paplūdimius teršiančių šiukšlių taršos šaltiniai yra turizmas ir rekreacija (Schernewski ir kt., 2017). Lotynų Amerikos rytinėje Ramiojo vandenyno pakrantėje nuo 2005 m. sparčiai daugėja turistų (World Bank, 2023), o turizmas ir rekreacija yra svarbūs pakrantes teršiančių makrošiukšlių šaltiniai (Honorato-Zimmer ir kt., 2024). Dėl didelio paplūdimius teršiančių šiukšlių kiekio prarandama estetinė vertė ir pajamos iš turizmo (Mouat ir kt., 2010).

Jūrą teršiančios šiukšlės skirstomos į nanošiukšles (< 1 µm), mikrošiukšles (< 5 mm), mezošiukšles (5–25 mm) ir makrošiukšles (> 25 mm) (GESAMP, 2019). Makrošiukšlės, dėl savo beveik nepažeistos formos, leidžia lengviau nustatyti taršos šaltinius ir valdymo priemones. Paplūdimius teršiančių šiukšlių stebėjimas plika akimi yra paprastas makrošiukšlių gausos vertinimo metodas (GESAMP, 2019). Nors šis metodas yra plačiai taikomas, pateikti vienetai labai svyruoja (objektų skaičius, svoris, objektai nustatytame plote) (Serra-Gonçalves ir kt., 2019), todėl sunku įvertinti erdvinį pasiskirstymą, nustatyti didelio taršos tankio zonas ir galimus taršos šaltinius. Stebėsenos metodai turėtų būti plačiai taikomi, palyginami, perkeliami ir ekonomiškai efektyvūs, kad būtų galima rasti sprendimus (JRC, 2013). Alternatyvių metodų, tokių kaip bepiločiai orlaiviai, pritaikymo ir ekonomiškumo testavimas tampa aktualus siekiant aptikti dideles akumuliacijos zonas, gauti didelę laiko ir erdvės aprėptį bei nuoseklius duomenis, leidžiančius palyginti skirtingus regionus.

Nors atlikta įvairių tyrimų, kuriuose vertinama šiukšlių pernaša vandenyne (Kaandorp ir kt., 2020; Chassignet ir kt., 2021; Onink ir kt., 2021), mažiau tyrimų nagrinėjo sudėtingus fizinius procesus, darančius įtaką šiukšlių pernašai ir kaupimuisi pakrantėse. Dėl bangų judėjimo, stipresnio vertikalaus maišymosi, intensyvaus biologinio apaugimo ir augmenijos plūduriuojančios atliekos upėse įstringa arba greitai nuskęsta (Van Sebille ir kt., 2020). Pakrančių paviršiniai vandenys gali būti laikinos šiukšlių kaupimosi ir pereinamosios zonos, o paplūdimiai, pakrančių augmenija, upių žiotys ir jūros dugnas yra taršos kaupimosi vietos (Koelmans ir kt., 2017; van Sebille ir kt., 2020). Dėl šios priežasties būtina įvertinti pakrančių pernašos dinamiką skirtingose pakrančių ekosistemose, siekiant geriau suprasti šiuos procesus ir patikslinti šiukšlių išmetimo į atvirą vandenyną skaičiavimus.

Jūrą teršiančių šiukšlių ir taršos plastiku valdymo priemonės gali būti procesai, technikos, žinios ar priemonės, taip pat reguliavimo susitarimai ir veiksmų planai (Ogunola ir kt., 2018; Williams ir Rangel-Buitrago, 2019). Visai neseniai derėtasi dėl Tarptautinės plastiko sutarties (UNEP, 2025), kaip teisiškai įpareigojančios priemonės, reglamentuojančios plastiko gamybą ir visą jo gyvavimo ciklą, tačiau susitarimas dar nepasiektas. Priemonės mažinti šiukšlių kiekį gali būti skirstomos į prevencines, mažinančias, šalinimo ir elgesio keitimo (Chen, 2015). Tik keliuose tyrimuose peržiūrėtos skirtinguose pasaulio regionuose taikomos priemonės (Löhr ir kt., 2017; Agamuthu ir kt., 2019; Williams ir Rangel-Buitrago, 2019; Schmaltz ir kt., 2020; Winterstetter ir kt., 2021), o dar mažiau tyrimų apėmė jų ekonomiškumą ir veiksmingumą (Willis ir kt., 2018; Urbina ir kt., 2020; Bellou ir kt., 2021; Nikiema ir Asiedu, 2022). Todėl reikia atlikti daugiau tyrimų, kad būtų galima kritiškai įvertinti valdymo priemonių veiksmingumą siekiant ilgalaikio taršos plastiku mažinimo skirtinguose geografiniuose regionuose.

Tyrimo tikslas ir uždaviniai

Šio darbo tikslas – kiekybiškai įvertinti ir apibūdinti taršą makrošiukšlėmis turistiniuose pakrančių regionuose, naudojant pažangius stebėsenos metodus, nustatyti šiukšlių pernašos kelius iš sausumos į jūrą ir įvertinti valdymo priemonių, skirtų mažinti makrošiukšlių kiekį skirtinguose geografiniuose regionuose, veiksmingumą. Tikslui pasiekti iškelti šie uždaviniai:

1. kiekybiškai įvertinti makrošiukšlių gausą labai užterštuose paplūdimiuose naudojant modifikuotus tyrimo metodus, skirtus nustatyti akumuliacijos zonas, bei identifikuoti vyraujančius šiukšlių objektus ir pagrindinius taršos šaltinius (publikacija Nr. 1);
2. įvertinti bepiločių orlaivių pritaikymo ir perkėlimo galimybes bei ekonominį efektyvumą ilgalaikei paplūdimius teršiančių makrošiukšlių stebėsenai ir nustatyti aplinkos bei technologinius veiksnius, turinčius įtakos aptikti šiukšles smėlėtuose paplūdimiuose (publikacija Nr. 2);
3. įvertinti pakrantėse vykstančių renginių metu susidarančių makrošiukšlių išmetimą ir išanalizuoti jų pernašos kelius bei akumuliacijos modelius estuarijų sistemoje (publikacija Nr. 3);
4. kritiškai išanalizuoti turistinėse pakrančių vietose taikomas makrošiukšlių mažinimo priemones, įvertinant jų veiksmingumą kovoti su vyraujančiomis šiukšlėmis, ir parengti rekomendacijas priemonių tobulinimui (publikacija Nr. 4 ir Nr. 5).

Darbo naujumas

Šiame darbe daugiausia dėmesio skirta pagrindiniam sausumos taršos šaltiniui – turizmui ir rekreacijai, bei teršalams – vienkartiniams plastikiniams gaminiams, pereinant nuo tradicinio taršos vertinimo prie pažangių stebėsenos technologijų bei kritinio taršos mažinimo priemonių vertinimo. Nauji taršos plastiku stebėsenos metodai naudojami kiekybiškai įvertinti taršos gausą ir nustatyti šaltinius bei pernašos kelius skirtinguose geografiniuose regionuose, o valdymo priemonės kritiškai įvertintos jų taikymo ir veiksmingumo atžvilgiu.

Pirmasis tarpvalstybinis paplūdimius teršiančių makrošiukšlių tyrimas atliktas Pietų Viduržemio jūros pakrantėje (Maroke, Tunise ir Egipte), kur trūko stebėsenos duomenų. Išsami objektų klasifikacija leido vietos ekspertams nustatyti taršos šaltinius. OSPAR/UNEP-IOC 100 m transektų metodas pritaikytas greitesniam 10 m transektų metodui, kuris padidino efektyvumą labai užterštuose paplūdimiuose ir išlaikė plačią erdvinę aprėptį bei trumpą tyrimo laiką.

Paplūdimius teršiančių makrošiukšlių stebėsenos tyrimas bepiločiais orlaiviais buvo vienas pirmųjų, kuriame išbandyti vartotojams pritaikyti dronai, skirti aptikti mezo- (1–25 mm) ir makrošiukšles (> 25 mm) smėlio paplūdimiuose. Sąnaudų efektyvumo analizė atskleidė bepiločių orlaivių potencialą ilgalaikei stebėsenai tikslumo, atkūrimo, lankstumo ir kokybės aspektais. Disertacijai atlikta atnaujinta analizė, atsižvelgiant į naujausius technologijų ir vaizdų analizės pasiekimus.

Naujoviškas didelės skiriamosios gebos (20 m) hidrodinaminis modelis naudotas modeliuoti plastiko pernašą sudėtingose estuarijų sistemose, kur dirbtinės konstrukcijos ir augmenija daro įtaką šiukšlių kaupimuisi. Dėl uosto veiklos ir buriavimo festivalių išmetamų teršalų kiekis įvertintas taikant įvairias plūduriuojančio plastiko ėminių ėmimo metodikas Warnow estuarijoje (detaliau 2.4 skyriuje), atsižvelgiant į lankytojų skaičių ir „Hanse Sail“ festivalyje surinktas šiukšles, o rezultatai ekstrapoliuoti kitiems 50 Baltijos jūroje vykstantiems renginiams. Rezultatai parodė, kad estuarijos veikia kaip galutinės šiukšlių kaupimosi vietos, o plastiko išmetimas į Baltijos jūrą yra nereikšmingas, todėl norint įvertinti plastiko išmetimą į atvirą vandenyną reikia atsižvelgti į plastiko kaupimąsi upėse ir estuarijose.

Kritiškai įvertintos dvi pagrindinės taršos mažinimo priemonės turistinėse pakrantėse: vienkartinių plastikinių gaminių pakeitimas biologinės kilmės, biologiškai skaidžiais ir kompostuojamais alternatyviais produktais pakrančių festivaliuose ir paplūdimių bei turizmo ekologinių ženklų diegimas siekiant sumažinti vyraujančių šiukšlių kiekį. Šie tyrimai yra vieni pirmųjų, kuriuose pateiktas holistinis taršos plastiku mažinimo priemonių vertinimas. Jame atsižvelgta į politiką ir reglamentus, visuomenės nuomonę, eksperimentus, skirtus įvertinti plastiko irimo realioje aplinkoje procesą, pastangų (laiko ir išlaidų) bei veiksmingumo vertinimą suinteresuotųjų šalių požiūriu ir įgyvendinimo sunkumus skirtinguose geografiniuose regionuose.

Galiausiai tyrimai atlikti skirtingų socialinių ir ekonominių sąlygų regionuose: Pietų Baltijos regione, Pietų Viduržemio jūros regione (Šiaurės Afrikoje) ir Čilės pakrantėje. Tarp regionų palyginti šiukšlių kiekiai, vyraujantys šiukšlių tipai, jų patekimo keliai ir šaltiniai, aptarta stebėsenos metodų ir mažinimo priemonių pritaikymo kituose regionuose galimybė bei pabrėžtos likusios tyrimų spragos.

Tyrimo mokslinis ir praktinis aktualumas

Tarpvalstybinė stebėsena Pietų Viduržemio jūros pakrantėje (Šiaurės Afrikoje) sumažino žinių spragas apie makrošiukšlių gausą ir pasiskirstymą. Vietiniai tyrėjai gali naudoti pritaikytą metodiką ilgalaikei stebėsenai. Rezultatai parodė didesnę taršą miestų ir turistiniuose paplūdimiuose, daugiausia dėl pakrantės veiklos ir prasto atliekų tvarkymo. Duomenys gali padėti specialistams laikytis Viduržemio jūros regiono ribinių verčių bei informuoti, ar Pietų Viduržemio jūros šalims reikalingos specifinės regiono ribinės vertės.

Tyrimas naudojant bepiločius orlaivius parodė vartotojams pritaikytų dronų potencialą aptikti paplūdimius teršiančias šiukšles. Atkūrimo eksperimentų ir transektų testai išryškino kartografavimo ir klasifikavimo stiprybes bei silpnybes ir suteikė gaires tolesnei plėtrai. Dėl santykinai švarių Baltijos jūros paplūdimių, kuriuose aptinkami mažesni šiukšlių objektai, dronai nebuvo laikomi tinkama priemone ilgalaikei stebėsenai. Vis dėlto, metodologiniai rezultatai ir sąnaudų efektyvumo analizė gali būti pritaikoma, o atnaujintas vertinimas suteikia naujų perspektyvų, atsižvelgiant į naujausius vaizdų analizės metodus ir technologinę pažangą.

„Hanse Sail" festivalio (Rostoke, Vokietijoje) atvejo tyrimas leido ekstrapoliuoti išmetamų teršalų kiekį 50 Baltijos jūros pakrantės festivalių ir atskleidė nežymų indėlį į bendrą metinį makrošiukšlių išmetimą. Vis dėlto, vietinė įtaka gali būti didelė esant nepakankamam atliekų tvarkymui. Didelės skiriamosios gebos hidrodinaminis modelis atskleidė plastiko pernašos ir kaupimosi estuarijose ypatumus – kaupimąsi nendrynuose, kurie dėl sudėtingo prieinamumo paprastai neįtraukiami į tyrimus, o tai pabrėžia tolesnių tyrimų poreikį.

Turizmo ir rekreacijos šaltinis ištirtas kritiškai vertinant vienkartinių plastikinių gaminių mažinimo priemones. Vienkartinių plastikinių stalo reikmenų pakeitimo biologinės kilmės, biologiškai skaidžiais ar kompostuojamais alternatyviais produktais Rostoke (Vokietija), Klaipėdoje (Lietuva), Hamamete (Tunisas) ir La Serenoje (Čilė) tyrimas parodė, kad nė vienas miestas neturėjo tinkamos infrastruktūros tvarkyti šių atliekų, ir atskleidė politikos tikslų neatitikimą. Visuomenės žinios apie objektų irimą ir tinkamą atliekų tvarkymą taip pat ribotos. Rezultatai rodo, kad netinkamai tvarkomi alternatyvūs produktai vis dar gali prisidėti prie šiukšlių susidarymo. Paplūdimių ir turizmo ekologinių ženklų, skirtų paplūdimius teršiančių šiukšlių mažinimui, tyrimas parodė, kad ekologiniai ženklai šiuo metu yra neveiksmingi, kadangi tik du iš jų apima daugiau nei 50 % veiksmingų šiukšlių mažinimo priemonių. Rekomendacijos apima ekologinių ženklų pritaikymą prie vietos sąlygų, veiksmingų priemonių integraciją, šiukšlių ribinių verčių suderinimą su tarptautine politika ir ekosistemų apsaugos akcentavimą. Ekologinių ženklų sąrašas bei sukartografuoti paplūdimiai ir viešbučiai su prieiga prie paplūdimių prieinami Zenodo duomenų bazėje būsimiems tyrimams.

Metodai

Disertacijoje daugiausia dėmesio skirta trims pakrančių regionams: Pietų Viduržemio jūros pakrantei, Pietų Baltijos jūros pakrantei ir Čilės Ramiojo vandenyno pakrantei, kurie pasižymi skirtingomis aplinkos sąlygomis ir tyrimų spragomis. Nors ne visi regionai analizuoti vienodu mastu, siekta sudaryti pasaulinę perspektyvą apie paplūdimius teršiančių makrošiukšlių problemą, kuri apima ir regionų palyginimus.

Pietų Viduržemio jūros pakrantėje (Maroke, Tunise ir Egipte) pritaikytas paplūdimius teršiančių makrošiukšlių monitoringas siekiant įvertinti dažniausiai pasitaikančius šiukšlių objektus ir taršos šaltinius (2.2 skyrius, publikacija Nr. 1). Pietų Baltijos jūros pakrantėje (Šiaurės Vokietijos ir Lietuvos paplūdimiuose) išbandyti ir įvertinti makrošiukšlių stebėsenos metodai naudojant bepiločius orlaivius (2.3 skyrius, publikacija Nr. 2). Warnow upės, esančios Rostoke (Vokietija), žiotyse naudotas dalelių sekimo modelis, siekiant įvertinti šiukšlių pernašos kelius (2.4 skyrius, publikacija Nr. 3). Galiausiai, kritiškai įvertintas priemonių, skirtų mažinti pakrančių taršą plastiku, veiksmingumas remiantis dviem atvejų tyrimais: vienkartinių plastikinių stalo reikmenų pakeitimu alternatyviomis medžiagomis pakrančių festivaliuose (2.5.1 skyrius, publikacija Nr. 4) ir paplūdimių bei turizmo ekologiniais ženklais, skirtais mažinti paplūdimius teršiančias šiukšles (2.5.2 skyrius, publikacija Nr. 5).

Rezultatai ir diskusija

Paplūdimius teršiančių makrošiukšlių tyrimais siekta užpildyti tyrimų spragas Pietų Viduržemio jūros pakrantėje, nustatyti vyraujančius taršos objektus ir taršos šaltinius. Pagrindiniai publikacijos Nr. 1 rezultatai parodė aukštą taršos lygį Maroke, Tunise ir Egipte – nuo 436 iki 24 270 makrošiukšlių objektų arba 0,22–13,69 vnt./m^2. Pagal Švarios pakrantės indeksą (CCI), dauguma paplūdimių klasifikuojami kaip nešvarūs arba itin nešvarūs. Sezoninė paplūdimius teršiančių šiukšlių analizė, atlikta remiantis papildoma literatūra publikacijoje Nr. 5, parodė, kad didelė tarša šiukšlėmis pastebėta tiek sezono, tiek ne sezono metu (nepaisant to, kad sezono metu paplūdimiai buvo valomi), išskyrus Maroką, kurio paplūdimiai buvo švaresni. Vis dėlto, norint gauti galutinius rezultatus, reikia daugiau laiko duomenų ir ilgalaikės stebėsenos. Vienkartiniai plastikiniai gaminiai sudarė 45 % visų Maroke, Tunise ir Egipte pastebėtų šiukšlių, o pagrindiniu taršos šaltiniu įvardyta „pakrantė, pasižyminti prasta atliekų tvarkymo praktika, turizmu ir rekreacine veikla". Šiuo atveju reikalinga išsamesnė taršos šaltinių analizė, kad būtų galima įgyvendinti priemones, nukreiptas į konkrečius teršėjus. Labai užterštų paplūdimių tyrimui pritaikytas 10 m transektų metodas buvo pakankamas norint lengviau reprezentuoti paplūdimius teršiančių šiukšlių charakteristikas, kadangi 25 dažniausiai aptinkami objektai rasti penkiuose 10 m transektuose, ir šie 25 objektai sudarė 82 % taršos.

Eksperimentų su bepiločiais orlaiviais metu siekta patikrinti šių įrankių potencialą paplūdimius teršiančių šiukšlių tyrimuose aptinkant didesnes nei 2,5 cm šiukšles, taikant prižiūrimą objektais paremtą klasifikaciją su trimis algoritmais. Pagrindiniai publikacijos Nr. 2 rezultatai atskleidė, kad geriausia klasifikacija gauta vaizdams iš 10 m aukščio. Naudojant skirtingus algoritmus rezultatai nesiskyrė. Visų algoritmų klasifikavimo tikslumas 100 m paplūdimio ruožuose buvo mažas, *kappa* vertės svyravo nuo 0,11 iki 0,64, todėl galima teigti, kad klasifikavimas buvo beveik atsitiktinis. Bendri rezultatai parodė, kad bepiločiai orlaiviai galėtų puikiai tikti kaip greito tikrinimo įrankis labai užterštiems paplūdimiams. Nauji metodai, kuriuose naudojami daugiaspektriniai arba hiperspektriniai jutikliai, arba gilaus mokymosi metodai, skirti aptikti šiukšles, parodė geresnius rezultatus ir turėtų būti svarstomi bepiločiais orlaiviais gautų vaizdų analizei. Atnaujinta bepiločių orlaivių kaip stebėsenos įrankių ekonominio efektyvumo analizė parodė, kad dronai pasižymi panašiais veiksmingumo ir sąnaudų rodikliais, užtikrinančiais aukštą ekonominį efektyvumą, todėl jie gali būti toliau tiriami kaip stebėsenos metodus papildančios priemonės.

Publikacijoje Nr. 3 pateiktas dalelių sekimo modelis, kuriame naudojamas didelės skiriamosios gebos estuarijų hidrodinaminis modelis, parodė, kad šiose sudėtingose pakrančių sistemose atliekų pernašai įtaką daro keli veiksniai, įskaitant estuarijos cirkuliaciją, vėjo greitį ir kryptį, uosto ir pakrantės morfometriją bei augmenijos buvimą. Po stiprių vėjų tik 0,4 % dalelių, išmestų į estuariją po pakrantėje vykusio renginio, pasiekė estuarijos žiotis (maždaug 11 km nuo išmetimo vietos). Tai rodo, kad estuarijos, veikiančios kaip galutinės šiukšlių kaupimosi vietos, pasižymi dideliu kaupimosi pajėgumu. Atsižvelgiant į Pietų Baltijos jūros upių šiukšlių išmetimo į aplinką kiekį, buriavimo renginiai ir uostų veikla sudaro mažiau nei 0,05 % bendro išmetamų teršalų kiekio. Vis dėlto tikėtina, kad šiukšlių išmetimas iš upių, neatsižvelgiant į kaupimąsi, gali būti labai pervertintas, todėl būtina peržiūrėti šiukšlių išmetimą į atvirą vandenyną.

Vienkartiniai plastikiniai gaminiai yra vienos dažniausiai randamų šiukšlių paplūdimiuose visame pasaulyje. Publikacijoje Nr. 4 kritiškai įvertinti pakrantėse vykstančiuose renginiuose naudojami alternatyvūs produktai, ypač biologinės kilmės, biologiškai skaidūs ir kompostuojami stalo reikmenys. Nors visose tirtose vietose egzistuoja vienkartinių plastikinių gaminių mažinimo politika, realybės neatitikimas tarp politikos siekių ir atliekų tvarkymo trukdo veiksmingai tvarkyti šiuos alternatyvius stalo reikmenis, kadangi dauguma jų yra deginami arba šalinami sąvartynuose. Visuomenė labai palankiai vertino alternatyvias medžiagas, tačiau jos suvokimas apie skaidumą, kompostavimą ir kitus aplinkosauginius aspektus yra šališkas neplastikinių pakaitalų naudai. Žinios ir informuotumas apie tinkamą atliekų tvarkymą yra menkas, todėl būtina nurodyti informaciją gaminių etiketėse ir šviesti visuomenę apie atliekų šalinimą. Skaidumas ir kompostavimas realioje aplinkoje nėra garantuotas. Dezintegracijos eksperimentai parodė, kad daugumos medžiagų irimo greitis tiek estuarijų vandenyse, tiek pramoninėje kompostavimo aikštelėje yra labai lėtas. Šie objektai vis dar skirti vienkartiniam naudojimui ir, jei patenka į pakrančių zonas, dėl lėto irimo gali dar labiau prisidėti prie taršos.

Taip pat įvertinti paplūdimių ir turizmo ekologiniai ženklai, siekiant nustatyti jų potencialą sumažinti paplūdimių taršą šiukšlėmis (publikacija Nr. 5). Tik 24 ekologiniai ženklai yra orientuoti į paplūdimių šiukšlinimo problemą ir tik du apima daugiau nei 50 % šiukšlių mažinimo priemonių. Nagrinėtos priemonės daugiausia apėmė sisteminius politikos pokyčius arba visuomenės švietimą, o ne tiesiogines ir įgyvendinamas praktines priemones, skirtas viešbučių, restoranų ir viešojo maitinimo sektoriui (HORECA). Įvertinus šiukšlių gausą Maroke sezono ir ne sezono metu, paaiškėjo, kad bendras taršos šiukšlėmis lygis yra mažesnis nei Tunise ir Egipte, tačiau lieka neaišku, ar tai vien ekologinio ženklo įdiegimo, ar visos šalies paplūdimius teršiančių šiukšlių stebėsenos ir vyriausybės pastangų didinti informuotumą pasekmė. Kadangi ekologiniai ženklai nėra nukreipti į veiksmingiausias priemones ir jie taikomi tik sezono metu, jų poveikis greičiausiai yra laikinas. Didelis užterštumas, pastebėtas turistiniuose Tuniso ir Egipto paplūdimiuose, kuriuose yra ekologiniu ženklu pažymėtų viešbučių (< 12 % visų viešbučių, turinčių prieigą prie paplūdimių), rodo, kad ši priemonė turi nežymų poveikį atliekų mažinimui. Dėl šios priežasties ekologiniai ženklai, tokie, kokie jie yra, nėra veiksmingi siekiant mažinti paplūdimius teršiančias šiukšles, nes jie neapima vyraujančių taršos objektų ir nesumažina bendro taršos lygio, be to, neįtraukia veiksmingiausių priemonių, todėl nėra pakankami kaip atskiri sprendimai.

Išvados

1. Vienkartiniai plastikiniai gaminiai buvo pagrindiniai paplūdimių taršos objektai visose tirtose vietose, o pagrindiniai taršos šaltiniai buvo turizmas, rekreacija ir netinkamas atliekų tvarkymas. Pietų Viduržemio jūros pakrantės (Marokas, Tunisas ir Egiptas), pagal Švarios pakrantės indeksą (CCI) klasifikuojamos kaip nešvarios arba labai nešvarios, pasižymėjo didele tarša makrošiukšlėmis. Sezoninė analizė, atlikta remiantis tyrimo duomenimis ir literatūra, atskleidė didelį taršos lygį tiek sezono, tiek ne sezono metu, tačiau norint gauti galutinius rezultatus reikalinga ilgalaikė stebėsena.

2. Pritaikytas 10 m transektų metodas padėjo veiksmingai nustatyti paplūdimius teršiančių šiukšlių charakteristikas mažesnėmis pastangomis, kadangi 25 dažniausiai aptinkami objektai, rasti penkiose 10 m transektose, sudarė 82 % nustatytos taršos. Šis metodas leistų greičiau nustatyti vyraujančius šiukšlių objektus ir taršos šaltinius, palengvinant tikslingų ir veiksmingų mažinimo priemonių kūrimą.
3. Bepiločiais orlaiviais atlikti eksperimentai pasiekė didžiausią tikslumą aptinkant didesnius nei 2,5 cm šiukšlių objektus ir naudojant vaizdus iš 10 m aukščio. Bepiločiai orlaiviai netinka Baltijos jūros paplūdimiams, tačiau gali būti naudojami kaip greita labai užterštų paplūdimių tikrinimo priemonė. Ekonominio efektyvumo rodiklis buvo panašus į OSPAR metodą, o tai rodo dronų, kaip papildomų stebėsenos įrankių, vertę, ypač jei jie derinami su naujausiomis bepiločių orlaivių technologijomis ir gilaus mokymosi vaizdų analizės metodais.
4. Dalelių sekimo modelis Warnow estuarijoje parodė labai didelį šiukšlių kaupimąsi – per 10 dienų į Baltijos jūrą pateko tik 0,4 % išmestų dalelių. Estuarijose šiukšlių pernašai įtakos turi keli veiksniai, įskaitant estuarijų cirkuliaciją, vėjo greitį ir kryptį, uosto ir kranto linijos morfometriją bei augmenijos buvimą. Šie veiksniai skirtingose sistemose skiriasi ir negali būti lengvai perkeliami. Dabartinis šiukšlių išmetimo iš upių įvertinimas turi būti peržiūrėtas atsižvelgiant į kaupimosi aspektus.
5. Biologinės kilmės, biologiškai skaidūs ir kompostuojami stalo reikmenys nėra tinkama vienkartinių plastikinių gaminių alternatyva pakrantėse vykstančiuose renginiuose. Dėl lėto jų irimo ir infrastruktūros trūkumo tvarkyti medžiagas po išmetimo, dauguma šių objektų būna sudeginti arba išvežti į sąvartynus. Visuomenės klaidingas supratimas apie medžiagų skaidumą gali padidinti šiukšlinimą. Šios medžiagos, patekusios į aplinką, išlieka panašiai kaip ir įprasti plastikai, dar labiau prisidėdamos prie taršos.
6. Paplūdimių ir turizmo ekologiniai ženklai nėra veiksmingi siekiant mažinti paplūdimių šiukšlinimą turistinėse pakrantėse. Tik 24 ekologiniai ženklai yra skirti paplūdimių šiukšlinimo problemai ir tik du apima daugiau nei 50 % šiukšlinimo mažinimo priemonių. Dauguma jų neapima dažniausiai pasitaikančių šiukšlių objektų ar veiksmingiausių priemonių. Jie pabrėžia valdymo veiksmus (pvz., valymą), o ne konkrečius rezultatus (pvz., taršos šiukšlėmis / konkrečių objektų mažinimą), ir apsiriboja tik sezoniniu laikotarpiu. Didelis taršos lygis, pastebėtas ekologiniu ženklu pažymėtuose Pietų Viduržemio jūros paplūdimiuose ir viešbučiuose, parodė šių ženklų ribotą poveikį, todėl reikia ilgalaikių sezoninių duomenų ir įrodymais pagrįsto vertinimo.

CURRICULUM VITAE

Gabriela Escobar Sánchez was born in Chile on November 23rd, 1993. From an early age, she showed curiosity for understanding how things work, which later evolved into an interest to explore complex environmental problems. She obtained her Bachelor´s degree in Molecular Ecosystem Sciences from Georg August Universität Göttingen, Germany, where she developed a strong foundation in the complexities of ecosystem functioning from the molecular to the ecosystem level. During her studies, she actively worked as a student research assistant in various projects, gaining early exposure to scientific research.

Motivated to address the role of humans in environmental impacts, she pursued a Master´s degree in Environmental Management at Christian-Albrechts-Universität zu Kiel, Germany, focusing on coastal zone dynamics and geospatial analysis. In the second year of her program, she spent an exchange semester at Wageningen University, The Netherlands, within the Urban Environmental Management program, where she developed an interest in solid waste management. She combined this topic with her interest for coastal systems and geospatial analysis in her Master's thesis "Aerial Drones as tools for beach litter monitoring in southern Baltic Sea Beaches" conducted in collaboration with the Leibniz Institute for Baltic Sea Research Warnemünde (IOW), under the supervision of Prof. Gerald Schernewski and Prof. Natasha Oppelt.

After completing her studies, Gabriela joined the IOW as a research assistant within the TouMaLi (Tourism and Marine Litter) Project and in the Interred South Baltic COP (Circular Ocean-bound Plastic) Project, contributing to research on plastic pollution in North Africa and the southern Baltic regions. Through these projects, she gained practical experience in litter monitoring methods, aerial and underwater drone operations, and collaboration with international experts and stakeholders for the implementation of monitoring and management measures, as well as in science communication, student supervision, and teaching activities.

In 2021, she began her PhD at Klaipėda University, Lithuania, under the supervision of Prof. Gerald Schernewski, focusing on marine litter management across the Baltic Sea, North Africa, and Chile. Her doctoral thesis titled "Macrolitter in coastal zones: an assessment of monitoring methods, pollution sources and mitigation measures across different geographical regions" integrates field data, geospatial analysis with aerial drones, identification of pollution sources, transport dynamics, and the evaluation of mitigation measures to reduce litter pollution. She also collaborated with Prof. Martin Thiel and colleagues from Universidad Católica del Norte, Chile, on two publications addressing the state of marine litter pollution on the coast of Latin America and Marine Protected Areas of the Pacific Ocean.

Gabriela's work reflects a broad interest in the interface between environmental science and management. She aims to apply her interdisciplinary skills and international experience to address pressing environmental challenges with particular attention to regions most affected by anthropogenic pressures, and to support evidence-based decision-making in diverse contexts.

Publications

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RESEARCH

Assessment of beach litter pollution in Egypt, Tunisia, and Morocco: a study of macro and meso-litter on Mediterranean beaches

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Abstract We conducted surveys of Mediterranean beaches in Egypt, Morocco, and Tunisia including 37 macro-litter (> 25 mm) and 41 meso-litter (5–25 mm) assessments. Our study identified key litter items and assessed pollution sources on urban, semi-urban, tourist, and semi-rural beaches. Macro-litter concentration averaged 5032 ± 4919 pieces per 100 m or 1.71 ± 2.28 pieces/m^2, with higher values observed on urban (mean 2.63 pieces/m^2 ± 3.03) and tourist (mean 1.23 pieces/m^2 ± 0.91) beaches. Similarly, urban (mean 9.91 pieces/m^2 ± 12.70) and tourist beaches (mean 5.32 pieces/m^2 ± 4.48) revealed elevated levels of meso-litter contamination, particularly in the upper third of the beach, which contained the highest quantities both in terms of number (51%) and weight (50%). 55% of the macro-litter and 35% of the meso-litter originated from human shoreline activities and poor waste management. Given the width of some beaches and their high levels of pollution, the standard 100 m macro-litter approach was impractical. To enable cost-effective, long-term

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monitoring, we adapted it to a faster 10 m transect approach, which provided reliable data on the top 25 litter items, accounting for 82% of beach pollution. Our Sand Rake method effectively quantified pollution on both cleaned and uncleaned beaches, addressing the often neglected meso-litter size fraction. The high pollution levels, top litter items, and identified sources indicate that beach cleaning alone will not solve the pollution problem. Efforts to raise environmental awareness, enhanced waste management, and law enforcement are needed to improve the situation in a sustainable way.

Keywords Monitoring · Sand Rake · Waste mismanagement · Single use plastic · Buried litter · Beach user

Introduction

Marine litter, defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP 2005) is one of the most significant global marine environmental challenges of our time (Bellou et al., 2021; UNEP, 2009; Urban-Malinga et al., 2020). Marine litter enters the environment in many categories, such as plastic, paper, metal, glass, and others (Ruiz-Orejón et al., 2021) through a variety of sea- and land-based sources and pathways (Veiga et al., 2016). It is found in different size classes such as micro-litter (<5 mm), meso-litter (5–25 mm), and macro-litter (>25 mm) (JRC, 2011). Regardless of time and place, plastic represents the vast majority of all marine litter (Reisser et al., 2013; Addamo et al., 2017; European Commission 2018) and it is found all over the world, from urban beaches to the remotest corners of the oceans (Pham et al., 2014).

The effects of marine litter have far-reaching consequences that extend across various sectors, including wildlife, aquaculture, tourism, and shipping (Cesarano et al., 2023; UNEP, 2021; Wagner & Lambert, 2018). In addition, marine litter threatens ecosystem services such as landscape quality, tourism, and recreation (Botero et al., 2017; Maziane et al., 2018; Rangel-Buitrago et al., 2018b). Between 2008 and 2015, marine litter damage in the Asian-Pacific region surged eightfold, costing $10.8 billion in 2015. According to McIlgorm et al. (2022), if plastic production continues as projected, the global costs could reach $229 billion by 2030 and $731 billion by 2050.

The Mediterranean Sea is one of the most polluted areas in the world and faces considerable challenges in relation to marine litter (Galgani et al., 2014; Suaria et al., 2016; UNEP, 2015). Beach tourism is vital to Mediterranean countries, representing around 80% of tourism in coastal regions and serving as a key economic source (Mejjad et al., 2022; UN, 2022). However, the challenges posed by tourism and high coastal population are significant. Mediterranean countries are the primary causes of their own beach pollution (Liubartseva et al., 2018). Approximately 80% of litter originates on land (Serra-Gonçalves et al., 2019), with coastal tourism being a significant contributor to marine and beach litter in the Mediterranean (ARCADIS, 2014). In some tourist areas, more than 75% of annual waste is generated during high season (JRC, 2011). This leads to a substantial increase in beach pollution, up to 4.7 times higher compared to the rest of the year (Grelaud & Ziveri, 2020).

While coastal pollution results from a combination of tourism activities and poor waste management practices (Nachite et al., 2019; Vlachogianni et al., 2018), tourists and beach users also demand clean coastlines. When choosing a local beach, clean sand, and water are the most vital factors (Ariza & Leatherman, 2012; NOAA, 2014), with "clean" often

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meaning free of litter and algae (Giorgio et al., 2018). Nevertheless, beaches are often polluted, including hazardous litter (sharp-edged and/or toxic), which can make up to 40% of all beach litter (Rangel-Buitrago et al., 2019b). In a survey conducted on beaches in Australia and New Zealand, 21.6% of respondents reported harm caused by beach litter, with 65% of these incidents being wounds (Campbell et al., 2016), and the occurrence of such harmful encounters doubled between 2007 and 2016 (Campbell et al., 2019).

Beach cleaning is often crucial for managing litter levels, and a significant amount of money is spent on regular, professional cleaning efforts. Mouat et al. (2010) calculated the average costs of beach cleaning per km per year in Europe (for 28 different municipalities in Denmark, Ireland, Portugal, Spain, and Sweden) to be on average €7295 (ranging from €171 to €82,101) with the highest costs in tourist areas. For Spanish beaches in Cadiz, the average cost was €50,376 (ranging from €12,050 to €96,150) per km of beach per year (Cruz et al. 2020). Tunisia quadrupled its funding for cleaning 130 km of beaches between 2016 and 2017, reaching a total of around €680,000 or an estimated €5230 per km of beach per year (jeuneafrique, 2017; Tourismeinfo, 2023). Despite significant investment in beach cleaning, pollution remains a persistent problem, which can lead to a decline in visitor numbers and a loss of income and jobs in the tourism sector (UNEP, GRID-Arendal 2016).

Research in Brazil by Krelling et al. (2017) found that over 85% of beach users would avoid heavily polluted beaches (> 15 litter pieces/m^2), leading to a 39.1% tourism revenue decrease and potential annual losses of US$8.5 million. Coastal areas in Tunisia, Morocco, and Egypt contributed significantly to their GDP in 2018 (5.4%, 7.5%, and 5.1%, respectively) (the Global Economy 2023). However, during high season, these areas face the challenge of managing extensive waste generated by tourists and found on beaches. With tourism expected to increase, this issue becomes even more significant.

To combat marine litter and promote sustainable Mediterranean development, the United Nations Environment Programme (UNEP) launched the Mediterranean Action Plan (MAP). In 2013, MAP introduced the "Regional Plan for Marine Litter Management in the Mediterranean," providing a comprehensive framework to effectively address pollution (UN, 2013). Here, marine litter characteristics should be evaluated in line with the Marine Strategy Framework Directive (MSFD) of the European Union (EU). In 2016, all Mediterranean countries adopted "The Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast" (UNEP/MAP 2016), including indicator 22, which focuses on the assessment of "trends in the amount of litter washed ashore and/or deposited on coastlines (including analysis of its composition, spatial distribution and, where possible, source)" (UNEP, 2017; MSFD TSG ML 2013). Beach litter surveys are vital for monitoring, as coastline litter is a key indicator of marine pollution (JRC, 2011), especially for litter originating from nearby land-based sources (ARCADIS, 2014). Beach surveys are environmentally friendly, cost-effective, and can be carried out by volunteers on a large scale over a long period of time (Haseler et al., 2018, 2020; Schneider et al., 2018).

While EU Mediterranean beaches are monitored seasonally (four times yearly) in regular programs (JRC, 2020; UNEP, 2015), North African monitoring is limited, with few reports on voluntary cleanups or surveys (Cesarano et al., 2023; UNEP, 2017). Morocco only conducts biannual national macro-litter monitoring on about 20 Mediterranean beaches (MTEDD, 2022). In Egypt, macro-litter monitoring efforts are limited to a regional area east of Alexandria, with no comprehensive nationwide data, while Tunisia has no ongoing national beach litter monitoring.

To monitor beach litter effectively, it is essential to prioritize different beach types. Rural beaches provide insights into background pollution levels and accumulation rates. Monitoring urban and tourist beaches near potential pollution sources allow us to understand land-based contributions and evaluate the effectiveness of litter mitigation efforts. Conducting standing stock surveys at different beaches allows comparison of litter composition, identification of hotspots, awareness raising, is cost-effective and can be used as a starting point for long-term monitoring.

Beach litter monitoring primarily focuses on visible macro-litter (> 25 mm) due to its ease of detection and collection. However, frequent cleaning of urban and tourist beaches, often daily in high season, hampers macro-litter monitoring efforts in areas where it is essential (Haseler et al., 2018). This is especially problematic during the summer when it is impractical to suspend cleaning for extended periods. To address this, it is crucial to find efficient ways to monitor litter on frequently cleaned urban beaches during both high and low seasons, ensuring standardized and comparable results.

One approach is to prioritize meso-litter, a size fraction that has received limited attention and, to the best of our knowledge, is not regularly surveyed in any of the three countries. However, it is an important litter fraction, both numerically abundant and potentially harmful (JRC, 2011). For instance, cigarette butts—one of the most commonly found litter items worldwide (Micevska et al., 2006; UNEP, 2015; Veiga et al., 2016)—are often underestimated in macro-litter surveys (Kataržytė et al., 2020), and their removal remains a significant challenge for both manual and mechanical cleaning (Zielinski et al., 2019). Consequently, meso-litter items, such as cigarette butts and plastic pieces, persist on the beach and accumulate over time (Loizidou et al., 2018), contributing to issues like injuries, scenery degradation, decreased tourism, and potential revenue loss (Araújo & Costa, 2019). Furthermore, these items continue to fragment, resulting in micro-plastics (Okuku et al., 2020).

Studying both macro and meso-litter is crucial to enhance our understanding of beach pollution and litter degradation. This knowledge empowers us to identify significant contributors and prioritize targeted mitigation and avoidance measures, thereby effectively addressing the issue of marine litter.

This research paper analyses beach pollution in Tunisia, Morocco, and Egypt through four survey campaigns. The objectives are as follows:

Analyse beach pollution, including the quantity of litter, top litter items, and litter sources, considering both macro and meso-litter across various beach types, such as urban, tourist, semi-urban, and semi-rural areas.

Investigate the small-scale distribution of litter on beaches and evaluate the feasibility of adopting a modified 100 m method for beach monitoring, especially in heavily polluted or cleaned areas.

Assess the potential of meso-litter monitoring as a replacement or support for macro-litter monitoring, particularly on cleaned beaches.

Serve as a foundational step for long-term monitoring and provide recommendations for its implementation.

Material and methods

Surveys were conducted using two different methods during four campaigns in November 2021 (Tunisia), March 2022 (Egypt), June 2022 (Tunisia), and January 2023 (Morocco), covering different Mediterranean beaches (Fig. 1). The surveys primarily focused on sandy beaches, with some inclusion of those featuring fewer pebbles and rocks. The selection of beaches aimed to provide a partial spatial overview of coastal areas. The beaches surveyed were classified

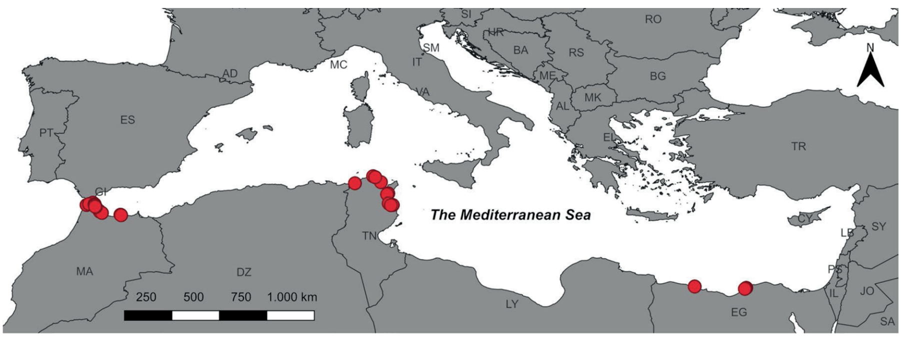


Fig. 1 Map of the study area in Morocco (MA), Tunisia (TN), and Egypt (EG). The red dots show the locations of the Macro-litter surveys and the Sand Rake surveys (Map by Eurographics 2020)

according to their development, using the classification proposed by Semeoshenkova et al. (2017). In addition to the three existing types: urban, semi-urban, and semi-rural—a fourth classification was introduced, termed "tourist." This addition was motivated by the need to distinguish beaches frequently used by national and international guests from urban beaches primarily used by locals. The Mediterranean Sea is a semi-enclosed system with a small tidal range of around half a meter (Dipper, 2022) and semidiurnal tides (NOAA, 2024). It is only connected to the Atlantic Ocean by the narrow and shallow Strait of Gibraltar (Bergamasco & Malanotte-Rizzoli, 2010).

The Macro-litter method was used 37 times, in Egypt (8 surveys), Morocco (14 surveys), and Tunisia (15 surveys) (Table 1a supplement material). Surveys were based on the 100 m monitoring method described in UNEP/MAP (2016). However, due to high pollution, resources, and time limitations (aiming for a daily survey), macro-litter was surveyed, counted, and analyzed in 10 m transects (Fig. 2). Beaches were initially categorized by development, followed by surveys conducted by 5 to 10 observers from the waterline to the back of the beach (dunes, cliffs, seawalls, or other structures). The number of 10 m transects surveyed depended on the time required per transect. Due to the limited time for each survey, heavily polluted beaches had fewer transects surveyed. During surveys, litter was systematically collected in labeled plastic bags along each transect. A minimum of two transects were surveyed, with the option to extend up to ten, collecting litter pieces > 2.5 cm. Later, litter from each transect was counted and analyzed. A maximum of 8 h was scheduled for each survey, including litter collection and analysis. Cigarette butts were excluded in the first 2021 Tunisia campaign. In Egypt and Tunisia, transects were placed adjacent to each other, while in Morocco transects were placed 10–150 m apart to allow for a broader comparison of litter distribution.

The Sand Rake method (Haseler et al., 2018) was used 41 times (Table 2a supplement material) to assess litter on sandy beaches. 19 surveys were conducted in Tunisia, 13 in November 2021, and 6 in June 2022. In Egypt, 10 surveys were conducted in March 2022, while in Morocco, 12 surveys were conducted in January 2023. The surveys focused on the dry backshore of sandy beaches, as the Sand Rake method is unsuitable for wet or coarse sediment. A mesh size of 5 mm was used. The beach width, measured from the waterline to the back of the beach, varied between 10 and 65 m, with a median width of 30 m. The survey process involved raking the beach to a depth of approximately 5 cm in 5 m subsections within columns (Fig. 3). If a column's area was less than 25 m^2, additional columns were added to meet the self-imposed 25 m^2 area requirement. Every column was examined, extending to the back of the beach, regardless of whether the 25 m^2 target area had already been reached. Per survey, the area ranged from 25 to 50 m^2, with a median of 30 m^2. Sand Rake surveys were conducted adjacent to the macro-litter surveys when the sediment was sufficiently fine, with a low number of pebbles, rocks, algae, etc.

Litter analysis for both methods was conducted using the Joint list of litter (j-list) (Fleet et al., 2021) and the allocated online photo catalogue of the j-list (EU, 2021). The highest level of detail was used for litter identification. Nine new litter items were added, as these items were frequently found on the beaches. New litter items in the artificial polymer category were medical masks; broom bristles; plastic strings from carpets; clothes pegs; sand bags and pieces; shisha tips and related; and paint particles. In the category paper/cardboard paper, tissues were added. In the category processed/worked wood, cotton candy sticks were added. All collected litter was categorized to determine if it belonged to the group of single-use plastics (SUP), as defined by the EU Single-Use Plastic Directive (EU, 2019/904) (EU, 2019).

For the macro-litter method, the pollution was measured in litter pieces per 100 m and pieces/m^2. If a macro-litter survey covered less than 100 m, the average transects pollution was extrapolated to represent a 100 m stretch, following the UNEP/MAP (2016) recommendation for heavily polluted beaches. For the Sand Rake method, the pollution was calculated in pieces/m^2.

The potential sources of litter were determined using the "matrix scoring technique" system E, as recommended in Veiga et al. (2016), following the method by Tudor and Williams (2004). The matrix is based on likelihoods, which consider the possibility that each litter item may originate from more than one source. The potential sources of litter were classified in eight major categories according to Vlachogianni et al. (2018) and Vlachogianni (2019) and are shoreline, including poor waste management practices, tourism, and recreational activities; fisheries and aquaculture; shipping; fly-tipping; sanitary and sewage related; medical related; agriculture; and non-sourced. A score indicating the potential source was assigned to each litter item within the top 25 of each survey campaign. Local experts familiar with the surroundings and beach activities provided assistance in this process. Litter items with a share of less than 1% of the total findings per country were not allocated to a source. The different likelihood scores are as follows: not considered/impossible (0), very unlikely (0.25), unlikely (1), possible (2), likely (4), and very likely (16). With this percentage allocation, each litter item is assigned to several possible sources on a percentage basis.

The Clean Coast Index (CCI) evaluates coastal cleanliness. To do this, macro-litter is counted per m^2 of the transect area (length x beach width), using a coefficient (K = 20) for simplification (Alkalay et al., 2007). For the macro-litter surveys in our study, the average pollution of all surveyed transects per beach survey was taken as the basis for the pollution in litter pieces/m^2. The CCI scale grades the pollution from 0 to 2 very clean beaches, 2–5 clean, 5–10 moderately clean, 10–20 dirty, and > 20 extremely dirty.

$$CCI = \frac{\text{Total of all litter pieces of all transects}}{\text{Total area of all transects}} \times \text{K}$$

The Hazardous Items Index (HII) was used to assess the risk posed by hazardous litter items on the beach. Hazardous litter includes sharp objects (e.g., metal, glass, bricks) and toxic items (e.g., cigarette butts, medical and sanitary waste). The HII evaluates beach quality based on the amount of hazardous litter present, classifying beaches into five types, with the HHI (number of hazardous pieces per square meter). HHI is the number of hazardous litter pieces/m^2, taking into account the existing relation between hazardous litter pieces and the log 10 of the total number of all litter pieces found per survey (area in m^2). The five types are as follows: I (No hazardous litter is seen; HHI 0); II (Some hazardous litter is seen over a large area; HHI 0.1–1); III (A considerable amount of hazardous litter is seen; HHI 1.1–4); IV (A lot of hazardous litter is on the beach; HHI 4.1–8); V (Most of the area is covered by hazardous litter; HHI + 8) (Rangel-Buitrago et al., 2019b). In this study, the HII was calculated for each macro-litter survey.

$$HII = \frac{\frac{\sum Hazardouslitterpieces}{log10 \sum Totallitterpieces}}{\text{Area}} \times 20$$

To evaluate the small-scale variability of macro-litter within surveys involving multiple 10 m transects, the coefficient of variation (CV) for pollution levels (per m^2) across two, three, four, and five directly adjacent transects, as well as the separated transects (Morocco) was calculated. This analysis aimed to assess the variability of pollution in close proximity within each beach survey.

$$CV = \left(\frac{\sigma}{\mu}\right) \times 100$$

The frequency of macro-litter items was assessed in each of the 22 beach surveys where five or more 10 m transects were surveyed. The analysis focused on the aggregated top 25 litter items from all 10 m transects per beach survey. This was followed by an assessment of how many transects (1–5) contained these top 25 litter items. If more than five transects were surveyed, a random selection of five transects was analyzed. The objective of this was to determine the number of transects that contained the top 25 litter items, gain insight into their distribution across the surveyed area, and establish the minimum number of transects needed to find all these items.

Litter weight was measured by weighing the litter collected using the Sand Rake method on an electronic scale model: G&G PLC-6000. Prior to weighing, all litter was air dried at room temperature for several days, and sand was removed with a small brush if necessary.

Polymer analysis was carried out using near-infrared spectroscopy (NIR) on 10% (randomly selected) of the non-identifiable plastic pieces collected by the Sand Rake method. For this, the Microphazir PC was used, offering polymer identification and accuracy (in %) within 5 s with a 12 nm (pixels)/8 nm (optical) resolution and 1600–2400 nm spectral range. Only particles with ≥ 95% accuracy were classified, into specific polymer types. Particles with lower accuracy were categorized as unidentified. Black particles were excluded from the analysis as they do not scatter visible light and absorb NIR laser wavelength (Haseler et al., 2020).

Results

In 37 macro-litter surveys a total of 71,391 litter pieces, composed of 157 different litter items, were collected on an area of 62,020 m^2. Both the mean and median number of investigated 10 m transects per survey were five. Across all campaigns, artificial polymers (57,502 pieces) were the dominant litter category, averaging 80.5%, with lesser amounts of other categories (Fig. 4). When extrapolating the findings, litter piece counts ranged from 436 to 24,270 (mean 5032 ± 4919 pieces per 100 m; median 3312). When considering overall beach pollution per m^2, it ranged from 0.22 to 13.69 litter pieces/m^2 (mean 1.71 pieces/m^2 ± 2.28; median 0.99 pieces/m^2).

In total, 25 litter items were responsible for 81.9% of the pollution. Any other litter item contributed less than 1.0% to the total pollution. The top ten litter items alone accounted for 59.3% of the total litter (Table 1). A total of 32,131 (45.0%) litter pieces were classified as SUP. The most common SUP item was cigarette butts with a share of 20.9% (6709 pieces) of all SUP, followed by crisp packets/sweet wrappers (5212; 16.3%), plastic caps/lids drinks (4993; 15.6%) and 4454 small plastic bags, e.g., freezer bags incl. pieces (13.9%). Regarding the CCI, only one beach, Cap Angela in Tunisia 2022, was classified as clean. Beaches were moderately clean seven times (18.9%), classified as dirty 11 times (29.7%), and as extremely dirty 18 times (48.6%). For details see Table 1a supplement material.

Hazardous litter pieces were found in each survey and ranged from 2.3 up to 49.2% of the total amount of litter per survey (mean 17.5% ± 9.9%; median 16.7%). In total, 12,522 hazardous litter pieces were found (mean 0.28 pieces/m^2 ± 0.32; median 0.15 pieces/m^2). The most common ones were cigarette butts (6709 pieces; 53.6%); Glass bottle pieces (734 pieces; 5.9%) and plastic cutlery (716 pieces; 5.7%). In 20 surveys some hazardous litter was found (0.1–1; Type II); in 12 surveys a considerable amount of hazardous litter was found (1.1–4: Type III); in five surveys a lot of hazardous litter was found (4.1–8; Type IV); and in none of the surveys, most of the area was covered by hazardous litter (+ 8; Type V). No significant difference in hazardous pollution was observed along the different beach types. For details see Table 1a supplement material.

Main pollution of each individual survey campaign

In Tunisia's November 2021 surveys (8 in total), 17,700 litter pieces were found on 14,160 m^2 (mean 2.73 pieces/m^2 ± 4.19; median 1.20 pieces/m^2). Pollution ranged from 1022 (0.41 pieces/m^2) to 12,325 (13.69 pieces/m^2) per 100 m (extrapolated results). Due to high pollution, a 100 m stretch was only surveyed once, a 50 m stretch was surveyed six times, and a 20 m stretch was surveyed once. 8234 litter items (46.5%) were classified as SUP, with five of the top ten litter items being SUP (Table 1).

Table 1 Top ten litter items found in the macro-litter surveys in total numbers, percentage and cumulative percentage. Note that no cigarette butts were surveyed in Tunisia 2021. In grey the SUP items are shown

	Tunisia 21	Tunisia 22	Egypt 22	Morocco 23	total
1	Plastic pieces 2.5 cm > < 50 cm	Plastic pieces 2.5 cm > < 50 cm	Cigarette butts and filters	Plastic pieces 2.5 cm > < 50 cm	Plastic pieces 2.5 cm > < 50 cm
	2546/14.4%	2023/17.3%	3662/16.8%	2720/13.4%	10055/14.1%
2	Plastic caps/lids drinks	Plastic caps/lids drinks	Plastic pieces 2.5 cm > < 50 cm	Cigarette butts and filters	Cigarette butts and filters
	1802/10.2%/24.6%	1071/9.2%/26.5%	2766/12.7%/29.5%	2350/11.6%/25.0%	6709/9.4%/23.5%
3	Crisp packets/sweet wrappers	Polystyrene pieces 2.5 cm > < 50 cm	Small plastic bags, e.g. freezer bags incl. pieces	Crisp packets/sweet wrappers	Crisp packets/sweet wrappers
	1674/9.5%/34.0%	791/6.8%/33.3%	1873/8.6%/38.1%	1299/6.4%/31.5%	5212/7.3%/30.8%
4	Shopping Bags incl. pieces	Small plastic bags, e.g. freezer bags incl. pie	Crisp packets/sweet wrappers	Plastic caps/lids drinks	Plastic caps/lids drinks
	1311/7.4%/41.4%	762/6.5%/39.8%	1487/6.8%/45.0%	1158/5.7%/37.2%	4993/7.0%/37.8%
5	Small plastic bags, e.g. freezer bags incl. piece	Crisp packets/sweet wrappers	Sheets, Industrial packaging, plastic sheeting	Polystyrene pieces 2.5 cm > < 50 cm	Small plastic bags, e.g. freezer bags incl. pieces
	1022/5.8%/47.2%	752/6.4%/46.2%	1282/5.9%/50.9%	853/4.2%/41.4%	4454/6.2%/44.0%
6	Slack/Coal	Cigarette butts and filters	Plastic caps/lids drinks	Foam sponge / foamed plastic items and	Polystyrene pieces 2.5 cm > < 50 cm
	657/3.7%/50.9%	697/6.0%/52.2%	962/4.4%/55.3%	801/4.0%/45.3%	2502/3.5%/47.5%
7	Polystyrene pieces 2.5 cm > < 50 cm	Slack/Coal	Straws and stirrers	Small plastic bags, e.g. freezer bags incl. p	String and cord (diameter less than 1cm)
	629/3.6%/54.2%	499/4.3%/56.5%	816/3.7%/59.0%	797/3.9%/49.3%	2138/3.0%/50.5%
8	Cotton bud sticks	String and cord (diameter less than 1cm)	Food contaimers incl. fast food containers	Food waste (galley waste)	Sheets, Industrial packaging, plastic sheeting
	616/3.5%/57.9%	490/4.2%/60.7%	758/3.5%/62.5%	796/3.9%/53.3%	2108/3.0%/53.5%
9	Paper fragments	Sheets, Industrial packaging, plastic sheetin	Food waste (galley waste)	Carpet plastic string	Slack/Coal
	611/3.5%/61.4%	416/3.6%/64.2%	720/3.3%/65.8%	748/3.7%/56.9%	2067/2.9%/56.4%
10	String and cord (diameter less than 1cm)	Straws and stirrers	String and cord (diameter less than 1cm)	Lolly sticks	Food waste (galley waste)
	505/2.9%/64.3%	344/2.9%/67.2%	653/3.0%/68.8%	740/3.7%/60.6%	1942/2.7%/59.3%

Fig. 2 Macro-litter surveys on the beach. On the left side, the 10 m transects were positioned directly next to each other (Tunisia and Egypt). On the right side, larger space of 10–150 m (horizontal dashed line) was used between transects, depending on the length of the beach (Morocco). Vertical dotted black line (on the far right) indicates the Sand Rake method used in direct proximity. The bottom pictures show the survey procedure, which includes systematic litter collection on the beach, placing the litter in plastic bags, and subsequently counting and categorizing the collected litter in the laboratory

During seven surveys in Tunisia in June 2022, a total of 11,681 litter pieces were found on an area of 11,120 m^2 (mean 1.16 pieces/m^2 ± 0.92; median 0.99 pieces/m^2). The pollution ranged from 436 (0.22 pieces/m^2) to 15,351 (3.20 pieces/m^2) per 100 m (extrapolated results). The beach surveys included two 100 m stretches, three 50 m stretches, and one 30 m and 20 m stretch each. 4730 litter pieces (40.5%) were classified as SUP. Half of the top ten litter items were SUP (Table 1).

Eight surveys in Egypt in March 2022 revealed a total pollution of 21,762 litter pieces on 9392.5 m^2 (mean 2.52 pieces/m^2 ± 1.36; median 2.38 pieces/m^2). Pollution ranged between 1964 (0.80 pieces/m^2) and 24,270 (4.95 pieces/m^2) litter pieces per 100 m (extrapolated results). 11,123 litter pieces (51.1%) were classified as SUP, with six out of the top ten litter items being SUP (Table 1). No 100 m stretches were surveyed due to high levels of pollution. In total, three 50 m stretches, one 40 m stretch, two 30 m stretches, and one 20 m stretch were surveyed. At one beach in Alexandria, a 35 m stretch was sampled as a single transect due to external circumstances.

In Morocco, 14 surveys were conducted in January 2023. A total of 20,248 litter pieces were found on an area of 27,347.5 m^2 (mean 0.71 pieces/m^2 ± 0.43; median 0.52 pieces/m^2). The pollution ranged from 1304 (0.29 pieces/m^2) to 5558 (3.00 pieces/m^2) per 100 m (extrapolated results). Altogether 8044 litter pieces (39.7%) were classified as SUP, with five out of the top ten litter items being SUP (Table 1).

Beach type pollution

The transnational and cross-campaign analysis of beach types revealed that the eight semi-rural beaches exhibited the lowest pollution levels. The amount of litter ranged from 0.22 to 1.69 litter pieces/m^2 (mean 0.62 pieces/m^2 ± 0.45; median 0.46 pieces/m^2). Per 100 m, the pollution was between 436 and 5558 litter pieces (mean 2196 ± 1500; median 1783). On six semi-urban beaches the litter density ranged from 0.40 to 1.98 litter pieces/m^2 (mean 1.05 pieces/m^2 ± 0.54; median 0.93 pieces/m^2). Per 100 m, the pollution was between 1352 and 6680 litter pieces (mean 3692 ± 1873; median 3784). The six identified tourist beaches had a pollution range of 0.41 to 3.20 litter pieces/m^2 (mean 1.23 pieces/m^2 ± 0.91; median 0.88 pieces/m^2). Per 100 m, the pollution was between 1226 and 15,351 litter pieces (mean 5465 ± 4726; median 3733). On the 17 urban beaches the highest pollution was found, with a range from 0.34 to 13.69 litter pieces/

m^2 (mean 2.63 pieces/m^2 ± 3.03; median 1.71 pieces/m^2). Per 100 m, the pollution was between 1022 and 24,270 litter pieces (mean 6687 ± 5939; median 3758) (Fig. 5).

Litter source allocation

Of 71,391 litter pieces collected throughout the survey campaigns, the top 25 accounted for 58,497 litter pieces (81.9%). These top 25 were used for the source allocation, with four of these top 25 litter items unable to be attributed to specific sources. Those items were plastic pieces 2.5 cm > < 50 cm (10,055; 14.1%); polystyrene pieces 2.5 cm > < 50 cm (2502; 3.5%); foam sponge/foamed plastic items and fragments (1541; 2.2%); and paper fragments (1418; 2.0%). The remaining 42,981 litter pieces were allocated to the litter sources.

The percentage of unclassifiable litter varied between the different campaigns, ranging from 19.2 to 31.8% (mean 26.5%). In all survey campaigns, the majority of identifiable litter was attributed to land-based sources and ranged from 58.2 to 68.8% (average 64.6%). In terms of individual sources, most litter was attributed to "shoreline, including poor waste management practices, tourism, and recreational activities" and ranged between 48.6% and 58.3% (average 55.4%). The lower amount of litter originated from the other land-based sources. Sea-based litter attributed with 6.9–11.9% (average 8.8%) to the pollution and is divided between the two sources of "fisheries and aquaculture" with a range from 3.2 to 4.7% (average 3.7%) and "shipping" with an average of 5.1% (range from 3.8 to 7.3%) (Fig. 6). All beach types—urban, tourist, semi-urban, and semi-rural—were equally polluted due to litter from the "shoreline, including poor waste management practices, tourism, and recreational activities" (average 55.4% ± 1.2%).

Small-scale distribution of litter

The pollution measured (litter pieces/m^2) showed variation across the transects per beach (Fig. 7). Of all the surveys (n = 22) analyzed, only four beaches (two adjacent transects) exhibited a CV below 10% (mean 17.7% ± 8.2; median 16.7). When considering surveys (n = 19) of three adjacent transects, the CV was twice below 10%, (mean of 21.6% ± 10.8%; median 19.8). For four adjacent transect surveys (n = 16), the lowest observed CV value was 7.3%, while no other value fell below 10%. The mean CV was 24.6% ± 11.4; median 23.3%. The highest CV values were recorded in surveys (n = 15) where five adjacent transects were analyzed, with the lowest CV of 11.7%. The mean CV was 28.3% ± 13.2; median 25.6%.

Considering the separated transects in Morocco, higher CV values were observed. For surveys (n = 4) with transects with a distance ranging from 10 to 50 m, the average CV was 17.7% ± 3.8; median 17.3. For the surveys (n = 5) where transects had distances between 50 and 100 m, the CV was higher (mean 24.1% ± 15.1; median 13.6). The highest range of CV was found if the distance between the transects (surveys n = 5) was between 100–150 m (mean 23.8% ± 5.4; median 24.8).

Frequency of the top litter items

The analysis, comprising 22 surveys, reveals the presence of the top 25 litter items on the different beaches (Fig. 8). Considering the total values of all top 25 litter items per beach of all surveys, they were found regularly (mean 4.03 ± 1.23; median 5) in the five transects. The 10 most common litter items were found in higher frequency (mean 4.6 ± 0.73; median 5). The other litter items (11–20) were found less frequently (mean 3.81 ± 1.26; median 4). The litter items (21–25) were the least common frequently (mean 3.27 ± 1.37; median 3). On the mean (and median), all of the top 25 litter items can be found within a survey area of 30 m. Considering only the results of Moroccan beaches, where the distance between the 10 m transects per survey ranged from 10 to 150 m, the frequency of litter findings was similar (mean 3.98 ± 1.22; median 4) compared to adjacent transects.

Sand Rake results

The litter collected in all 41 surveys (1287.25 m^2) of the four campaigns was 12,877 litter pieces (mean 10.00 pieces/m^2 ± 12.72; median 4.50 pieces/m^2). The aggregated results per survey showed a maximum of 55.50 litter pieces/m^2 and a minimum of 0.26 pieces/m^2. In total, 8376 meso-litter pieces (65.0%) and 4501 macro-litter pieces (35.0%) were collected. Artificial polymers were predominant in all survey campaigns, and had a total share of 11,289 litter pieces (87.2%) (Fig. 4). Other litter categories had a lower percentage. Examining only meso-litter, the pollution ranged between 0.08 and 35.9 litter pieces/m^2 (mean 6.35 pieces/m$^2 \pm 8.93$; median 2.38 pieces/m^2). SUP litter had a share of 32.7% (4204 litter pieces) of the total pollution, with four of the top ten litter items being SUP (Table 2). Most litter could be allocated to land-based sources (Fig. 9).

Tunisia November 2021: During 13 surveys (413 m^2), a total of 5192 litter pieces were found (mean 12.06 pieces/m$^2 \pm 15.49$; median 5.83 pieces/m^2); with a maximum of 55.50 litter pieces/m^2 and a minimum of 2.37 pieces/m^2. Artificial polymers accounted for the majority with 4544 litter pieces (87.5%). Considering only meso-litter, the pollution varied between 1.23 and 35.9 pieces/m^2. 2205 litter pieces (42.5%) of the total pollution were SUP.

Tunisia June 2022: In 6 surveys on an area of 166.75 m^2, a total of 879 litter pieces were found (mean 5.33 pieces/m$^2 \pm 5.82$; median 2.07 pieces/m^2). The maximum pollution found was 17.28 litter pieces/m^2 and the minimum of 1.04 pieces/m^2. Artificial polymers were predominant with 807 litter pieces (91.8%). The meso-litter pollution was between 0.08 and 12.12 pieces/m^2. In total, 879 litter pieces, accounting for 35.5% of the collected litter, were classified as SUP. Five out of the top ten litter items belonged to the category of SUP.

Egypt March 2022: In 10 surveys (345.5 m^2) a total of 6054 litter pieces were found (mean 17.88 pieces/m$^2 \pm 12.91$; median 15.41 pieces/m^2); with a maximum of 47.43 litter pieces/m^2 and a minimum of 2.34 pieces/m^2. Artificial polymers dominated the collected litter, accounting for 5277 pieces (87.2%). When considering only meso-litter, the pollution levels varied between 1.69 and 35.15 pieces/m^2. Out of the total pollution, 1488 litter pieces (24.6%) were SUP.

Morocco 2023: In 12 surveys on 362 m^2, a total pollution of 752 litter pieces was found (mean 2.02 pieces/m$^2 \pm 1.16$; median 2.03 pieces/m^2); with a maximum of 4.53 litter pieces/m^2 and a minimum of 0.26 pieces/m^2. Artificial polymers were predominant with 661 litter pieces (87.9%). Considering only meso-litter, the pollution ranged between 0.1 and 4.13 litter pieces/m^2. Altogether, 199 litter pieces (26.5%) were classified as SUP.

Beach type and litter abundance of the Sand Rake surveys

The combined pollution of meso- and macro-litter varied between the different beach types. Semi-rural beaches were found to be the least polluted. The litter density on these beaches ranged from 0.26 to 1.60 litter pieces/m^2 (mean 0.87 pieces/m$^2 \pm 0.55$; median 0.76 pieces/m^2). On semi-urban beaches the litter abundance was slightly higher, ranging from 0.64 to 6.07 litter pieces/m^2 (mean 3.18 pieces/m$^2 \pm 1.95$; median 2.44 pieces/m^2). Tourist beaches exhibited a higher level of pollution between 1.29 and 17.28 litter pieces/m^2 (mean 5.32 pieces/m$^2 \pm 4.48$; median

Table 2 Top ten litter items found with the Sand Rake method in total numbers, percentage, and cumulative percentage. In grey, the SUP items are shown

	Tunisia 21	Tunisia 22	Egypt 22	Morocco 23	all litter
1	Plastic pieces 0.5 - 2.5 cm 1285/24.7%	Plastic pieces 0.5 - 2.5 cm 230/26.2%	Sheets, Industrial packaging, plastic sheeting 1447/23.9%	Plastic pieces 0.5 - 2.5 cm 262/34.8%	Plastic pieces 0.5 - 2.5 cm 2871/22.3%
2	Cigarette butts and filters 1048/20.2%/44.9%	Cigarette butts and filters 98/11.1%/37.3%	Plastic pieces 0.5 - 2.5 cm 1094/18.1%/42.0%	Plastic pieces 2.5 cm > < 50 cm 63/8.4%/43.2%	Cigarette butts and filters 1974/15.3%/37.6%
3	Plastic caps/lids drinks 617/11.9%/56.8%	Plastic caps/lids drinks 78/8.9%/46.2%	Cigarette butts and filters 776/12.8%/54.8%	Cigarette butts and filters 52/6.9%/50.1%	Sheets, Industrial packaging, plastic sheeting 1727/13.4%/51.0%
4	Plastic pieces 2.5 cm > < 50 cm 268/5.2%/62.0%	Sheets, Industrial packaging, plastic sheeting 70/8.0%/54.2%	String and cord (diameter less than 1 cm) 433/7.2%/61.9%	Small plastic bags, e.g. freezer bags incl. pieces 35/4.7%/54.8%	Plastic caps/lids drinks 878/6.8%/57.9%
5	Sheets, Industrial packaging, plastic sheeting 186/3.6%/65.6%	String and cord (diameter less than 1cm) 68/7.7%/61.9%	Polystyrene pieces 0.5 - 2.5 cm 296/4.9%/66.8%	Plastic caps/lids drinks 33/4.4%/59.2%	String and cord (diameter less than 1 cm) 700/5.4%/63.3%
6	String and cord (diameter less than 1cm) 182/3.5%/69.1%	Plastic pieces 2.5 cm > < 50 cm 52/5.9%/67.8%	Plastic pieces 2.5 cm > < 50 cm 202/3.3%/70.2%	Crisp packets/sweet wrappers 27/3.6%/62.8%	Plastic pieces 2.5 cm > < 50 cm 585/4.5%/67.8%
7	Small plastic bags, e.g. freezer bags incl. pieces 170/3.3%/72.3%	Small plastic bags, e.g. freezer bags incl. pieces 45/5.1%/72.9%	Crisp packets/sweet wrappers 195/3.2%/73.4%	Sheets, Industrial packaging, plastic sheeting 24/3.2%/66.0%	Polystyrene pieces 0.5 - 2.5 cm 474/3.7%/71.5%
8	Polystyrene pieces 0.5 - 2.5 cm 141/2.7%/75.1%	Plastic rings from bottle caps/lids 35/4.0%/76.9%	Plastic caps/lids drinks 150/2.5%/75.9%	Polystyrene pieces 0.5 - 2.5 cm 24/3.2%/69.1%	Small plastic bags, e.g. freezer bags incl. pieces 346/2.7%/74.2%
9	Paper fragments 126/2.4%/77.5%	Crisp packets/sweet wrappers 24/2.7%/79.6%	Slack/Coal 119/2.0%/77.8%	Foam sponge / foamed plastic items and fragments 21/2.8%/71.9%	Crisp packets/sweet wrappers 322/2.5%/76.7%
10	Plastic rings from bottle caps/lids 123/2.4%/79.9%	Slack/Coal 16/1.8%/81.5%	Small plastic bags, e.g. freezer bags incl. pieces 96/1.6%/79.4%	Bottles incl. pieces 18/2.4%/74.3%	Slack/Coal 224/1.7%/78.4%

3.87 pieces/m^2). Among the beach typologies, urban beaches were found to be the most polluted. The litter density on these beaches ranged widely, from 0.26 to 55.50 litter pieces/m^2 (mean 9.91 pieces/m$^2 \pm 12.70$; median 4.80 pieces/m^2) (Fig. 10).

Litter source allocation—Sand rake

Of the 12,877 litter items collected during the Sand Rake surveys, the top 25 used for source allocation accounted for 11,890 litter items (92.3%). Due to the high amount of fragmented litter found, it was not possible to assign sources to 4678 litter pieces (39.3%) of the top 25 litter items. These were unidentifiable pieces of plastic, polystyrene, and foam in the meso and macro-litter size classes, as well as paper fragments and other textile, glass, and metal fragments. The remaining 7212 litter items could be allocated to the different litter sources. Most of the identifiable litter found originates from land-based sources regardless of the type of beach (Fig. 9) and ranged between 34.5 and 56.7% (average 43.8%).

Small scale distribution

Due to variations in beach width, the number of subsections surveyed differed across beaches, ranging from one up to thirteen subsections (mean 6.3; median 6). Examining the small-scale distribution of litter along from the lower part (first subsection) towards the end of the beach (last subsection), it was visible that higher pollution was found on the back of the beach. The results are presented as percentages due to the varying levels of litter pieces/m^2 on the individual beaches. The combined results indicate that, on average, 50.9% of the litter in terms of numbers was in the upper third of the beach, with 27.6% in the middle section and the remaining 21.5% concentrated in the lower third (Fig. 11). Higher pollution in subsections of the lower or middle part of the beach was mostly due to accumulation zones.

Weight of litter

Litter weight was analyzed for 29 Sand Rake surveys (excluding Morocco). The total average litter weight per m^2 per beach survey was between 0.25 and 22.66 g/m^2 (mean 3.63 ± 4.22; median 2.22 g/m^2). The weight of collected meso-plastic, excluding cigarette butts, ranged from 0.004 to 2.33 g/m^2 (mean 0.45 g/m$^2 \pm 0.54$; median 0.22 g/m^2). For macro-plastic, the weight ranged from 1.4 to 8.04 g/m^2 (mean 1.40 g/m$^2 \pm 1.49$; median 1.10 g/m^2). Calculated for the average six subsections, the highest pollution was on the upper third of the beach. The combined findings reveal that, on average, 50.3% of the litter weight was in the upper third of the beach, 30.8% in the middle section, and the remaining 18.9% in the lower third (Fig. 12).

Polymer analysis

Using the Sand Rake method, a total of 4045 (31.4%) non-identifiable plastic pieces were found: 2871 plastic pieces (0.5–2.5 cm), 585 plastic pieces (> 2.5 cm), 474 polystyrene pieces (0.5–2.5 cm), and 115 polystyrene pieces (> 2.5 cm). Randomly 10% of the plastic pieces were analyzed with a NIR handheld device and the results were extrapolated to the total amount of non-identifiable plastic pieces. Most of these plastic pieces were composed of polyethylene (PE: 2038 pieces, 50.38%), polypropylene (PP: 1077 pieces, 26.6%), and polystyrene (PS: 589 pieces, 14.6%) and other polymers (90 pieces, 2.2%). Altogether for 251 pieces (6.2%), the polymer type could not be identified.

Discussion

Macro-litter pollution

Artificial polymers were the most common litter category found, regardless of country, season, or survey campaign. This reflects the global trend of plastics as the main contributor to marine and beach litter, as shown in other studies (Addamo et al., 2017; Heinrich Böll Stiftung, 2019; Nachite et al., 2019). The top ten litter items in this study's campaigns are similar to those found in other Mediterranean beach surveys (MTEDD, 2022; Nachite et al., 2019; Vlachogianni et al., 2018). Our findings on SUP accounted for 45% of the pollution, which is comparable to European beaches (43%) where items such as cigarette butts, food containers, plastic bags, and sweet wrappers are also commonly

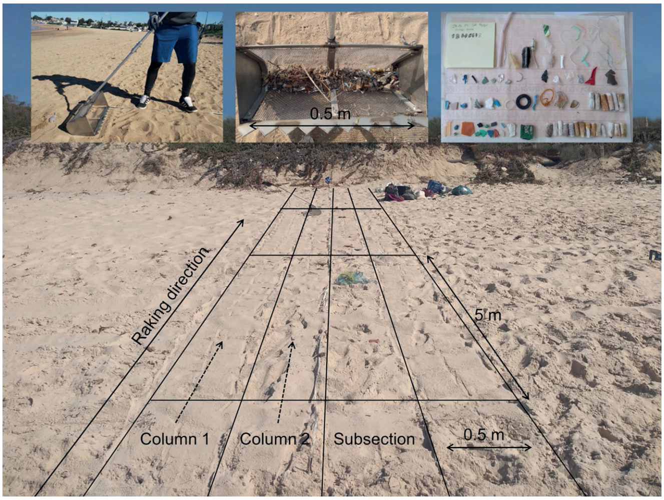


Fig. 3 Sand Rake method survey on a sandy beach. Raking direction is from the waterline to the back of the beach (backshore). Operation width of the Sand Rake is 0.5 m; the mesh size used is 5 mm. Each survey is divided in subsections of 0.5 m×5 m resulting in an area of 2.5 m^2. Subsections at the back of the beach may be smaller. One survey consists of one or more columns, with different number of subsections. The minimum area per survey is 25 m^2. The sediment is raked down to a depth of about 5 cm. The upper left picture shows the use of the Sand Rake, while the middle one shows the rake containing litter and organic material, and the right picture shows the analysis of the collected litter, measured and categorized by subsection

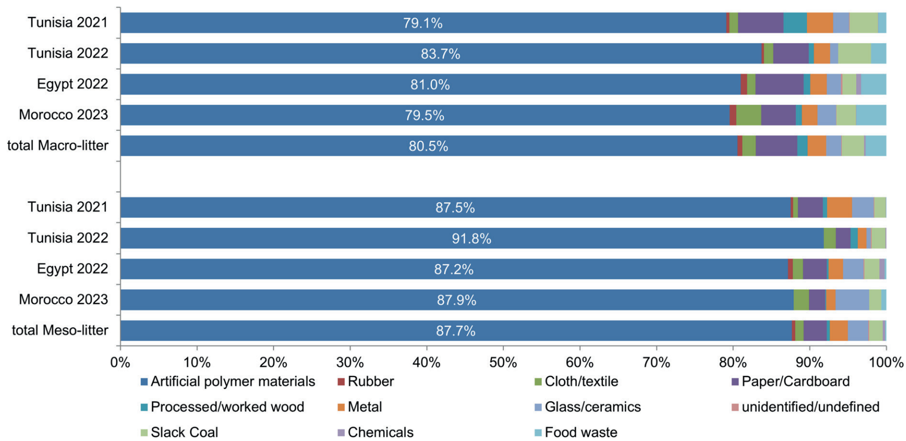


Fig. 4 Categories of litter found during the survey campaigns. On top for the macro-litter surveys, and on the bottom for the Sand Rake surveys, with the aggregated results (total)

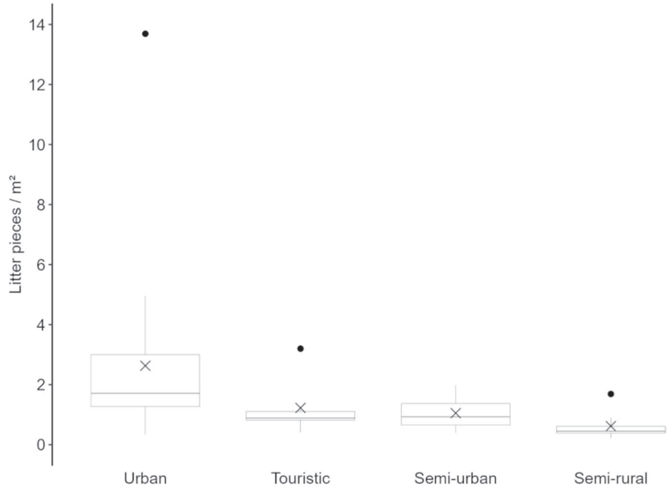


Fig. 5 Macro-litter survey campaigns pollution in litter pieces/m^2 per beach type. Mean value is indicated by cross. Error bars reveal minimum and maximum, dots exhibit outliers

found (European Commission 2018; Vlachogianni et al., 2020).

In this study, we discuss marine litter densities using pieces per m^2, given that land-based sources dominate. This unit is more appropriate than pieces per 100 m, which is suitable for sea-based sources and associated with floating litter fluxes washed ashore (Vlachogianni et al., 2018).

In a Tunisian study, Rym et al. (2022) investigated three beaches of Monastir (Tunisia) in the four seasons of 2021 and the pollution fluctuated strongly from 0.53 to 8.49 pieces/m^2 (mean 3.09 pieces/m^2 ± 2.29; median 2.19 pieces/m^2). This pollution is comparable to what we found on average in Tunisia 2021 (mean 2.73 pieces/m^2 ± 4.19; median 1.20 pieces/m^2) but is nearly 2.5 times higher than our detected pollution in 2022 (mean 1.16 pieces/m^2 ± 0.92; median 0.99 pieces/m^2).

Although Morocco has a beach litter monitoring in place for several years, the results are only reported in pieces per 100 m (MTEDD, 2022), making comparisons difficult. However, if we compare our pollution with the national monitoring in autumn 2022, we find that our results are on average four times higher (min 1.2; max 9.3). Between 2015 and 2017, 14 Moroccan Mediterranean beaches were seasonally surveyed and the pollution was 0.054 ± 0.036 litter pieces/m^2 (Nachite et al., 2019), which is on average 13 times lower than our findings. At a study of five Moroccan Mediterranean beaches the average pollution was 0.20 ± 0.098 pieces/m^2 (Mghili et al., 2020).

A study conducted in Alexandria, Egypt, in summer 2020 found an average of 7.20 plastic pieces/m^2 ± 1.03 (Hassan et al., 2022). Based on our findings in Egypt, where 81% of the litter consists of plastic, we estimated a total pollution of 8.57 litter pieces/m^2 by multiplying this percentage by 1.19. However, our measured pollution (3.03 litter pieces/m^2) is almost three times lower than the estimated value. The high pollution observed by Hassan et al. (2022) can be partly explained by the lack of beach cleaning in 2020 during the COVID-19 shutdown. Further, a significant amount of litter found by Hassan et al. (2022) was personal protective equipment (PPE). PPE such as gloves and masks (COVID protection) accounted for approximately 40% of the pollution, equivalent to 2.79 ± 0.31 litter pieces/m^2. In contrast, such PPE items were found only sporadically (0.001/m^2; 0.09%) in our study.

The percentage of hazardous litter found in our study (mean 17.5%) is lower compared to two studies conducted in Chile, which reported 43% and 28.9% hazardous litter, respectively (Rangel-Buitrago et al., 2019b, 2020) but higher as in a Moroccan study (8.7%) (Bouzekry et al., 2022).

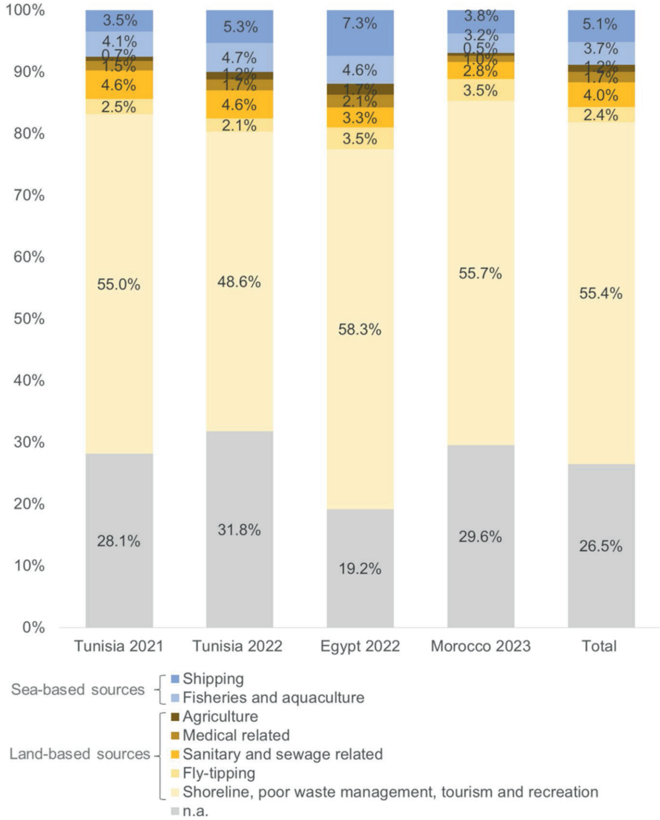
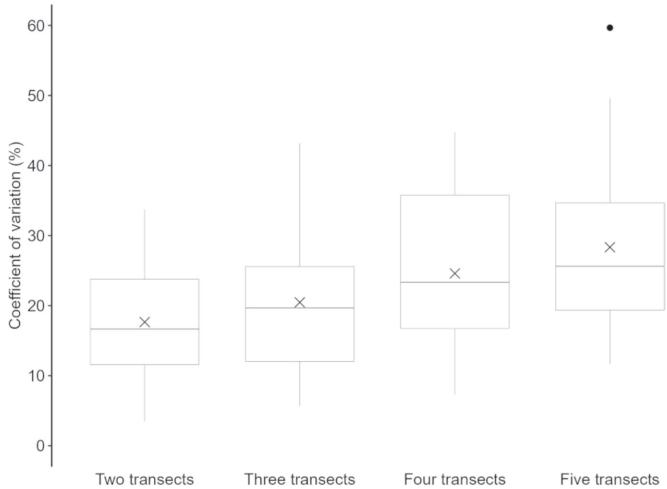


Fig. 6 Litter source allocation for the different macro-litter survey campaigns and in total

Our average pollution level of 0.28 hazardous litter pieces/m^2 is higher than that of both the Chilean and Moroccan studies, which reported 0.071; 0.15; and 0.22 pieces/m^2, respectively. The overall high levels of pollution on our beaches are also reflected in the CCI. In our study, 78.4% of the beaches were classified as either dirty or extremely dirty. In contrast, the Chilean studies reported no beaches categorized as extremely dirty, with only 14% and 25% classified as dirty (Rangel-Buitrago et al., 2020) (Rangel-Buitrago et al., 2019b). Similarly, in the Moroccan study, 25% of the beaches were classified as dirty, while the majority were rated as moderate (33.3%) or clean (41.7%) (Bouzekry et al., 2022).

Comparing macro-litter pollution, whether within or across studies, is complex due to factors such as seasonality, beach type, and cleaning practices that significantly influence the observed pollution. For instance, the extended suspension of beach cleaning, particularly in urban and tourist areas like Alexandria, Egypt, during the COVID-19 years likely contributed to elevated pollution levels, providing a snapshot rather than a steady state of pollution. Preliminary results from ongoing macro-litter monitoring in Alexandria (2023) indicate pollution levels at approximately 25–30% of those recorded during our monitoring campaign (personal statement of beach manager). To obtain a

Fig. 7 Box-Whisker-Plot of coefficients of variation (CV) [%] for different numbers of adjacent transects (2, 3, 4, and 5). Mean value is indicated by cross. Error bars reveal minimum and maximum, dots exhibit outliers



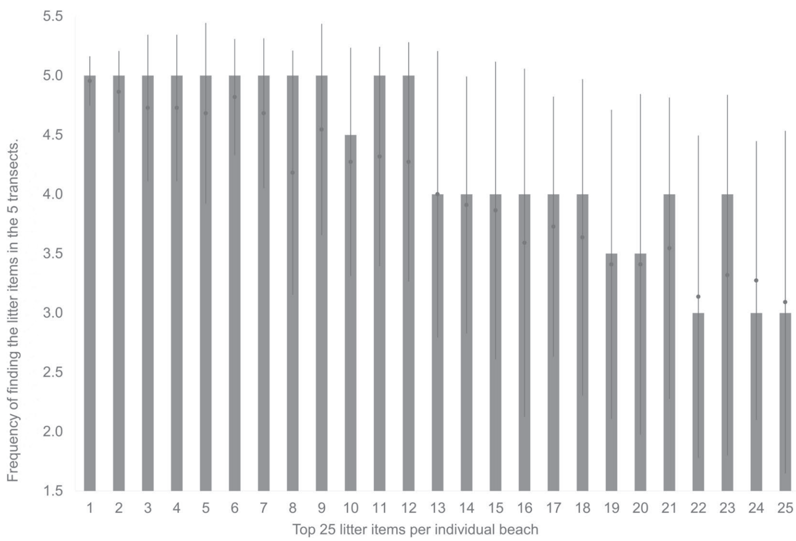


Fig. 8 The quantity of transects (y-axis) in which each of the top 25 litter items (x-axis) was found. The median value is represented by the grey bar with the standard deviation; mean value (black dot)

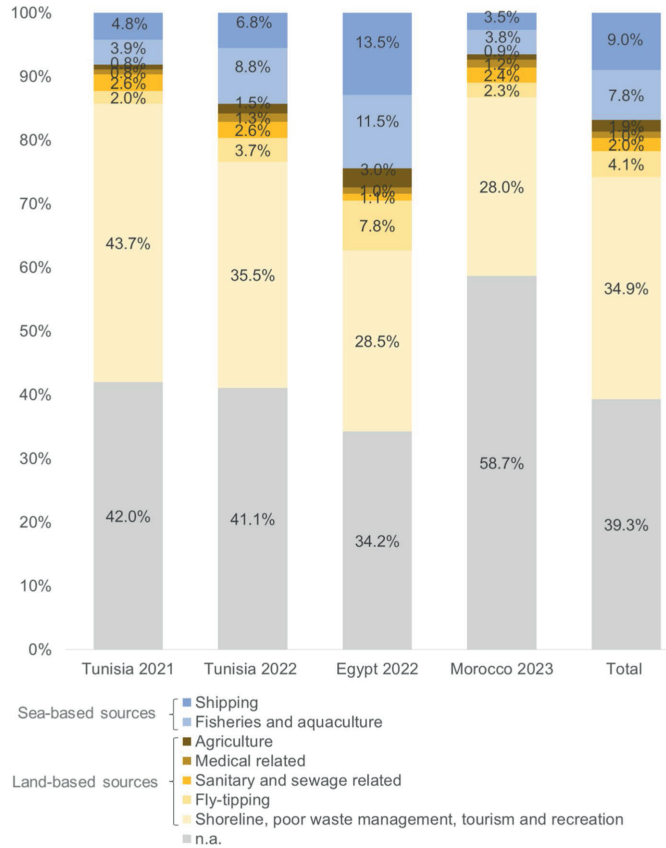


Fig. 9 Litter source allocation for the different Sand Rake survey campaigns and in total

more comprehensive understanding of beach pollution, regular monitoring is essential to capture seasonal variations and long-term trends, as discussed further in the recommendations chapter.

Sand Rake results

The smaller litter fraction was predominantly composed of artificial polymers, which is consistent with findings from other studies (Okuku et al., 2020; Olivelli et al., 2020). The average litter density in this study was 9.86 pieces/m^2. This is an order of magnitude higher than the 0.91 pieces/m^2 ± 1.50 reported by Haseler et al. (2020) which used the Sand Rake method on Baltic Sea beaches. There is no other method for meso-litter focusing on the whole backshore of the beach. The following results are therefore only partially comparable with other studies.

Examining meso-litter on 12 Mauritius beaches with 5 mm sieves to a 5 cm depth in five transects perpendicular to the shoreline revealed an average pollution of ~4.0 pieces/m^2 (Mattan-Moorgawa et al., 2021). In a study of 13 Turkish beaches, an average aggregated meso- and macro-plastic concentration was found to be 12.2 ± 3.5 pieces/m^2 (Gündoğdu & Çevik, 2019). Meanwhile, similar methods in Kenya

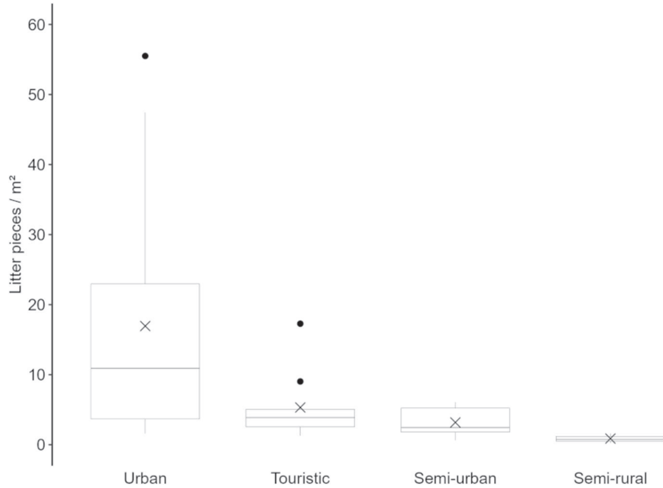


Fig. 10 Sand Rake surveys with combined meso- and macro-litter pollution in litter pieces/m^2 per beach type. Mean value is indicated by cross. Error bars reveal minimum and maximum, dots exhibit outliers

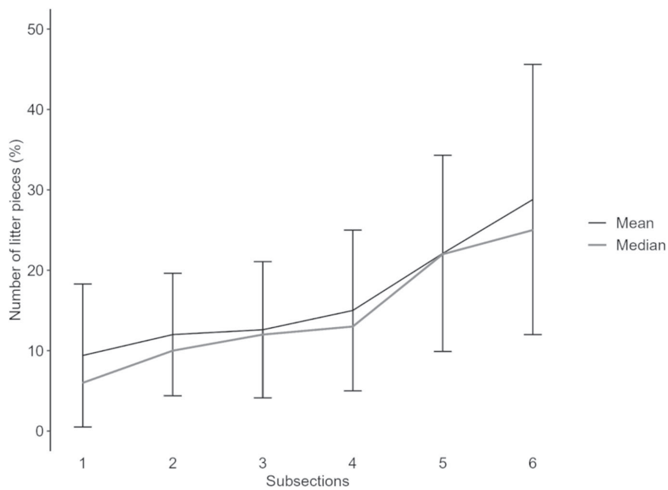


Fig. 11 Sand Rake data: Small-scale distribution of litter pieces in % from the lower part of the beach (subsection 1) to the back of the beach (subsection 6), shown for the average beach width of 30 m (6 subsections). Each subsection represents 5 m of the beach. Percentage is shown as mean value with standard deviation and median

showed generally higher pollution at tourist beaches (4464 pieces/m^2 ± 2249.6) compared to remote/rural beaches (328.5 pieces/m^2 ± 94.0) (Okuku et al., 2020).

In contrast to macro-litter monitoring, it was possible to determine the position of meso-litter along the width of the beach. Our results show a consistent increase in meso-litter pollution from the lower to the upper beach, aligning with findings by Lee et al. (2017) and Okuku et al. (2020) who stated that wind blows litter up the beach. The accumulation of litter in the dunes, which we observed but did not investigate further supports findings of Ryan et al. (2020b) that light litter is carried inland by wind and trapped

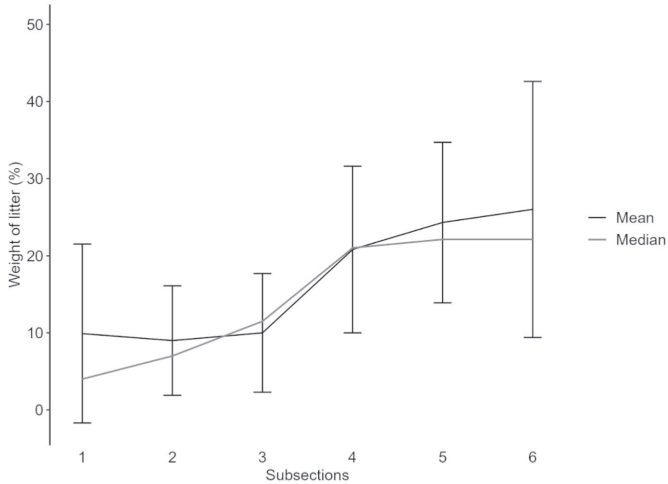


Fig. 12 Sand Rake data: Small-scale distribution of litter weight in % from the lower part of the beach (subsection 1) to the back of the beach (subsection 6), shown for the average beach width of 30 m (6 subsections). Each subsection represents 5 m of the beach. Percentage is shown as mean value with standard deviation and median

there. The beaches we studied experience predominantly onshore winds throughout the year (meteoblue, 2024), reinforcing these observations. On the basis of the visual examination and the usual distribution of sediments on beaches (Komar, 1997) we can report that in general, the sediment was finer in the upper part of the beach. As reported by Fulfer and Walsh (2023) litter and sand are transported up the beach and accumulate there, and this finer sediment contains a higher accumulation of litter (Browne et al., 2010; Martins & Sobral, 2011). Furthermore, accumulated litter on the upper beach is less affected by waves, storms, and tides than litter on the surface of lower beach parts (Serra-Gonçalves et al., 2019). Therefore upper beach areas are probably a sink for beach litter.

Olivelli et al. (2020) attribute higher litter densities in the upper beach to Stokes and longshore drift, onshore wind transport, and low departure rates of accumulated litter. Longshore drift moves sand and litter along a beach. It occurs due to the angle of waves hitting the shore, the shape of the coastline, and the direction of the longshore current (NOAA, 2024). Such local beach dynamics play an important role in the distribution of beach litter (Prevenios et al., 2017) and would have provided more information on its (small-scale) distribution, since litter in sediment is most likely to adopt the dynamics of beach sediment transport. But due to the limited time available for each survey, such information could not be determined.

According to Ryan et al. (2020b), only 10.6% of the litter found on the beach is on the surface, with the remaining 89.4% buried in the sediment. Carson et al. (2011) found half of the buried plastic in the top 5 cm of the sediment. To enhance data reliability, we suggest integrating meso-litter surveys with macro-litter surveys. However, it is important to note that most meso-litter studies focus on accumulation zones, which are generally more polluted than other beach areas (Esiukova, 2016; Haseler et al., 2019). Consequently, these results have limited utility in calculating a pollution baseline. Accordingly, we recommend here the Sand Rake method (Haseler et al., 2018; MSFD TSG ML 2023) as it proved useful, particularly on cleaned beaches where macro-litter fractions on the beach surface are often underestimated. Further, it reaches a depth of around 5 cm which helps to find around half of the buried plastic according to Carson et al. (2011). This is important for (long-term) studies and to calculate the total plastic budget of litter on beaches.

Our Sand Rake surveys uncovered that identical litter categories and items were present in smaller sizes fractions and with a higher frequency per m^2 compared to the macro-litter surveys, this is consistent with other studies (Gyraite et al., 2022; Haseler et al., 2018, 2020). 33% of the litter collected using the Sand Rake method could be classified as SUP, regardless of its small size. However, this is less than in the macro-litter studies because often only plastic fragments were found. But the NIR analysis of such unidentified fragments showed that polyethylene, polypropylene, and polystyrene—polymers often used for SUP—were the dominating polymer types found on the beaches, similar to Haseler et al. (2020), Jeyasanta et al. (2020), and Urban-Malinga et al. (2020). This observation suggests that SUP tends to break down into smaller pieces relatively quickly, potentially explaining the higher percentage (87.7%) of artificial polymers found by the Sand Rake method compared to the Macro-litter method (80.5%).

Beach type classification and litter sources

Our findings indicate that urban and tourist beaches exhibit higher pollution levels compared to semi-urban and semi-rural beaches, aligning with global trends reported by Poeta et al. (2016), Okuku et al. (2020), Nachite et al. (2019), and MTEDD (2022). 55.4% of the macro-litter could be allocated to tourism, recreation, and poor waste management, regardless of season or country. These results are consistent with other studies around the Mediterranean Sea (Alshawafi et al., 2017; Nachite et al., 2019; Rym et al., 2022; UNEP, 2015; Vlachogianni et al., 2018), where up to 84% of the total pollution originated from recreational and smoking-related activities (Mghili et al., 2020). The litter collected using the Sand Rake method had a higher proportion of unidentified litter (39.3%) compared to the litter collected using the macro-litter method (26.5%). Similar to Meakins et al. (2022), we assume, however, that a significant amount of this unidentified litter, particularly between the high tide line and the back of the beach, originates directly from land-based sources such as beach users. This litter lacked signs of sea origin, such as algae colonization or the distinctive abraded shape resulting from swirling currents or wave action. Furthermore, identifying the source of each litter piece is unnecessary. If the majority of litter is from sources like shoreline, poor waste management, tourism, and recreation, it is logical to conclude that many unidentified pieces share the same origin (Tudor & Williams, 2004). We estimate approximately 70–80% of total litter originates from local or regional land-based sources. This estimate aligns with the proportion of plastic litter from land-based sources in the respective countries (Egypt ~ 84%; Morocco ~ 92%; Tunisia ~ 82%), called the "boomerang effect" in Liubartseva et al. (2018). However, this does not mean that the litter was thrown away or deposited directly where it was found on the beach. Litter can be transported for kilometers along the coast. Sediment drift, driven by currents, waves, and wind, affects how and where litter is shifted. Studies indicate that beaches exposed to stronger winds and currents tend to have higher concentrations of litter compared to more sheltered areas (Camedda et al., 2021). Further, storms cause sediment shifting and as a result, winds can also be the reason for the shifting of beach litter from urban beaches to the less visited beaches (Esiukova, 2016). Wave energy and the beach width are further factors for the state of pollution and determine trends in accumulation and/or backwashing (Bowman et al., 1998). The upper parts of wider beaches with gently slope further seem to be traps for beach litter accumulation as waves can push litter further up the beach (Kataoka et al., 2013; Turrell, 2018). Therefore, in addition to human behavior, beach dynamics need to be further considered when assessing pollution sources of specific beaches, as they are most important for accumulation patterns (Ryan et al., 2009).

Furthermore, the impact of litter of continental origin from watersheds and rivers needs to be considered. For our beaches the Nile River is considered most important. The Nile River, stretching over 6600 km, is the longest river in the world (Soto Chalhoub, 2022), with a watershed covering 2,916,242 km^2 (Boucher & Bilard, 2020). It is estimated that around 55,000 tonnes of macro-plastic litter enter the Mediterranean Sea annually through the Nile's watershed, primarily due to rapid urbanization, population growth, littering, inadequate waste management practices, agriculture, and industrial activities. The Nile River itself is considered one of the largest contributors of plastic litter to the Mediterranean, though estimates of its annual macro-plastic input vary significantly. Figures range from 200 to 2000 tonnes (Lebreton et al., 2017), to 6772 tonnes (Liubartseva et al., 2018), and up to 7043 tonnes per year (Schmidt et al., 2017). However, some studies suggest that most plastic litter entering rivers does not reach the oceans but is instead retained within the rivers themselves (van Emmerik et al., 2022) (Schernewski et al., 2024). This could also be the case with the Nile, where the presence of 11 major dams may contribute to the retention of plastic litter along the river's course (Boucher & Bilard, 2020). As a result, it remains uncertain how much litter entering the Nile far from the Mediterranean reaches the sea, while litter entering closer to the coast has a higher chance of reaching the Mediterranean. In addition to the Nile, numerous of smaller watersheds in our research area contribute plastic litter to the Mediterranean Sea environment, with concentrations ranging from 0.01 to 10,000 tonnes per year (Boucher & Bilard, 2020). Watersheds that extend mainly along the coast have a more direct and immediate impact on plastic pollution along Mediterranean beaches. Lebreton et al. (2017) estimate that at least 11 (temporary) rivers in North Africa contribute to plastic pollution in the Mediterranean, often flowing only during the rainy season or specific periods, with each river releasing between 2 and 200 tonnes of plastic annually. This surely impacts the amount of beach pollution at least seasonally or during high rainfalls and needs to be further focused on in long-term studies including the monitoring of remote beaches that can represent the input of (smaller) watersheds. In general, due to the diversity (size, density, shape) of the litter found, it is often impossible to determine whether or how long a piece of litter has been transported before being collected. But, due to their homogeneity and as one of the most important litter items worldwide, cigarette butts could play an important role as tracers. Loss of mass, degradation, aging, and chemical composition could provide information on how long a cigarette butt has been on the beach (Araújo et al., 2022) and how long or far it has been transported. The density of cellulose acetate, from which cigarette filters are made, is typically around 1.3 g/cm^3 (Turner & Cundell, 2024) which is similar to beach sand (1.5–1.6 g/cm^3) (Civil & Structural Engineering 2024). Therefore, cigarette butts could be tracers for the drift of litter along the beach and in the sediment. This could be considered for future beach litter studies.

Frequency and Small-scale distribution of litter—Macro-litter

The results show that the top 25 litter items are highly variable in terms of the quantity of each item per 10 m transect. This variability increases with more 10 m transects and greater distance between them, making it difficult to determine a representative survey length. This prompts consideration of the effectiveness of a standard 100 m survey versus extrapolating mean values from 10 m transects, especially in terms of time efficiency. A study conducted on a German beach with low pollution levels recommended replicating a similar transect survey approach (Schulz et al., 2021). Considering the high pollution levels of our beaches, we suggest that 3–5 transects per beach would provide reliable information on pollution. The results can be extrapolated to the standard 100 m. Based on our experience, motivating volunteers for regular sampling on heavily polluted beaches has proven difficult. The UNEP reports a similar trend, indicating a 50% decrease in the number of volunteers participating in beach clean-ups from 2002 to 2015 (UNEP, 2015).

Beach cleaning and steady-state pollution

Research on remote or protected beaches (Merlino et al., 2020; Schulz et al., 2013) suggests that a steady state between litter input and erosion is typically reached within two to three months beaches. However, this may not be the case for our mostly urban and touristic beaches due to several factors, such as the highly developed urban environment, the uncertain impact of the COVID-19 pandemic, the seasonal use of beaches, irregular beach cleaning, unknown and unreliable quality of beach cleaning, poor waste management practices, and other interacting factors within the study areas. Therefore, it is questionable if a steady state between litter inputs from both land and sea-based sources and the outputs resulting from erosion, burial, degradation, and clean-ups will ever achieve.

Beach cleaning is mainly carried out manually by workers during the high season, with an emphasis on macro-litter. Smaller pieces of litter (meso) are often overlooked. Cleaning activities are typically reduced or stopped from September (Nachite et al., 2019), and often only resume at the start of the following high season (personal communication from general beach managers). Pollution continues throughout the year, exposing litter to weathering, sunlight, wind, and mechanical forces that result in fragmentation, transport, size reduction, and burial. As a result, beach sediments contain a significant amount of meso- and micro-litter in addition to macro-litter. Meso-litter in the sediments at the back of the beach remains undetected and untargeted by manual cleaning and accumulates over time (Angelini et al., 2019; Laglbauer et al., 2014; UNEP, 2015). Intense pollution was visible in the dunes and the surrounding hinterland. However, it was not investigated. In general, we assume new beach litter input exceeds litter removal, particularly in the months when no cleaning is carried out.

Recommendations

To ensure harmonized and comparable results, it is recommended to follow the guidelines for beach macro-litter monitoring (UNEP/MAP 2016; JRC, 2020), where seasonal surveys should be carried out four times per year per beach. Each survey should be carried out in as short a time as possible and not spread over several days (UNEP/MAP 2016). Litter analysis should be carried out by using standardized lists (Fleet et al., 2021) and allocated photo guides (EU, 2021). However, despite having an experienced team, we were only able to complete four out of 37 surveys (incl. litter analysis) over a full distance of 100 m within 8–9 h due to high pollution levels. Therefore, when staffing levels are low and pollution levels are high, it is recommended to shorten the survey to a 30–50 m stretch with a corresponding number of 10 m transects. As our results show a 30–50 m stretch is sufficient to cover the top 25 litter items accounting for more than 82% of the pollution. For affordable and sustainable long-term monitoring, ideally carried out by volunteers, the monitoring process must be time efficient. Otherwise, there is a potential risk of rushed surveys and litter analysis, resulting in poor data quality. The flexibility of the 10 m transect approach allows for adjustments to the number of transects if necessary, and for pollution levels to be extrapolated to the standardized unit of litter pieces per 100 m, while results should also be calculated in litter pieces/m^2.

It is vital to conduct seasonal surveys including the high season, on all types of beaches. Monitoring urban beaches, which are more impacted by recent land-based litter like "shoreline, including poor waste management practices, tourism, and recreational activities," enables a rapid evaluation of litter mitigation and avoidance measures (Prevenios et al., 2017). Here, collaboration with professional beach cleaners is essential to prevent survey result bias due to cleaning activities. On urban and tourist beaches with regular cleaning, involving professional cleaners in a study on litter turnover rates could prove beneficial. Collecting and analyzing litter from 10 m transects regularly (for at least 10 days) (Ryan et al., 2020a) provides data on accumulation rate, quantity, weight, and source contributions. Trained staff should conduct the subsequent litter analysis. To gain a comprehensive understanding of pollution drivers, similar surveys should be conducted in parallel at other beaches.

It is further recommended to investigate remote beaches that are difficult for users to access, as described by Rangel-Buitrago et al. (2018b), and that are not subject to any cleaning operations. These remote beaches can be heavily polluted by litter carried by ocean currents, rivers, and smaller watersheds (Rangel-Buitrago et al., 2018a, 2019a, 2019b). Since they are untouched by beach users and unaffected by cleaning efforts, they provide valuable baseline data on pollution levels and sources, offering insights into potential future pollution trends on more accessible urban or tourist beaches if waste management and cleaning practices are not improved. Remote beaches connected to smaller watersheds can reveal the impact of flash floods and heavy rainfall, which often carry large amounts of plastic litter from a variety of continental sources, including agriculture, industry, and urban areas. This litter may have been trapped for years within the watershed before finally entering the Mediterranean Sea environment (Laverre et al., 2023). Flash floods dramatically increase water discharge, leading to sharp surges in macro-plastic flows, with up to 73% of the annual litter from a watershed being released during just a few days of rain events (Laverre et al., 2023).

The consideration of fragmentation and sediment deposition into deeper layers becomes critical in assessing the ultimate presence and mass balance of litter on the beach. Here, Sand Rake results offer insights into the small-scale width-wise distribution of litter, aiding in balancing the plastic budget of beach litter. For a mass balance of beach litter, it is further recommended to analyze the plastic litter weight (MSFD TSG ML 2023). However, this weight analysis can be challenging as the macro-litter method collects a significant amount of litter which is often wet and/or contains sand either in the litter (e.g., in bags or sweet wrappers) or stuck to it. This falsifies the weight results of the litter. Drying and cleaning this sand from the litter is impractical and too time-consuming. In contrast, litter collected using the Sand Rake method is smaller and easier to dry, weigh, and quickly cleaned with a brush. Furthermore, 60.7% of the litter collected using the Sand Rake method was applicable for source allocation and spatial analysis showed that the upper beach is most polluted. Therefore, the method is useful for designing and evaluating targeted litter avoidance and mitigation measures.

Although standing stock surveys can be useful for identifying pollution hotspots and providing an initial overview of litter composition, a comprehensive understanding of litter dynamics requires long-term monitoring over several years. This includes analysis of the influence of external conditions such as wind (direction and speed), tides, sediment drift, and litter deposition in deeper layers. Therefore, initial investigations should include pilot studies to assess the variability within sample data. This should be followed by a power analysis to determine the survey size required to detect a pre-specified change in the amount of beach litter. To improve the accuracy of detecting changes over time, it may be more effective to focus on specific litter items rather than the total amount of litter. For example, concentrating on the most common litter items, cigarette butts, SUP or other land-based litter can provide more precise results. By following these recommendations, more reliable and comprehensive data can be collected, which is essential for the implementation and evaluation of effective measures to reduce and prevent marine litter.

In this context, the use of satellites and drones should be considered to improve beach litter monitoring. Spatially precise monitoring over large areas can be achieved in a harmonized way using satellite remote sensing with multi- and hyperspectral optical sensors (Martínez-Vicente et al., 2019; Paula M. Salgado-Hernanz et al., 2021). Subsequently, drones could be used for more detailed national and regional surveys. As reviewed by Veettil et al. (2022), drones have been used effectively in several beach litter studies and can help identify litter hotspots and litter categories. By comparing the litter identified in situ (from the 10 m transects) with the corresponding drone images, it may be possible to calculate a recovery rate (for different litter items and their quantity) for the drone results. This recovery rate can then be used to project the results to larger areas surveyed by drones alone.

Consideration could also be given to how frequent voluntary beach clean-ups (e.g., Coastal Clean-up Day) could be combined with, for example, drone and macro-litter surveys. In many places around the world, beach clean-ups take place regularly throughout the year, but there is often a lack of systematic data collection during these activities. As a result, important information is lost, that could otherwise be used for ongoing monitoring. A systematic use of data from such clean-ups could improve our understanding of beach pollution trends.

To prevent beach users from migrating to cleaner regions and causing financial losses to the local tourism industry, it is imperative to improve manual beach cleaning and extend it throughout the year. According to Ballance et al. (2000), 85% of beach visitors avoid beaches with more than 2 litter pieces per meter. Our average pollution of macro litter (1.71/m^2) is close to this value, while the meso-litter exceeds this value by a factor of five. Particularly concerning are the CCI and HII indicators: only one out of 37 beaches is classified as clean (CCI). Hazardous litter was found in every beach survey, and it can be assumed that this type of litter has an even more negative impact on beach users compared to litter that is considered less harmful to humans. The presence of dangerous litter likely heightens health and safety concerns, further diminishing the beach experience. Considering that beach users typically enter from the back, where most litter tends to accumulate, this could further enhance the deterrent effect. Further, the implementation of mechanical beach cleaning should be considered to address the high meso-litter pollution in the upper sediment layers. It should be further evaluated to what extent such mechanical beach cleaning equipment can be used for monitoring purposes.

For almost all Mediterranean countries, beach tourism is of great social and economic importance (Mejjad et al., 2022), yet Mediterranean beaches are highly polluted. Kiessling et al. (2017) found that the extent of the pollution problem is not automatically related to local action; large quantities of litter do not guarantee an adequate reaction from the population or authorities. It is important for the tourism sector, beach managers, and politicians to understand that coastal ecosystems, like beaches are key providers of leisure and recreational ecosystem services (Krelling et al., 2017). However, for these beaches and coastal areas to provide these services effectively, they must be kept clean. People avoid polluted beaches and more time and money is spent visiting clean beaches or pursuing other activities (NOAA, 2014). The experience of a polluted beach reduces the likelihood of return visits and leads to a corresponding loss of revenue (Jarvis et al., 2016). The "Big Fives" are most important to beach visitors: safety, facilities, water quality, no litter, and scenery (Giorgio et al., 2018). The last three can only be achieved by following the principles of sustainable tourism, the 2030 Agenda for Sustainable Development, and the 17 Sustainable Development Goals (SDGs), valuing coastal ecosystems as the very resource on which all beach tourism is based.

Furthermore, it is important to understand, that a sustainable approach and lasting solutions require a shift towards comprehensive marine litter avoidance measures. Considering that nearly half of the litter found is SUP, it is crucial to address the principles of a circular economy and a transition away from the linear use of short-lived plastic. The design of products should aim for durability, recyclability, reuse, and towards the innovation of SUP alternatives. Here, the Extended Producer Responsibility (EPR), where producers are accountable for the entire lifecycle of their products, can play an important role in financing the transition towards a circular economy and promote the production of environmentally friendly products. It is recommended to implement pilot projects for litter monitoring, testing specific measures to reduce litter from tourists, hotels, and other recreational activities, and strengthening the waste management sector.

Although this study has provided information on how to improve beach litter monitoring on heavily littered beaches, it has only focused on the beach surface up to a depth of 5 cm. Future studies should also include the hinterland or dunes, which are often heavily littered but were not part of our study.

Conclusion

Regional land-based litter sources, specifically poor waste management practices, littering from beach users, tourism, and recreational activities, have been identified as the main contributors to the beach pollution conducted in this study. The consistent dominance of the top 25 litter items, which account for 82% of the pollution in each survey campaign, highlights the need to focus on each of these items with specific avoidance and mitigation measures. The implementation of short- and medium-term mitigation measures such as beach clean-ups, mechanical removal of litter from coastal areas, and the enforcement of policies and regulations to control littering are necessary; especially, as beach tourism plays a significant role of income for Egypt, Morocco, and Tunisia. Clean and litter-free beaches are highly valued by tourists, making their maintenance essential for sustaining tourism revenues and attracting international visitors to the region. Here, a marine litter monitoring program is of great importance to evaluate the effectiveness of mitigation and avoidance measures. It provides essential insights into the progress made in reducing overall marine litter. For a practical and cost-effective approach, we recommend initiating long-term macro and meso-beach litter monitoring using the 10 m transect and the Sand Rake method. These are effective and low-cost methods that can be implemented on a large scale with the help of volunteers.

Supplementary information.

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Author contribution Conceptualization: Mirco Haseler, and Gerald Schernewski. Methodology, data acquisition, analysis, and interpretation: Mirco Haseler, Lilia Ben Abdallah, Loubna El Fels, Bouchra El Hayany, Gasser Hassan, Gabriela Escobar-Sánchez, Esther Robbe, Miriam von Thenen, Assala Loukili, Mahmoud Abd El-Raouf, Fadhel Mhiri, Alaa El-Bary, Gerald Schernewski, Abdallah Nassour. First draft preparation of the manuscript by Mirco Haseler. All authors read, commented, reviewed, and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval All the authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Animal ethics and consent to participate. Not applicable.

Consent for publication The authors certify that the publisher is permitted to publish this work.

Competing Interests The authors declare no competing interests.

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PAPER II

frontiers in Environmental Science

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Efficiency of Aerial Drones for Macrolitter Monitoring on Baltic Sea Beaches

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Marine litter is a global problem that requires soon management and design of mitigation strategies. Marine litter monitoring is an essential step to assess the abundances, distributions, sinks and hotspots of pollution as well as the effectiveness of mitigation measures. However, these need to be time and cost-efficient, fit for purpose and context, as well as provide a standardized methodology suitable for comparison among surveys. In Europe, the Marine Strategy Framework Directive (MSFD) provides a structure for the effective implementation of long-term monitoring. For beaches, the well-established 100 m OSPAR macrolitter monitoring exists. However, this method requires a high staff effort and suffers from a high spatio-temporal variability of the results. In this study, we test the potential of aerial drones or Unmanned Aerial Vehicles (UAVs) together with a Geographic Information System approach for semi-automatic classification of meso- (1–25 mm) and macrolitter (>25 mm) at four beaches of the southern Baltic Sea. Visual screening of drone images in recovery experiments (50 m^2 areas) at 10 m height revealed an accuracy of 99%. The total accuracy of classification using object-based classification was 45–90% for the classification with four classes and 50–66% for the classification with six classes, depending on the algorithm and flight height used. On 100 m beach monitoring transects the accuracy was between 39–74% (4 classes) and 25–74% (6 classes), with very low kappa values, indicating that the GIS classification method cannot be regarded as a reliable method for the detection of litter in the Southern Baltic. In terms of cost-efficiency, the drone method showed high reproducibility and moderate accuracy, with much lower flexibility and quality of data than a comparable spatial-OSPAR method. Consequently, our results suggest that drone based monitoring cannot be recommended as a replacement or complement existing methods in southern Baltic beaches. However, drone monitoring could be useful at other sites and other methods for image analysis should be tested to explore this tool for fast-screening of non-accessible sites, fragile ecosystems, floating litter or heavily polluted beaches.

Keywords: cost-efficiency, Image classification, OSPAR, unmanned aerial vehicle, marine litter, marine strategy framework directive, recovery experiment

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INTRODUCTION

The pollution of seas and coasts with marine litter, especially plastics, is a growing global problem (United Nations Environment Programme, 2019). The state of pollution of beaches with macrolitter (>25 mm), and its associated problems are well known and documented for many regions worldwide (Abu-Hilal and Al-Najjar, 2009; Jayasiri et al., 2013; Rosevelt et al., 2013; Topçu et al., 2013; Duhec et al., 2015; Hidalgo-Ruz et al., 2018). In Europe, the pollution of beaches ranges from a few up to more than 1,000 litter items on a 100 m beach stretch, depending on factors such as exposition, accessibility or population density (e.g., Marlin 2013; Gago et al., 2014; Schulz et al., 2015; Schernewski et al., 2017). Here the most common items are plastics, and the main sources of pollution vary between fishing in the North Sea (Schulz et al., 2015) and tourism and recreation in the Mediterranean Sea (Vlachogianni, 2019), Baltic Sea (Schernewski et al., 2017) and North East Atlantic (Schulz et al., 2015).

Marine litter is addressed as one of the UN Sustainable Development Goals (SDG 14.1) aiming at preventing and significantly reducing pollution in the world oceans by 2025 (United Nations, 2019). In order to design mitigation strategies and fulfill SDG 14, as well as national and regional goals timely, managers require monitoring methods that are time and cost-efficient, fit for purpose and context. Although *in-situ* beach litter monitoring is a commonly applied survey worldwide, until today there is no clear consensus on the monitoring strategy to be used and units are difficult to compare (Serra-Gonçalves et al., 2019).

Efforts directed to monitor marine litter and to implement measures for its reduction in Europe have been reflected in the creation of the Marine Strategy Framework Directive (MSFD, 2008/56/EC); a comprehensive legislation to effectively protect the marine environment across Europe, including a detailed implementation procedure. Within this framework, the European Union included marine litter as a descriptor for a Good Environmental Status (GES) to be reached by 2020 (MSFD, 2008/56/EC). The implementation involves an initial assessment of the current environmental status and environmental impact, the determination of the GES, the establishment of environmental targets and associated indicators as well as the development of a monitoring program and cost estimates. Since 2013, a joint, harmonized monitoring strategy is carried out (JRC, 2013) which adapts and further develops the OSPAR Guideline (OSPAR, 2010) and ensures that data is comparable among monitoring surveys. The OSPAR guideline evaluates the trend of abundance of litter over an extended period of time (every 3 months) at sites fulfilling specific criteria, recording the number of items over beach transects of 100 m, from the sea edge to the highest strandline or edge of vegetation, and identifying items according to an item category list (OSPAR, 2010). Although the OSPAR guideline is a flexible and relatively low-cost method that can be carried out with volunteers; it suffers from several weaknesses, being time-intensive, subjective upon litter types, site conditions, frequency of sampling and the training and experience of volunteers and staff (Smith and Markic, 2013; Lavers et al., 2016; Schernewski et al., 2017). This increases the challenge considering the inherent temporal and spatial variability of marine litter subject to beach exposition, winds, currents and distance to pollution sources (Ryan et al., 2009; Critchell and Lambrechts, 2016; Schernewski et al., 2017). As a consequence, Schernewski et al. (2017) conclude for Baltic Sea beaches that the macrolitter beach monitoring method in practice is spatially restricted, does not provide the required reliable data to provide long-term trends and should only serve as a method in combination with others. Optional methods such as the 1 km beach sampling method to monitor marine litter above 50 cm (OSPAR, 2010) or the Rake method (Haseler et al., 2019) focusing on the mesolitter size class, are suitable complementary approaches for Baltic beaches but rarely applied. Therefore, a need for complementary beach litter monitoring methods for macrolitter still exists. Since the MSFD expands the environmental monitoring and reporting requirements, responsible authorities in Europe face the pressure to meet these new demands with limited financial and staff resources (JRC, 2013). Therefore, cost-effectiveness is a pre-condition that additional beach litter monitoring methods must meet.

Aerial drones or Unmanned Aerial Vehicles (UAVs) offer new opportunities for marine litter monitoring and the remote collection of high temporal and spatial resolution data. So far, remote sensing studies have mainly relied on satellite or airplane images to monitor floating marine debris at sea (Veenstra and Churnside, 2012), derelict fishing gear (Moy et al., 2018) and other litter in islands (Kataoka et al., 2018) or after disaster events (Murphy, 2015); however all at much lower spatial resolutions. The higher flexibility and smaller size of UAVs allow capturing images at lower altitudes, obtaining images in cloudy conditions and in narrower areas at higher spatial resolutions, thus collecting more specific information on the surfaces recorded (Pajares, 2015).

Consumer-based drones are nowadays accessible tools used in various environmental purposes, such as monitoring of invasive plant management (Lehmann et al., 2017) or mapping of ecologically sensitive habitats (Ventura et al., 2018). Although their use for scientific purposes is still new and limitations exist, these commercial aerial drones have shown promising results for rapid assessment and mapping of marine litter at beaches. First studies developed abundance and density maps with georeferenced location of specific litter items and hotspots (Hengstmann et al., 2017; Deidun et al., 2018), while most recent studies have tested the potential of machine learning (Atwood et al., 2018; Martin et al., 2018), deep learning approaches (Fallati et al., 2019) and most recently, the combination of photogrammetry, geomorphology, machine learning and hydrodynamic models (Goncalves et al., 2020) for the automatic identification of macrolitter. Based on these findings, drone-based monitoring could have the potential to cover larger spatial scales in less time, provide with standardized units of litter abundance and assess distribution patterns and pollution hotspots. Thus, it already seems reasonable to assess the potential of consumer UAVs for regular and official beach monitoring in practice.

The purpose of this study is to evaluate the applicability of commercial aerial drones for the implementation of long-term

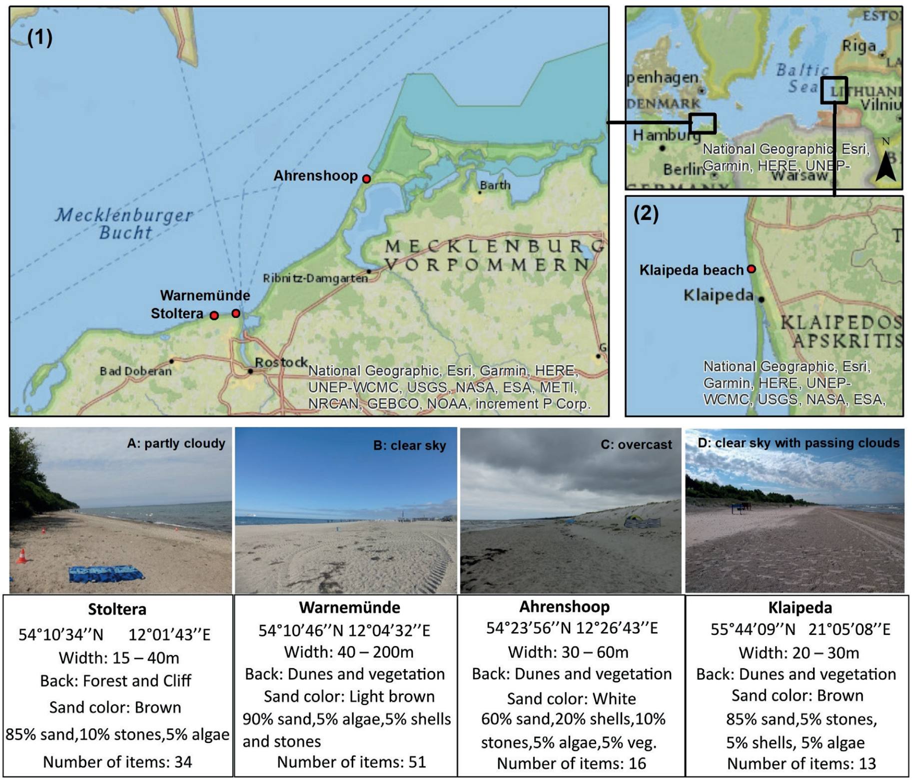

FIGURE 1 | Study sites for drone mapping and *in-situ* data collection of beach litter in the Southern Baltic Sea, specifically Germany (1) **(A)**: Stoltera, **(B)**: Warnemünde, **(C)**: Ahrenshoop) and Lithuania (2) **(D)**: Klaipeda).

monitoring strategies within regional environmental agencies in the Southern Baltic Sea. Nonetheless, this evaluation could also serve as a template for the evaluation of drone-based monitoring for other regions. Here, we intend to answer: could drone-based monitoring complement the 100 m OSPAR method to extend its spatial coverage and provide a pollution pattern over e.g. an entire coastline? We 1) explore and test an UAV approach for marine litter monitoring of meso- (1–25 mm) and macrolitter (>25 mm) with a GIS based semi-automatic object-based classification; 2) apply this methodology at four different southern Baltic beaches and 3) evaluate its suitability and cost-efficiency as a complementary method in monitoring programs.

METHODOLOGY

Study Sites

The Baltic Sea is an enclosed sea with a population of 90 million people and 15 major coastal cities, 10 main rivers (Marlin, 2013) and with an economy that highly focuses on tourism, with cruises and ferries frequently transporting people and goods across the sea, and to a smaller extent on fishing and shipping (HELCOM, 2017). Four beaches in the southern Baltic Sea, three in northeastern Germany and one in Lithuania, were selected for the study (**Figure 1**). Beaches were selected based on their accessibility and for presenting different beach geomorphology, sand color, background substrate (i.e. stones, shells, algae and vegetation) and level of tourism. Two of the sites, Warnemünde and Klaipeda, are urban beaches. Stoltera and Ahrenshoop are peri-urban beaches located close to Nature Conservation Areas. Beach visitors and hikers were present in different quantities at all sites during the sampling time.

Aerial images were captured under different weather conditions (**Figure 1**). At all German beaches, official cleaning activities takes place regularly. In Stoltera and Warnemünde, cleaning occurred every day from 5–9 a.m. during high season and three times per week during low season. This is carried out

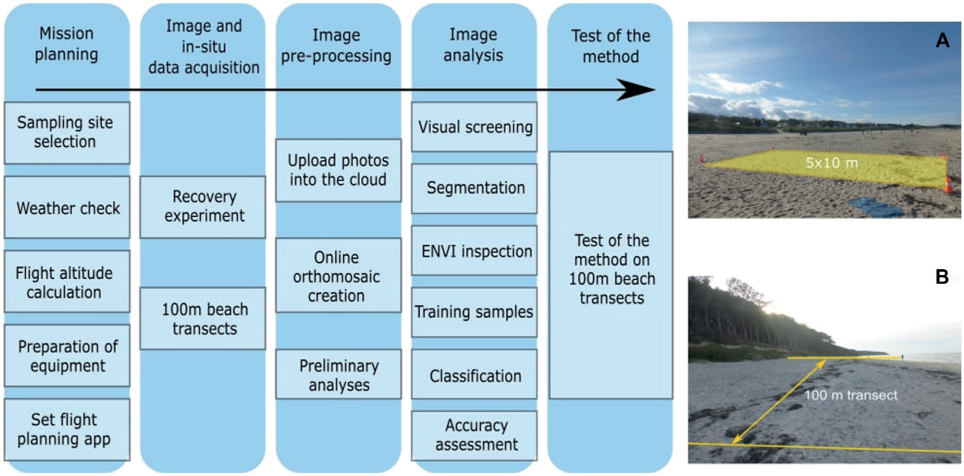

FIGURE 2 | (1) Workflow for drone-based monitoring and object-based supervised classification based on five main steps, each with separate single steps to follow. (2) Set up for sampling of the recovery experiment **(A)** and 100 m beach transects **(B)**. In the recovery experiments, selected items (based on most common items found in the Baltic region) were placed in a cleaned area of 5 × 10 m. The 100 m monitoring was based on OSPAR guidelines. After drone mapping of the zone, litter was collected on the area from the intertidal to the back of the beach with two people and then counted and classified according to the OSPAR list of items.

with a mechanical vehicle ("Beach Tech 2000") which removes litter and seaweed and is able to clean 22,000 m^2 per hour (pers. com. Rostocker Gehwegreinigung, July 2019; Tourismuszentrale, 2019). In Ahrenshoop, regular cleaning takes place by hand two times a week during high season (June–September) and no cleaning the rest of the year (pers. com. Kurverwaltung Ahrenshoop, October 2020). In Klaipeda, the beach belongs to the protected area "Coastal Region Park" and cleaning takes place only after extreme weather events (pers. com. A. Balciunas, 2019). In addition, removal of beach litter is also carried out by NGOs at all sites, serving as environmental awareness raising mechanisms (e.g., Battisti and Gippoliti, 2019).

Equipment and Software

Study areas were mapped with a low cost quadcopter DJI Phantom four Pro V2.0 with an integrated RGB CMOS camera of 20 Megapixels (focal length 8.8 mm) to develop and test an UAV-based approach for marine litter monitoring of meso- (1–25 mm) and macrolitter (>25 mm). The drone had a GPS/GLONASS system with a hover accuracy of ±0.5 m (vertical) and ±1.5 m (horizontal), a gimbal unit to provide near nadir observations and obstacle avoidance, automatic flight and Return To Home (RTH) features. A controller, which uses a smartphone device as display, allows monitoring of battery life and drone status. In this study, two smartphone devices (Android and iOS) were tested to run the flight mapping apps and fly the drone. PolarPro ND filters were used to adjust shutter speed under different light conditions, with ND 8 for cloudy, ND 16 for sunny and ND 32 for very sunny conditions.

For mapping, two apps were tested: DroneDeploy v.3.13.1 and Pix4D Capture v.4.5.0. The apps set the mapping area, flight altitude, speed, field of view (FOV), front and side overlap and create an orthomosaic with the images obtained. Agisoft Metashape was used for image stitching for one orthomosaic where neither of the mapping apps provided satisfactory results, using a standard process of photo alignment which uses images and point cloud data to create mosaics or 3D data (Agisoft, 2020). Moreover, the geospatial analysis software ENVI 5.3 and ArcGIS v.10.5 were used for image analyses. ENVI 5.3 served to explore the spectral signatures of different objects in the image, while ArcGIS v.10.5 was used to carry out supervised object-based classification.

Field Approach and Image Acquisition

The methodology for image acquisition and analysis followed five main steps (**Figure 2**). A total of four flights per beach (three for Klaipeda and Warnemünde) were carried out as one-time sampling in the same day at three different altitudes near the highest sun zenith angle (between 11 a.m and 1 p.m CET) in May, June, July and October 2019. All sampling was carried out under the permission of the Ministry for Energy, Infrastructure and Digitalization in MV, Germany and following the guidelines of the German Air Traffic Control (Deutsche Flugsicherung, DFS). In Lithuania, drone flights for small devices (<25 kg) do not require permission, thus sampling was not restricted but followed regulations (Civil Aviation Administration, CAA, 2020). Care was taken during all surveys to avoid impacts such as crashing on people or structures (e.g. trees), or cause disturbances to birds by the noise and start/landing of the drone. We carried out sampling away from conglomeration of people and chose a start/land site with sufficient distance from trees and structures. The drone was always kept on sight to maneuver in case of danger. The flight heights used were low and thus more noise was produced, but we kept flights short (3 min for recovery experiments and max. 20 min for one sampling of 100 m beach transect) to minimize disturbance. The sampling was carried out only under good stable weather conditions (noon, clear sky or homogeneous cloud cover, wind speed <20 km/h, no rain). **Supplementary Table S1** shows the settings used for drone-based mapping following Martin et al. (2018) and own experiences. Ground Control Points (GCPs) were not used for georeferencing. The drone gives good positional relative accuracy- that is how points on a map are placed relative to each other- which we suggest is sufficient for image classification, as we are not overlaying different orthomosaics but rather making a comparison of the classification results between different flight altitudes and algorithms.

Previous studies using consumer drones with a camera resolution similar to ours, tested flight altitudes between 5 and 35 m (Deidun et al., 2018; Martin et al., 2018; Fallati et al., 2019) and up to 60 m (Atwood et al., 2018; Goncalves et al., 2020). The flight altitudes chosen for this study were set based on the *Pix4D Ground Sampling Distance (GSD) calculator* to obtain a GSD <5 mm as optimal spatial resolution to detect litter in the meso (5–25 mm) and macro (>25 mm) scale; namely 10, 15, and 18 m, which would give spatial resolutions of 2.7, 4.1, and 4.9 mm, respectively. This is also in accordance with the EU law regulations for drone flights, limited to a range of 10 m to 120 m, based on the aircraft settings and EU law (European Parliament and Council, 2018).

To assess the detection accuracy of litter items at these different flight heights, recovery experiments were carried out on a previously cleaned area of 5 × 10 m (**Figure 2**) where litter items of different colors, shapes and sizes (1–30 cm) were displayed (**Supplementary Figure S1**). These included the most common item categories for the Baltic (Schernewski et al., 2017). The sites mapped had different number of items (14–57 items) and background substrates and were sampled under different weather conditions (**Figure 1**). In addition, beach transects of 100 m (with unknown number and type of litter) were mapped from the intertidal zone to the back of the beach (**Figure 2**) at a flight height of 10 m. After mapping, two people collected the items seen by naked eye and classified them according to the OSPAR list of items (OSPAR, 2010). All captured images were converted into orthomosaics and these were integrated in a Geographic Information System (GIS) for image analyses.

Image Processing and Pre-analyses

A total of 14 orthomosaics were created in GeoTIFF format which presented spatial resolutions of 2.7–8 mm/px, based on flight height and mapping app used. In general, all apps use photogrammetry approaches based on image orthorectification with point clouds and elevation data to produce orthomosaics, however, different image processing may have caused the differing spatial resolutions between the apps (e.g., use of image stitching enhances image spatial resolution). For each site, three orthomosaics (one for each flight height) of recovery experiments (Klaipeda and Warnemünde, only two) and one orthomosaic of a 100 m beach transect taken at 10 m altitude. Image analysis was carried out on ArcGIS, using Digital Numbers (DN) with a radiometric resolution of 8 bit. The projection used was WGS1984 UTM Zone 33N/34N for Germany and Lithuania, respectively.

First, the orthomosaics obtained from the recovery experiments at 10 m height were visually screened to assess and compare the accuracy of litter detection from drone imagery vs. ground truth data. Here, the analyst knew the number and type of items but not their position in the image. The items were counted from left to right, starting at the top of the image towards the bottom, zooming at the objects to mark them. Preliminary analyses were conducted to find the best classification method between pixel-based vs. object-based classification. Similarly, the influence of different number of classes (2, 4, and 6 classes) was tested in ArcGIS and ENVI. The latter was used to inspect the spectral differences of each background material by taking 10–20 samples of objects in each orthomosaic.

Object-Based Supervised Classification

Image classification followed a standard procedure of object-based supervised classification incorporated in ArcGIS including four steps, i.e. segmentation, the selection of training samples, classification and accuracy assessment.

Segmentation groups pixels into "objects" based on homogeneity criteria set by spectral and spatial values and minimum segment size. This aims at reducing noise from the background and highlighting objects of interest for object-based classification. Based on the gained knowledge from the investigated sites, a decision tree for choosing segmentation parameters was created (**Figure 3**). Spectral and spatial values were chosen individually per site. The minimum segment size used here was between 2 and 10 pixels (1–5 cm^2) with the aim to allow recognizing small litter items like cigarette butts (1–2.5 cm). It is important to consider that only four beaches were studied, thus the employment of this decision tree should be further tested for its application in more sites. For an example of the segmentation result, see **Supplementary Figure S2**.

The classification approach used is supervised and therefore requires training data. Training samples were taken as segments to obtain 4–6 distinct classes. The criteria used here were: 1) select >20 samples (if possible), proportional to the class size but not exceeding the number of objects per class in the image, 2) select samples with enough distance from one another to increase variability of the training set, 3) select samples at the center of the item to avoid mixed pixels and 4) include different color tones for each class, i.e. if vegetation was present in different tones of green, training samples included these to provide an accurate classification of the class. Additionally, histograms and scatterplots on ArcGIS were checked to ensure that each class was spectrally distinct from one another. The training samples taken at each recovery experiment were used for classification of the recovery sites and 100 m beach transects.

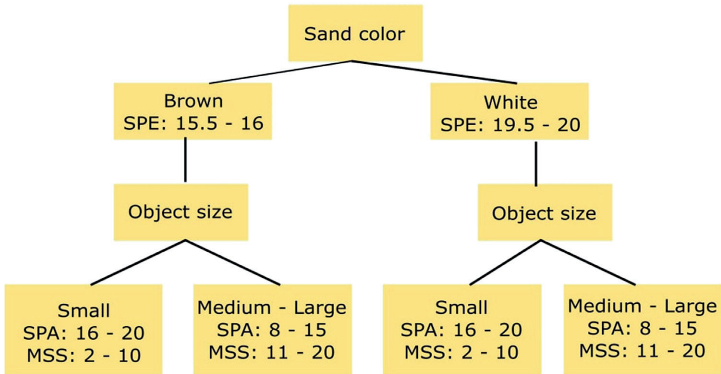

FIGURE 3 | Decision tree for segmentation parameters based on beach characteristics of the four study sites. SPE: Spectral Value, SPA: Spatial Value, MSS: Mean Segment Shift Value.

Three supervised classification algorithms were tested: Maximum Likelihood (ML), Random Forest (RF) and Support Vector Machine (SVM). These algorithms follow different set of rules in respect to the training samples to be used. For the RGB camera used, ML classification in ArcGIS requires a minimum number of 20 training samples per class and assumes normal distribution of the samples, while RF classification and SVM can work with fewer samples, do not assume normal distribution and are less susceptible to noise in the image. The functioning of each algorithm is also different. ML is based on the concept of normal distribution and Bayes theorem of decision making, based on the probability that every pixel in an image belongs to a particular class. The strength of ML is that it considers the variability within each class using the covariance matrix to classify the candidate pixel (Lillesand et al., 2004). RF uses multiple decision trees trained to use small variation of the data, where the majority vote from the trained trees decides the class assignment for each pixel (Berhane et al., 2018). SVM is a non-parametric statistical learning approach and therefore there is no assumption made on the underlying data distribution. SVM maps input data as vectors into a higher dimensional space to separate data into different classes using hyperplanes (Mountrakis et al., 2011). The output of the approaches is a classified image (*.tif*) of a number of classes as defined in the training samples.

Accuracy assessment of the image classifications was carried out with a set of 500 validation points created in an "equalized stratified random" manner, i.e. distributed within each class, each one having the same number of points. A confusion matrix, based on the comparison between the classification and reference data, revealed the accuracy of each algorithm by calculation of commission and omission errors for each class, total accuracy and kappa value of agreement. The total accuracy (TA) is the percentage of correctly classified validation pixels and measures the accuracy of the classified image. The producer's accuracy (PA), also known as recall, indicates the true positive rate or the proportion of true positives in relation to true positives and false negatives in the model classification. It is also a measure of omission error. The user's accuracy (UA), also known as precision, indicates the positive predictive power or the proportion of true positives in relation to true positives and false positives in comparison to the reference data. It is also a measure of commission error (Story and Congalton, 1986; Campbell and Wynne, 2011). Cohen's Kappa gives an overall assessment of accuracy of the classification in respect to randomness, with a value of 0 indicating no better than random, >0 better than random and <0 worse than random (Cohen, 1960).

Because only one replicate classification was carried out per height and algorithm, statistical tests for significant differences were not conducted. Instead, we provide an overview of the accuracy measures obtained from each image classification and a comparison of the mean and standard deviation between the classifications at different flight heights for each sampling site.

Cost-Efficiency Analysis

Official marine litter monitoring methods need to be time and cost efficient. The MSFD requires the comparison of methods for marine litter monitoring to meet the practical demand of cost-efficiency (JRC, 2013) considering implementation and annual running costs to fulfill the MSFD Descriptor 10 and to be implemented by national authorities within their national marine litter monitoring programs. The following approach provides a subjective comparison of a set of two monitoring methods: an UAV monitoring method with a commercial RGB drone and a hypothetical non-established spatial-OSPAR monitoring method to evaluate aspects of costs and efficiency. The evaluation of efficiency was based on four criteria: accuracy, reproducibility, flexibility and quality. Accuracy refers to the share of items identified at the beach transects vs. ground truth data. Reproducibility reflects the likelihood that, when a method is applied by different persons, drones and software, the same results will be obtained. Flexibility is defined as how flexible the method is with respect to weather conditions, external disturbances, permissions and battery life. Quality refers to how well are items defined and whether sufficient data is provided, i.e. type and number of items, type of material and spatial distribution.

In contrast to the current OSPAR method, spatial-OSPAR considers the spatial distribution of litter items per area, thus comparable to the output of the drone approach, and taking into account 100 m beach transects (or 1 km beach transects for items >50 cm) with smaller transects of 10 m and 3–6 quadrats of 9 m^2, displayed from the tide line, middle and to the back of the beach (an adapted version after Bravo et al., 2009).

Costs of the UAV and the spatial-OSPAR methods were calculated considering implementation costs (equipment, software and testing period) and annual running costs for office and field/lab work to be carried out at four beaches, four times a year, by a minimum of two persons. Our time and costs estimations follow own experiences. These estimations may, therefore, vary based on type of drone used, analysis method and level of training required, as well as currency and salary estimations for the country. The initial costs include equipment costs as well as the costs for a testing period for both methods (6 months for the UAV-method and 3 months for the spatial-OSPAR method). Annual running costs include field/lab (travel, survey and analysis) working time and office (planning, organization and reporting) working time. The total monitoring costs were calculated as the sum of initial costs and annual running costs for field/lab and office work, and were classified as: 5 (very low) < 15,000 €; 4 (low) < 30,000 €; 3 (moderate) < 45,000 €; 2 (high) < 90,000 € and 1 (very high) > 90,000 €.

Each method and criteria was scored separately, evaluated by three experts as: 1 (very low), 2 (low), 3 (moderate), 4 (high) and 5 (very high). The efficiency score is the average of the scores for each criterion. To obtain the final cost-efficiency score, the cost and the efficiency scores were multiplied and classified as: <5 (very low), <10 (low), <15 (moderate), <20 (high) and >20 (very high).

RESULTS

Preliminary Analyses

Accuracy Assessment by Visual Screening

Visual screening carried out on images captured at 10 m flight height revealed a mean recovery rate of 99.4 ± 16.2% for the four beaches (Ahrenshoop 87.5%, Stoltera 97%, Warnemünde 90%, in Klaipeda 16 instead of 13 items were found again, 123%). These results gave the first "green light" towards testing a semi-automatic method for classification with ArcGIS. The objects easier to find by visual screening were larger items (>2.5 cm), items placed close to each other, items of bright colors and shapes normally not found naturally at the beach (e.g. bottle caps in yellow, blue, pink, orange, red, bright green). The objects most difficult to find were mainly in colors white, black, brown and transparent and shapes like string/cord, lines and squares, especially of small sizes and diameters (<2.5 cm).

Pixel Based vs. Object Based Classification

The high spatial resolution of drone images, which is needed for the detection of small litter, also led to noise from shadows, differences in sand color and tread marks, which disturb the classification, and thus needed to be handled accordingly. Pixel-based unsupervized classification (A) resulted in a complex image due to high variations on sand, background substrate (i.e. sand color and amount of stones, shells and vegetation), colors and shades. Using object-based unsupervized classification (B) objects were clearly separated from sand and the "noise" from shadows and differences in sand color were reduced or eliminated (**Supplementary Figure S3**). The results of this test classification also showed that images at 10 m height gave a closer and sharper look into smaller objects than images obtained at 15 and 18 m height (**Supplementary Figure S4**), which reduced the noise of the background but smaller objects were more difficult to identify and classify.

Influence of Different Number of Classes

Unsupervized classification into two classes highlighted all objects from sand (**Supplementary Figure S5A**), whereas classification into four classes (**Supplementary Figure S5B**) showed clustering of the objects, however with high variability in the classification, i.e. one object was classified as three different ones. The classification into six classes showed even higher variability in the classification: objects of white and black color were clustered separately and colorful litter items were highlighted from the sand but classified in non-coherent clusters with single items belonging to more than one class (**Supplementary Figure S5C**).

The analysis of spectral profiles of objects on ENVI 5.3 revealed that each object had a different spectral profile and could therefore be classified separately into a total of maximum six classes: litter, algae, vegetation, shells, stones and sand. For Warnemünde, the class "shadows" was added (**Supplementary Figure S6**). Between all classes present, algae, vegetation and sand presented characteristic and consistent spectral profiles that could allow the differentiation from other classes. However, for the case of litter the high variation in color presented no consistent curve in which classification could be based upon. Lastly, shells, stones and shadows that were present in either white or dark colors had similar spectral profiles with flat DN values at either extreme (0–255).

Like this, four to six classes were chosen for the selection of training samples to carry out object-based supervised classification with three algorithms. For classification with four classes, algae and vegetation as well as stones and shells were considered together as two classes. For classification with six classes, algae and vegetation as well as stones and shells were considered as separate classes. This latter classification was carried out only for the sites where the presence of stones and shells as well as of algae and vegetation was clear, in this case Stoltera and Ahrenshoop. Although these classes are not the object of interest, it was important to understand how white and black objects would be classified.

TABLE 1 | Accuracy of image classification on recovery sites with 4 and 6 classes (litter, vegetation, algae, stones, shells and sand) for each site, algorithm and flight height. The values are presented as percentage from top to bottom: Total Accuracy (TA), Producer's accuracy (PA) of litter class, User's accuracy (UA) of litter class and kappa value of agreement (k).

		Four classes				Six classes			
Site	**Algorithm/Height**	**10 m**	**15 m**	**18 m**	**Mean ± SD**	**10 m**	**15 m**	**18 m**	**Mean ± SD**
Stoltera	ML	0.75	0.76	0.62	0.71 ± 0.06	0.64	0.58	0.56	0.59 ± 0.03
		0.85	0.80	0.45	0.70 ± 0.18	0.79	0.70	0.46	0.65 ± 0.14
		0.55	0.57	0.18	0.43 ± 0.18	0.70	0.59	0.30	0.53 ± 0.17
		0.66	0.68	0.50	0.61 ± 0.08	0.56	0.49	0.47	0.51 ± 0.04
	RF	0.58	–	–	–	0.50	0.51	–	0.51 ± 0.01
		0.95				0.35	0.28		0.32 ± 0.03
		0.39				0.16	0.13		0.15 ± 0.01
		0.43				0.40	0.42		0.41 ± 0.01
	SVM	0.73	0.74	0.73	0.73 ± 0.00	0.62	0.65	0.63	0.63 ± 0.01
		0.81	0.72	0.61	0.71 ± 0.08	0.48	0.75	0.59	0.61 ± 0.11
		0.42	0.47	0.42	0.44 ± 0.02	0.91	0.99	0.99	0.96 ± 0.04
		0.63	0.66	0.64	0.64 ± 0.01	0.54	0.58	0.55	0.56 ± 0.02
Ahrenshoop	ML	0.84	0.82	0.79	0.82 ± 0.02	0.66	0.65	0.61	0.64 ± 0.02
		0.97	0.98	0.98	0.98 ± 0.00	0.92	0.92	0.86	0.90 ± 0.03
		0.50	0.45	0.36	0.44 ± 0.06	0.28	0.29	0.15	0.24 ± 0.06
		0.78	0.76	0.71	0.75 ± 0.03	0.59	0.58	0.53	0.57 ± 0.03
	RF	0.73	0.73	0.73	0.73 ± 0.00	0.56	0.56	0.57	0.56 ± 0.00
		0.77	0.73	0.92	0.81 ± 0.08	0.22	0.18	0.18	0.19 ± 0.02
		0.08	0.09	0.09	0.09 ± 0.00	0.02	0.04	0.02	0.03 ± 0.01
		0.63	0.63	0.64	0.63 ± 0.00	0.47	0.47	0.48	0.47 ± 0.00
	SVM	0.74	0.76	0.75	0.75 ± 0.01	0.60	0.63	0.64	0.62 ± 0.02
		0.96	1	0.94	0.97 ± 0.02	0.87	0.44	0.54	0.62 ± 0.18
		0.19	0.21	0.14	0.18 ± 0.03	0.16	0.20	0.26	0.21 ± 0.04
		0.66	0.68	0.66	0.67 ± 0.01	0.52	0.55	0.56	0.54 ± 0.02
Warnemünde[a]	ML	0.90	0.75	–	0.83 ± 0.08				
		1	0.99		1.00 ± 0.01				
		0.88	0.70		0.79 ± 0.09				
		0.87	0.66		0.77 ± 0.11				
	RF	0.71	0.61	–	0.66 ± 0.05				
		0.93	0.67		0.80 ± 0.13				
		0.22	0.08		0.15 ± 0.07				
		0.62	0.48		0.55 ± 0.07				
	SVM	0.76	0.62	–	0.69 ± 0.07				
		0.97	0.95		0.96 ± 0.01				
		0.74	0.30		0.52 ± 0.22				
		0.68	0.49		0.59 ± 0.10				
Klaipeda[b]	ML	–	0.69	0.54	0.62 ± 0.07				
			0.88	0.93	0.91 ± 0.03				
			0.88	0.79	0.84 ± 0.05				
			0.59	0.38	0.49 ± 0.11				
	RF	–	0.54	–	–				
			0.74						
			0.11						
			0.38						
	SVM	–	0.71	0.44	0.58 ± 0.14				
			0.89	0.76	0.83 ± 0.07				
			0.69	0.36	0.53 ± 0.17				
			0.61	0.25	0.43 ± 0.18				

[a]drone images taken only at 10 and 15 m. Classification was done only with 4 classes because only 4 features were present

[b]drone images taken only at 15 and 20 m instead of 18 m. Classification was done only with 4 classes because only 4 features were present

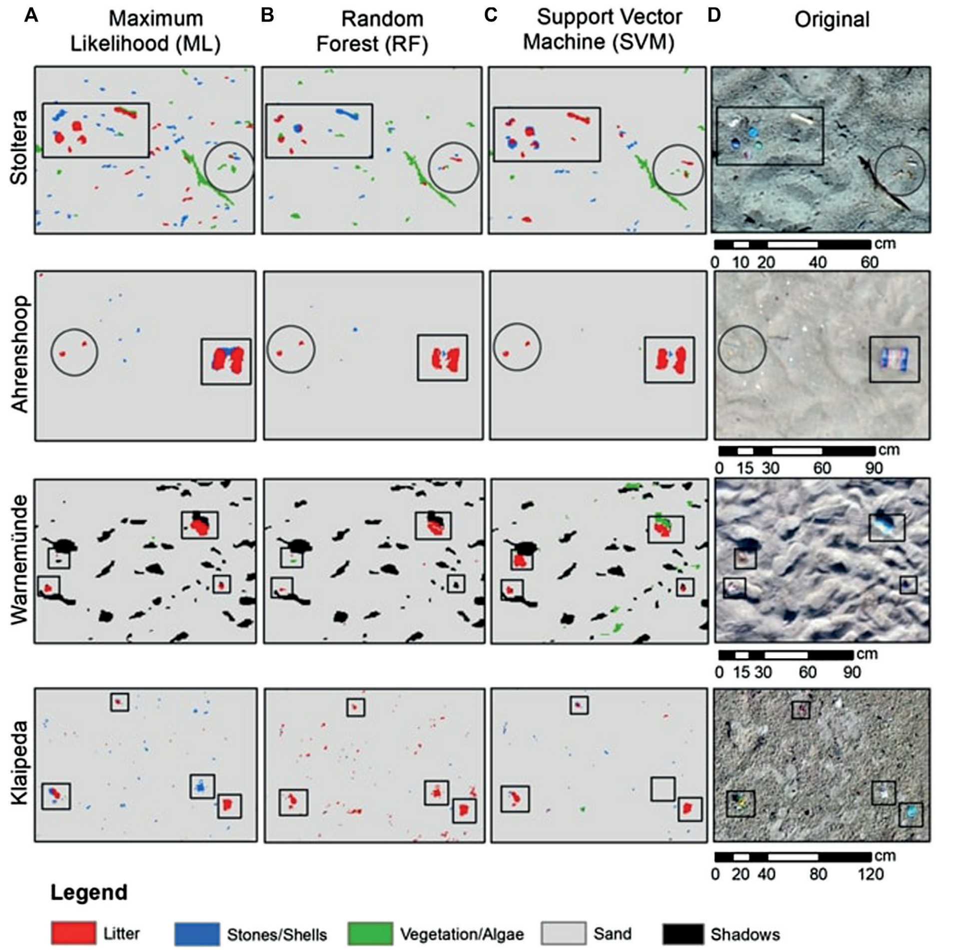

FIGURE 4 | Comparison of supervised classification with four classes with the algorithms ML, RF, and SVM on erial images at 10 m for the site Stoltera, Ahrenshoop, Warnemünde and Klaipeda. Each close-up image shows litter objects on the recovery site **(D)** and their classification result **(A–C)**, such as litter objects of different sizes (square) and cigarette butts (1–2.5 cm) (circle).

The criterion to "select >20 training samples" was not possible to fulfill in all beaches and taking a larger amount of training samples in the small recovery area contradicted the goal of the semi-automatic classification. For the object of interest (i.e. litter), most beaches had at least 20 training samples. For Klaipeda, which had the lowest density of litter in the recovery area, 10 training samples were chosen. Since stones and shells were not easy to distinguish from white or black objects (e.g., litter or algae pieces) from the spectral profiles, only a few samples were taken based on their shape and distance from algae or water, to avoid misclassifications.

Object-Based Classification

The accuracies of image classification for recovery experiment (5×10 m) are shown in **Table 1**. The classification with four

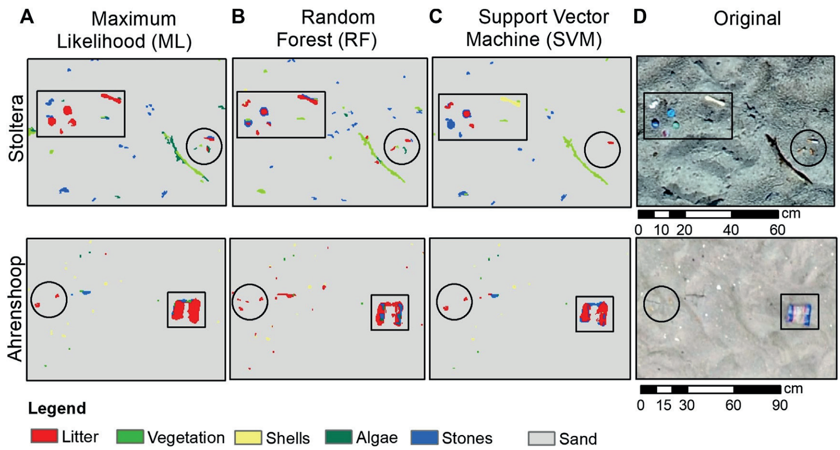

FIGURE 5 | Comparison of supervised classification with six classes with the algorithms ML, RF, and SVM on erial images at 10 m for the site Stoltera and Ahrenshoop. Each close-up image shows the distribution of litter objects on the recovery site **(D)** and their classification result **(A–C)**, such as litter objects of different sizes (square) and cigarette butts (1–2.5 cm) (circle).

classes showed total accuracies (TA) that ranged between 36% and 90% for ML, 54% and 73% for RF and 44% and 76% for SVM, depending on flight height and site. Producer's accuracy (PA) for litter showed similar ranges: 45–100% for ML, 67–95% for RF and 61–100% for SVM. Whereas user's accuracies (UA) for litter were lower. Kappa values were in most cases >0.60 indicating that classification was better than random. Classification with six classes showed in general lower values for TA, PA and UA for all algorithms and sites. Here kappa values were in most cases <0.60 indicating that classification was closer to random.

In most cases, measures of accuracy (TA, PA, and UA) decreased at images taken at higher flight altitudes. Classification of images taken at 10 m showed highest TAs, highest PA for litter classification and highest kappa values in most sites for the three algorithms. In some cases, higher TAs were also seen at images taken at 15 m or 18 m; however, this was mainly due to higher accuracies in classes other than litter. User's Accuracy (UA) for litter was lower for all classification algorithms, with values of 18–88% for ML, 8–39% for RF and 14–75% for SVM with four classes and 15–70% for ML, 2–16% for RF and 16–99% for SVM with six classes, depending on flight height and site (**Table 1**).

Due to a lack of replicates, an assessment of significant differences for measures of accuracy between algorithms was not possible to carry out and thus is not possible to statistically assess if an algorithm performs better than another. Nevertheless, **Table 1** shows that no clear differences were found between algorithms for samples taken at different sites. Similarly, no clear differences were observed between measures of accuracy for images taken at different heights, which in general showed low standard deviations from the mean.

The resulting classified images showed that ML and SVM gave a better representation of litter and background features in contrast to RF (**Figure 4**). In the case of Warnemünde, similar classifications were seen between the three algorithms but SVM showed misclassifications between vegetation/algae and shadows (**Figure 4**). For 6-class classification, these results were similar, but as more classes were used, more detail was defined and misclassifications were seen between shells and white litter objects (**Figure 5**). In general, both ML and SVM were able to classify meso- and macrolitter size with varying accuracies relative to sand color, background substrate, weather conditions and litter objects.

The classification of 100 m beach transects (at 10 m flight height for German sites and 15 m for Klaipeda) showed lower accuracy values than achieved on the recovery experiments, independent from site and image resolution. Classification with four classes showed kappa values between 0.23 and 0.53, which indicated that classification was rather random among different algorithms and no single algorithm could show a good performance in all cases (**Table 2**). Similar patterns were seen for the classification with six classes. The high range of difference for PA and UA for litter is due to how AAPs are placed on the image, sometimes hitting only one or no litter item, which skewed the results to either extreme (0 or 100%).

The classified 100 m beach transects showed similar classification patterns as in the recovery experiments but could not be representative of the litter found on the sites during collection (Stoltera: 174 items, Warnemünde: 167 items,

TABLE 2 | Accuracy of image classification on 100 m beach transects at 10 m flight height with 4 and 6 classes (litter, vegetation, algae, stones, shells and sand) for each site, algorithm and flight height. The values are presented as percentage from top to bottom: Total Accuracy (TA), Producer´s accuracy (PA) of litter class, User´s accuracy (UA) of litter class and kappa value of agreement (k).

Algorithms/Sites	Stoltera		Ahrenshoop		Warnemünde	Klaipeda
	Four classes	Six classes	Four classes	Six classes		
ML	0.44 0 0 0.27	0.25 0 0 0.11	0.55 1 0.007 0.39	0.64 0 0 0.56	0.47 0.25 0.02 0.31	0.54 1 0.02 0.37
RF	0.72 0 0 0.49	0.39 0 0 0.15	0.51 0 0 0.35	0.57 0 0 0.46	0.74 0 0 0.54	0.39 1 0.02 0.23
SVM	0.66 0 0 0.36	0.36 0 0 0.13	0.44 1 0.01 0.31	0.74 1 0.04 0.64	0.73 0.25 0.11 0.52	0.52 0.75 0.03 0.34

TABLE 3 | Cost-efficiency analysis for UAV and spatial-OSPAR for beach litter monitoring methods. The values are based on our experience taking into account the MSFD guidelines (JRC, 2013) and federal state authority staff salaries (37.5 € per hour) for a monitoring of four beaches, four times a year. In bold are shown the scores for cost and efficiency, giving the cost-efficiency score.

Costs	Description	Items >2.5 cm 100 m monitoring		Items >50 cm 1 km monitoring	
		UAV	Spatial-OSPAR	UAV	Spatial-OSPAR
Investment and initial test for implementation[a]	Costs of equipment, software, methodological tests in the field, training for field work and analysis	48,000 €	15,100 €	48,000 €	15,100 €
Annual office costs[b]	Orders, selection of sites, drone permissions and licenses, reporting, annual replacement costs for materials	10,000 €	10,000 €	10,000 €	10,000 €
Annual field/lab costs[b]	Travel to site, survey, analysis of data	10,600 €	5,800 €	16,000 €	4,000 €
Annual running costs		20,600 €	15,800 €	26,000 €	14,000 €
Total annual costs[c]		36,600 €	20,833 €	42,000 €	19,033 €
Person hours/year		1,296	768	1,440	720
Cost score		**3**	**4**	**3**	**4**
Efficiency					
Accuracy		3	4	5	5
Reproducibility		5	3	5	5
Flexibility		1	4	2	4
Quality		3	5	4	4
Efficiency score		**3.0**	**4.0**	**4.0**	**4.5**
Cost—efficiency		**9.0** Low	**16** High	**12** Moderate	**18** High

[a] *One-time investment to be done every 3 years, considering a drone lifetime of 3 years and renewal of training.*
[b] *Considers brutto salary for a federal state authority in Germany (37.50 € per hour).*
[c] *Considers a third of the investment and initial costs added to the annual running costs.*

Ahrenshoop: 77 items and Klaipeda: 214 items) (**Supplementary Figure S7**). **Figure 5** shows the classification results with highest TA, PA for litter and kappa values for each site (seen at **Table 2**). Both images and confusion matrices showed that misclassifications occurred in all algorithms (**Supplementary Table S2**). ML showed misclassification between litter and vegetation in Warnemünde (**Supplementary Figure S12**) and between vegetation, stones and litter in the classification with four classes in Ahrenshoop (**Supplementary Figure S10**). RF showed an overestimation of litter abundance in Klaipeda (**Supplementary Figure S13**) and in the classification with six classes in Ahrenshoop (**Supplementary Figure S11**). SVM misclassified vegetation and litter in Stoltera (**Supplementary Figures S8, S9**) and stones and litter in Klaipeda (**Supplementary**

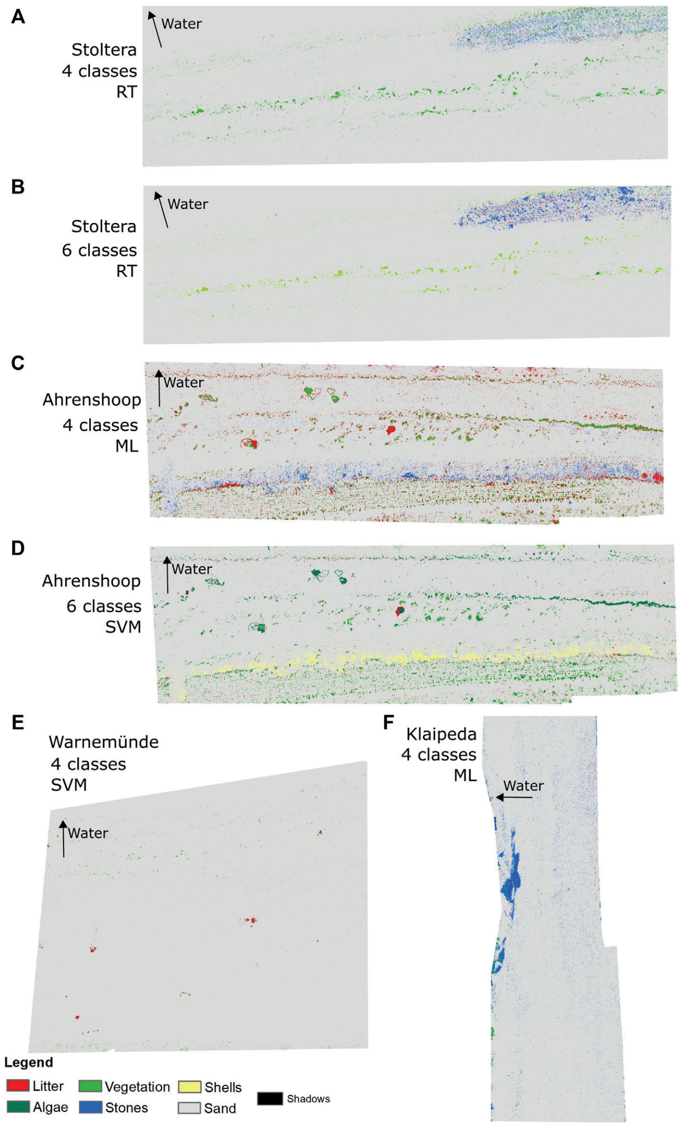

FIGURE 6 | Object-based supervised classification of 100 m beach transects taken at 10 m flight height. Only the results with best total accuracy (TA), producer's accuracy for litter (PA) and kappa value of agreement for with 4 and 6 classes are shown for each site: Stoltera **(A,B)**, Ahrenshoop **(C,D)**, Warnemünde **(E)** and Klaipeda **(F)**.

Figure S13). Objects that were correctly classified were anthropogenic items (beach tents of ca. 2 m in Warnemünde–**Supplementary Figure S12**—and Ahrenshoop–**Supplementary Figures S10, S11** classified as litter), algae and beach wrack in Stoltera (**Supplementary Figure S8**) and Ahrenshoop (**Supplementary Figure S10**), vegetation (**Supplementary Figure S10**) and shells (**Supplementary Figure S11**) in Ahrenshoop, and stones in Klaipeda (**Supplementary Figure S13**).

Time and Cost-Efficiency

As seen on **Table 3**, the UAV spatial method for 100 m and 1 km beach monitoring involves higher initial costs and about two times more costs and time effort for field work and analysis than the spatial-OSPAR method. The higher investment costs for the UAV method are related to software costs, since license software is often required within official federal agencies. If these software costs were not considered, the investment costs would decrease to only 3,000 € for the drone and other materials. Costs for testing period of implementation were higher for the drone method, estimated as 30,000 € for the 100 m and 1 km monitoring vs. 15,000 € for the spatial-OSPAR method. Office costs are the same for both methods. Annual running field costs (survey on site) were lower for the UAV method at 100 m beach transects (1,800 € vs. 2,400 € for the spatial-OSPAR), but higher once spatial extension increased to 1 km (2,400 € vs. 1,800 € for the spatial-OSPAR method). Annual running costs for analysis of the data (lab work) was considerably higher for the UAV method than for the spatial-OSPAR method (4,800 € vs. 2,400 € for 100 m and 9,600 € vs. 1,200 € for 1 km) (**Table 3**).

The overall cost-efficiency score for beach litter monitoring was 9–12 (low to moderate) for the UAV method vs. 16–18 (high) for the spatial-OSPAR method.

DISCUSSION

Lessons Learned From Object-Based Classification

Results from the recovery experiment showed that litter sizes >2.5 cm (i.e. macrolitter size) were the minimum size detectable. PAs for litter for the recovery experiments at different sites were between 77% and 100% with kappa values between 0.43 and 0.87 for images taken at 10 m height. These accuracy values were comparable to those obtained through visual screening of the same images (>87%, mean 99.4% ± 16.2). Even if smaller litter items were detected and classified (e.g., **Figures 4**, **5**, cigarette butts <2.5 cm), in reality many were misclassified. Another study also showed limitations in the detection of smaller items size, where items <4 cm were also most misclassified (Martin et al., 2018). TA was lower for classification into six vs. four classes (**Table 1**), but the PA for litter was in some cases similar, reaching values between 70 and 80%. In the 6-class classification, white and dark litter items were better classified than with the 2-class or 4-class classification (**Supplementary Figure S5**), but at the same time introducing more classes increased the complexity of the image.

The results from visual screening and spectral curves gave an initial indication of misclassification. Objects with a flat spectral curve (e.g. white shells and black stones) in colors white, black, transparent and brown, and litter which did not present any consistent curve (**Supplementary Figure S6**) were most misclassified on RGB images, whereas the objects of bigger size (>2.5 cm) and bright colors were correctly classified as litter (e.g. **Figure 4**). This is because object color, weather, light conditions and background substrate influence DN values and thus classification. In addition, the selection of training samples based on DN values depends on the judgment of the observer, increasing chances of error and misclassifications. Furthermore, it was not possible to establish whether one algorithm can cope better with background complexity than others, since factors like weather conditions differed in each site. We suggest that the higher complexity of sand and background substrate challenges segmentation of the image, which in turn, influences classification results. This was also observed by Martin et al. (2018) where shadows, vegetation and non-uniform background as well as the variability of each item within the same category (different sizes and colors) presented limitations in classification. In our study, as complexity of the background increased, the use of more classes became beneficial (e.g. in Ahrenshoop, **Supplementary Figures S10, S11**). However, in order to derive accurate statistics, the use of replica on each site and condition as well as further explore the influence of litter quantities and background substrate should be explored.

No clear differences of performance accuracy could be assessed between the algorithms; however, in contrast to previous studies, RF was the algorithm that presented most problems in performance in our images (**Table 1**). Martin et al., (2018) used RF classification obtaining an accuracy of 61.8% for detection of litter, 39.5% total accuracy and F-score of 0.13. Their classification presented an overestimation of 5-times due to false positive items, as similarly seen in the classified images with RF in our study. Another study by Goncalves et al. (2020) at beaches in Portugal also used RF, obtaining 75% sensitivity (≈Producer's accuracy) and 73% positive predictive value (≈User's accuracy) with a F-score of 0.75. These studies used approaches related to changes in the color space of spectra (Martin et al., 2018; Goncalves et al., 2020) which were not used in this study.

Observations of the classified images from recovery experiments suggest that ML better highlighted small features (stones or shells) (**Figure 4**, **5**) but did not necessarily classify litter better (**Table 1**), yet bottle caps and larger macrolitter were detected. In contrast, SVM gave less importance to small features leading to less noise from stones, shells or sand heterogeneity within the images. Still, small objects (also litter) were well classified in most cases, up to large mesolitter sizes like cigarette butts (**Figures 4**, **5**). Some studies suggest that a higher litter abundance leads to higher detection of litter by RF and other algorithms (Martin et al., 2018; Atwood et al., 2018), which was not observed in our study.

The image classification used in this study did not provide a distinction of litter composition and only focused on detection of litter items to provide an estimation of abundance and distribution. Based on the litter collected on site, the highest amounts of litter were in the categories plastics and paper (mainly due to cigarette butts), mainly macrolitter size of white or brown color and colorful mesolitter items (**Supplementary Figure S7**). Our results showed, however, that GIS classification based on RGB data was not satisfactory to provide estimations of abundance, since litter items were not possible to identify from the classified images at large spatial scales (100 m beach transect). TAs at the 100 m beach transects were much lower than at recovery experiments and PAs for litter were in most cases 0% (**Table 2**). This may be due to uncertainties in the method, because accuracy assessment depended on whether one or more points hit a litter object or not, bringing accuracy to extreme values of 0 or 100%. Due to the low segment size used for segmentation, large items were constructed with several segments, thus litter "objects" could not be counted as such in the classified images since the number of segments per item would overestimate the real count. Future studies should consider taking the GPS coordinates of litter items as a method to get reference data for larger transects.

Our analysis method did not prove to be sufficiently accurate or time-efficient. It is important to consider other methods for analysis, while following requirements for official beach litter monitoring. As technology develops and advanced equipment becomes more accessible, many of the limitations encountered in our study (mainly related to image resolution and processing time) will be overcome. Other methods including deep learning have demonstrated to be an alternative for the classification of objects on RGB images since it does not rely only on DN values (Fallati et al., 2019). In their study, object recognition reached a sensitivity (≈Producer's accuracy) of 67%, positive predictive value (≈User's accuracy) of 94% and F-score of 0.49, arguing the tool can be well used for the monitoring of litter and detection of hotspots in the study sites.

Strengths and Limitations of Consumer Drones for Beach Litter Monitoring

Taking into account our experiment results and assessment on cost and time efficiency, drones are still a method that needs to be explored and adjusted for efficient monitoring. The images from drones provide high spatial resolution which is required for the detection of small litter items. Our results showed that litter sizes >2.5 cm (i.e. macrolitter size) were the minimum size detectable. Even if smaller litter items were detected and classified (e.g., **Figure 4**, cigarette butts <2.5 cm), in reality many were misclassified. Thus, the accuracy of consumer RGB drones can be regarded as high (**Table 3**) for large particles but decreases with smaller item size and additionally depends on parameters such as item color, shape and weather conditions. These limitations could be overcome with more advanced drone sensors (e.g. multispectral) or the use of other analysis methods (e.g. deep learning) which increase accuracy; however, this would involve higher costs and expertize. In terms of type of data obtained and quality, our results suggest that the drone method (with RGB camera) can only provide data on the number of items and spatial distribution (moderate to high quality), in contrast to the spatial-OSPAR method where litter objects are collected by hand and can be better visualized to define also type of item and material, and give indications of pollution sources (**Table 3**).

A clear strength of drones is reproducibility (**Table 3**). Our results showed that the mapping of sites can be easily carried out after simple training of staff with the help of free mapping apps. These apps automatically map a site of interest at a set height, speed and area, enabling long term monitoring of the same site under consistent conditions. Although our analysis method did not prove to be sufficiently accurate and time-efficient, analysis of data in general would follow a strict protocol, carried out semi-automatically, decreasing chances of human error once the method is set up and sufficiently evaluated. For the 100 m OSPAR beach monitoring it is known that a difference of at least ± 10% is common, depending on who is carrying out the field work (Schernewski et al., 2017). In this respect, the drone method shows very high reproducibility in contrast to moderate reproducibility for the spatial-OSPAR method, and comparable values for 1 km beach transects (**Table 3**). Nevertheless, our own experiences showed that drone and GIS based monitoring is time-intensive (creation of orthomosaics 2–8 h, classification of the images, 3–8 h) and analysis of the images requires higher skills than for data obtained with an adapted spatial-OSPAR method.

Flexibility was the main limitation for monitoring with commercial drones in contrast to current monitoring methods (**Table 3**). The drone method depends on wind, weather and light conditions and can hardly be applied according to a fixed timetable. However, the dependence on weather conditions is a factor that all remote sensing studies need to consider (Murphy, 2015). At our study sites, ideal weather conditions initially involved wind speeds <20 km/h and enough sun light; however, overcast conditions and wind speeds of 27 km/h at Ahrenshoop also demonstrated good results (**Table 1**: **Figures 4**, **5**). Cloudy conditions showed best image outputs to avoid direct sunlight and shadows which led to sun glint and darker areas that disturbed image classification (**Supplementary Figures S8, S9**). ND Filters helped to minimize the reflection from sand under strong sunlight but shadows and sun glint could not be fully corrected. Issues with GPS signal, battery life (max. 20 min) and compatibility between smartphone device and mapping apps were also limitations encountered during our sampling. In addition, drone licenses are nowadays needed for all types of aerial drones and legal permissions are required at most places in Germany and limited to zones outside nature protected areas and of high urban density or conglomerations of people (§ 21a LuftVO, BMVI, 2017). From December 31, 2020, new EU regulations will apply and replace national regulations for each country (European Union Avitation Safety Agency, 2020).

Another important factor to discuss is the common natural trade-off of remote sensing approaches where decreasing flight altitude increases image resolution, but also decreases the area of coverage, increasing post-processing times and costs (Murphy, 2015). The large number of images obtained (44–234 images for recovery experiments and 459–1,247 images for 100 m beach transects) at 10 m led to high processing time for orthomosaic creation (12–24 h). Drone images in our study had a high spatial resolution (2.7–8 mm, 20 MP camera) and litter objects were possible to see on images taken at all flight heights, but higher flight altitudes (e.g., 18 m) were not enough to classify objects (i.e. stones, shells, vegetation) accurately. Low flight height has also been related to blurry images and vigneting effect especially on sites with homogenous ground, like sand, which hinders orthomosaic construction (DroneDeploy, 2020). Studies that carried out mapping at much higher altitudes, focused on litter patches or much larger litter at the coastline or rivers (Atwood et al., 2018; Deidun et al., 2018) or combined geomorphological and hydrodynamic variables into one model that allowed more specific detection (Goncalves et al., 2020).

Contrarily to our results, a recent study using a similar set up suggests drone survey to be a cost-efficient method for litter quantification, however their study inspects a beach area of 20 × 20 m by visual screening done by people (Lo et al., 2020). The higher costs, and thereby lower cost-efficiency suggested in our study are likely related to the method used for analysis and the larger areas of beach inspected, as required by OSPAR (2010).

The main constraint for remote sensing of plastic litter is the various shapes, dimensions, colors and materials in which litter is present, making its recognition complex. Litter that is partially or completely buried or hidden between the back vegetation are not easily detected (Kataoka et al., 2018), especially with colors white, black, brown and transparent, as seen in our study. NIR spectroscopy with a MicroPhazir hand-held device is used to complement OSPAR studies and obtain more detailed information on material composition of mesolitter (Haseler et al., 2018; 2019); however, to our knowledge there is no published study using multi- or hyperspectral data on drones for the purpose of marine litter monitoring. Methods by Acuña-Ruz et al., (2018) used supervised classification for the detection of Styrofoam and other macrolitter items (>0.5 m^2) on hyperspectral data using Visible and Near Infrared (VNIR), Short Wave InfraRed (SWIR) and Thermal InfraRed (TIR) wavelengths of satellite imagery for the creation of a spectral library of macrolitter items and natural features at the beach (e.g., sand, algae, stones and shells) for classification. The spectral signature of marine plastics has shown to have three absorption features at 1,215 –1732 nm (Garaba et al., 2018) as well as 2,313 nm specifically for PE (Levin et al., 2006) and between the blue and green bands and NIR spectrum for the detection of Styrofoam and other macrolitter items at the beach (Acuña-Ruz et al., 2018). Although the use of multi- and hyperspectral data can provide more detailed data, it also implies higher costs due to equipment and expertize needed.

Application of Aerial Drones as Official Beach Monitoring Methods

The MSFD encourages developing a comprehensive knowledge on the sources and sinks of marine litter to adopt policies that adapt to its current status. In the OSPAR guideline, currently in use at the Baltic, trends on abundance and types of litter are assessed every 3 months (OSPAR, 2010). Fulfilling the requirements from the MSFD and carrying out monitoring for all marine compartments to get a complete overview of the marine litter problem can be challenging in time and cost efforts. The data acquired needs to be reliable and accurate for the design of mitigation strategies. With drone-based monitoring, efforts during sampling can be reduced and the fatigue aspect and visual differences can be eliminated if automatic detection is carried out. However, as it is common when using remote sensing approaches, implementation costs for the drone-based method are higher (Murphy, 2015) in contrast to OSPAR, as also seen in our results. In addition, the skills needed for analysis require prior professional training and longer processing times, leading to higher annual running costs. Furthermore, the drone-based method requires the removal of litter, when carried out within a monitoring program. Thus, despite a shorter time spent at the field and higher reproducibility, the implementation of consumer RGB drones as beach monitoring strategy involves significantly higher costs, lower accuracy and provides less information on the type of litter and material, thus can hardly be regarded as a cost-efficient tool for this purpose in southern Baltic Sea beaches.

Nonetheless, UAV-based monitoring has proven successful at other sites; and comparing our results to previous studies already suggests that accuracy results depend upon the method chosen for image analysis. Drones have been used for the monitoring of litter in the Maldives (Fallati et al., 2019) and Maltese islands (Deidun et al., 2018), showing satisfactory results in countries of comparable pollution levels. These studies also highlight the importance of density and distribution maps (Deidun et al., 2018); data that is not normally obtained from current OSPAR monitoring. UAV-based methods could also become interesting for highly polluted sites like Indonesia (Purba et al., 2019), India (Kaladharan et al., 2017) or the Mediterranean coasts (Vlachogianni, 2019) to give a fast overview of litter abundance and distribution to design fast removal and mitigation strategies.

Although drones did not prove successful at beaches in our study, other sites become of interest to further explore this tool. At the Baltic Sea, many beaches cannot fulfill the OSPAR criteria, with beaches at the north (e.g., Finland, Sweden) having rocky coasts and cliffs not accessible for monitoring (Schernewski et al., 2017) where drones could also become a helpful monitoring tool. Furthermore, drones could also expand our understanding of marine litter pollution by covering the back of the beach, dunes, river mouths, fjords and the sea to monitor floating litter, as these sites have not yet been considered during monitoring approaches or by default require more expensive equipment (e.g., like monitoring at sea, JRC, 2013). Drones could also serve to assess pollution levels of proximate urban areas that work as sources of pollution, as well as after specific weather events, disasters like tsunamis or storms (Murphy 2015; Kataoka et al., 2018), or even social events. Moreover, drone methods allow for storage of data long-term which can take into account physical factors (like weather, light conditions and geomorphology of the beach) for more spatio-temporal analysis (Kataoka et al., 2018). Due to the high initial investment required in remote sensing methods, it becomes necessary decreasing costs through opportunistic research, partnerships and collaborations between members of the state and the research community (Murphy, 2015).

Drone sensors for multi- or hyperspectral data operating in the VNIR and SWIR domain are still expensive, nevertheless, the fast development of technology and lower costs for drones and software suggest future studies could provide promising results and cover this niche. In this sense, we suggest that monitoring of litter items <50 cm and less polluted areas should continue to occur under current *in-situ* methods, whereas for highly polluted sites with macrolitter and sites with litter items >50 cm, drone monitoring could become an option in the future.

CONCLUSION

Although the results from image acquisition and drone performance at recovery sites were promising, methods for litter detection and classification need to be further tested, especially when applied to larger spatial scales. In frame of the EU Marine Strategy Framework Directive (MSFD), this study showed that drone monitoring with an integrated RGB camera is not suitable to complement 100 m monitoring for Southern Baltic beaches; however, there is potential for improving cost and time efficiency in the 1 km monitoring for litter >50 cm with alternative methods to decrease processing time while increasing accuracy of data. Drone monitoring has the potential to expand spatial coverage to larger areas, monitor fragile or inaccessible sites and provide maps of litter abundance and distribution, especially in the context of hotspots. However, all these alternative methods need to consider cost-efficiency in factors such as type of equipment, processing time, effort and level of expertize needed for the analysis of larger and more complex data for establishing long-term monitoring strategies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

G-ES developed the methodology, carried out the field work, took care of data analyses and led the article writing. MH contributed to the research design, acquired the equipment and permissions, supported the field work and commented the article. NO and GS developed the general concept, supervised the work, and supported the article writing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.560237/full#supplementary-material.

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PAPER III

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Article

Emission, Transport and Retention of Floating Marine Macro-Litter (Plastics): The Role of Baltic Harbor and Sailing Festivals

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Abstract: Every year, harbor and sailing festivals attract close to 20 million visitors in the Baltic Sea region, but their consequences on marine litter pollution are still unknown. We combine field studies with model simulations and literature reviews to quantify the annual emissions of floating macro-litter and to assess its retention in estuaries and role in Baltic Sea pollution. Results focusing on Hanse Sail in Rostock and Kiel Week are extrapolated to the entire Baltic Sea region. After the Hanse Sail 2018, the harbor pollution amounted to about 950 floating macro-litter particles/km²; 85–90% were plastics. We calculated an emission between 0.24 and 3 particles per 1000 visitors, depending on the year and the waste management system. About 0.02% of all waste generated during a festival ends up in the harbor water. The Hanse Sails contributes less than 1% to the total annual macro-litter emissions in the Warnow estuary. Model simulations indicate that over 99% of the emitted litter is trapped in the estuary. Therefore, Hanse Sails are not relevant to Baltic Sea pollution. The extrapolated Baltic-Sea-wide annual emissions are between 4466 and (more likely) 55,830 macro-litter particles. The over-30 harbor and sailing festivals contribute an estimated <0.05% to the total annual macro-litter emissions in the Baltic Sea region.

Keywords: Kieler Woche; Hanse Sail; Baltic Sea; macro-plastic; deposition; waste management; public awareness; citizen science; model simulations; marine litter

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1. Introduction

For the year 2010, it was estimated that 275 million metric tons of plastic waste were generated worldwide and that between 4.8 and 12.7 million metric tons entered the ocean [1]. Results by Erikssen et al. [2] indicate that macro- (>25 mm) and meso-plastic (>5 mm) together have a mass share of 86% of global marine plastic pollution and are, quantitatively, the most important size fraction. This is the reason why macro-litter is still a research focus. Marine macro-plastics (>25 mm) can be distinguished into floating and sinking material depending on their density. Floating material can be transported by wind and currents over long distances [3], but a large share is accumulated at beaches in the vicinity of the emission pathways via surface wave activity [4,5].

Globally, it is estimated that rivers transport between 1.15 and 2.41 million tons of plastic waste to the oceans, and river transport is considered to be the major pathway for marine litter [6]. For Europe, it is assumed that between 307 and 925 million macro-litter pieces enter the seas via rivers and that 82% are plastics [7]. The largest absolute emissions of floating macro-litter (>25 mm) to the Baltic Sea are calculated to take place via major rivers, namely, the Odra, Vistula, Nemunas, Daugava and Newa (above 500,000 pieces per year and river) [7].

Besides providing important information for macro-litter management, the emission data have been utilized to simulate transport, behavior and deposition in several seas, such as the North Sea [8], the Mediterranean Sea [9], or the Baltic Sea [10]. The model simulations are based on many simplifications. One major weakness is that the retention of litter particles in the coastal zone is neglected [5,11]. Especially in the Baltic Sea, with its complex coastal zone and a multitude of fjords and lagoons, it can be expected that much of the emitted macro-litter is kept back, i.e., deposited on the sea bottom near the coast or washed ashore, and does not reach the open Baltic Sea. Retention in the coastal zone is, alongside retention in rivers, still a missing link in our knowledge that needs to be addressed.

Enclosed seas such as the Baltic Sea, the Black Sea and the Mediterranean Sea are considered as potential hotspots for marine litter (plastic) pollution due to their highly populated coastlines (relative to the sea surface area) and their restricted water exchange (e.g., [12,13]). In a recent study, the annual flux of macro-plastic to the Baltic Sea, excluding riverine loads, is estimated to be between 73 and 226 macro-plastic pieces per 100 m coastline, depending on the urbanization level [14]. This is in the same order of magnitude as riverine inputs to the Baltic Sea [10]. According to Tsiaras et al. [14], the total calculated input of macro-plastic from coastal cities to enclosed seas can far exceed the input via rivers. These calculations are based on population data and sometimes take into account sewage treatment data. However, the present data on macro-litter emissions from coastal cities and along the coastline are highly uncertain because they are merely based on assumptions and calculations. This indicates an urgent need for concrete field studies on macro-litter emissions, especially from coastal urban areas to the sea.

In most parts of the Baltic Sea, coastal city centers do not host industrial ports anymore; instead, the city seaside has been transformed into leisure and recreation areas, hosting leisure boat marinas and offering water access for locals and tourists. The increasing number of people in the city harbor area may have increased emissions, but there is another aspect that moves city and leisure ports into the foreground. City tourism gained importance and the ports became tourist attractions. To promote city tourism, the number of sailing events and port festivals increased, and most cities host at least one port or sailing festival per year. Very large events, such as the Baltic Sail in Gdansk or the Kiel Week, last between four and seven days and report above three million visitors [15,16]. Located directly on the coast, the risk of marine plastic pollution during these events is high (e.g., [17,18]). In the Baltic Sea region, festivals might potentially be a significant source of macro-plastic pollution to the Baltic Sea. However, data concerning sailing events and festivals and their role in litter/plastic emissions to the sea are lacking.

Our overall aim is to gain an insight into the role of harbor festivals on floating macro-litter pollution. Our specific objectives are (a) the calculation of emissions during one major Baltic Sea harbor festival, the Hanse Sail in Rostock, Germany, based on field studies over several years; (b) model simulations on how macro-litter emitted in Rostock city harbor is transported and retained in the estuary as well as a quantification of how much is exported to the open Baltic Sea; (c) an analysis of changes in pollution and their reasons, additionally taking into account the Kiel Week in Kiel, Germany; and (d) the compilation of information about Baltic Sea harbor festivals and the extrapolation of the emissions to the entire Baltic Sea region to acquire an impression of the overall relevance of harbor festivals to the question of marine pollution.

2. Materials and Methods

2.1. Study Area

The cities of Rostock (210,000 inhabitants) and Kiel (246,000 inhabitants) are located in the western Baltic Sea and are the most important Baltic Sea harbor cities in Germany. With the Kiel Week (Kieler Woche) and the Hanse Sail Rostock, these cities host major annual sailing and harbor events. The Kiel week is the largest sailing event world-wide and the largest summer festival in the Baltic Sea region. In 2023, it attracted 3.8 million visitors during its nine days, the highest number ever recorded. More than 100 larger historic steam and sailing ships offered boat trips; over 4000 sport-sailors with about 1500 boats took part in the competitions; and 22 cruise ships visited the harbor during the event [15]. The Hanse Sail was founded in 1991 and always takes place on the second weekend in August, from Thursday evening until Sunday evening. In 2023, the Hanse Sail Rostock counted about 500,000 visitors over four days and about 150 ships offered boat trips for visitors [19]. Before the COVID-19 pandemic, for example in 2009, Hanse-Sails counted over 1 million visitors and, in some years, involved over 200 historic ships [20]. The Hanse Sail takes place in the southern part of the Warnow estuary in the city harbor (Figure 1b).

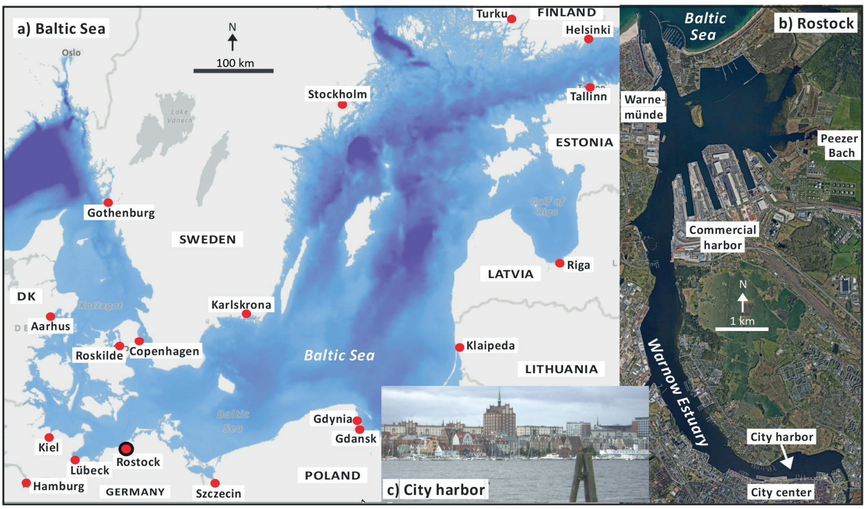


Figure 1. (**a**) The central and southwestern Baltic Sea region with major harbor cities and Baltic Sea bathymetry. (**b**) The Warnow estuary and surrounding areas of the Hanseatic city of Rostock (map based on Google Maps). (**c**) The city harbor of Rostock.

2.2. Sampling of Macro-Litter during Hanse Sails in Rostock

Field data were gathered during Hanse Sails in 2017, 2018 and 2019, before the COVID-19 pandemic, and in 2023, after the COVID-19 pandemic. During the pandemic, the Hanse Sails did not take place. The sampling concepts and methodologies strongly differed between the years, depending on staff availability as well as synergistic opportunities, such as co-operations with NGOs and public cleaning events. Our focus was on macro-litter above 25 mm, but cigarette butts were always taken into account.

During the Hanse Sail 2017, which took place between 10 and 13 August, a cleaning of floating macro-litter took place on Saturday, 12 August. Using 300 µm plankton nets on sticks, near-shore floating surface litter was sampled along the entire 2.2 km Hanse Sail festival waterfront, with a focus on locations where litter was trapped between ships. After the Hanse Sail, on 14 August, the second sampling took place using the same method. The particles were classified using a simplified OSPAR litter list [21].

In 2018, a public litter collection was carried out the day after the Hanse Sail, which took place between 9 and 12 August. The state of pollution before the Hanse Sail was not assessed. Over 20 persons with a total of 14 canoes cleaned the water surface of the entire Rostock city harbor (1.4 km²) of visible floating litter [22]. The participants were divided into nine groups and each group covered one city harbor sub-area (indicated in Figure 3). The particles where collected, weighed in the laboratory and classified according to the OSPAR litter list [21].

In 2019, the near-shore harbor surface water was cleaned, and the litter was removed the week before the Hanse Sail using a landing net (about 5 mm mesh size) from the harbor wall since much litter is temporarily trapped between boats. During the Hanse Sail 2019, sampling was conducted on Thursday evening, after the first day, on Friday evening, on Sunday morning, as well as on Monday morning, after the event. On Monday morning, landing nets were additionally used from a boat in the harbor. The particles were collected and, later in the laboratory, classified according to the OSPAR litter list [21].

In 2023, the Hanse Sail took place between 10 and 13 August and was accompanied by a data collection campaign. The sampling strategy was based on previous model simulations carried out for comparable wind situations. Weak winds with an average of 3 m/s (light breeze) dominated, and the average hourly maximum wind speed did not exceed 5 m/s. According to the official weather data for Rostock, during the first two days, wind directions between south and west prevailed, followed, subsequently, by turning winds [23]. During all four days, litter emissions were visually assessed three times a day by walking along the festival waterfront. Macro-litter on the floor, overflowing bins and other potential litter emission pathways to the harbor were documented. Additionally, litter particles floating on the sea surface near the harbor walls were photographed, the number estimated, and the type of particles was partly visually determined.

Reed belts around the city harbor were considered as a major trap for floating litter. Consequently, the day before Hanse Sail 2023, the water surface and selected reed belts around the harbor festival area were cleaned of floating litter manually by boat. The same took place on the water around the festival area. The litter was collected and analyzed according to the OSPAR item list [21]. The day after the Hanse Sail, the reed belt front was revisited again by one boat and all floating particles were collected.

2.3. Complementary Data on Ports and during Harbor/Sailing Festivals

To enable general information on macro-litter emissions during events and water pollution, several approaches were applied to strengthen the data and information basis.

Once a year in September, different environmental groups organize the Coastal Clean-up Day around the Warnow Estuary. The aim is the removal of litter from the coastal zone, including the water surface area. The number of involved citizens and the specific locations vary from year to year. In 2022, a total of 139 participants collected a total of 628 kg of macro-litter, including about 3500 cigarette butts, at 17 locations around the Warnow estuary. In 2021, 513 kg od litter were removed at 11 locations. Since 2017, the Citizen Science project, "Natur- & Erlebnisraum Warnow-Ästuar", carried out by the NABU Regionalverband Mittleres Mecklenburg e.V., has organized an additional clean-up in March. For one location, the coastline around the Peezer Bach (Figure 1), the common beach monitoring method according to OSPAR [21] was applied, including the protocol and the item categorization. The sampling covered 350 m of coastline and a 10 m strip landward and provided comparable and sufficiently reliable pollution data. The internal reports and datasheets were made available by NABU.

In early May 2023, we investigated floating macro-litter at four reed belts areas in the Warnow estuary (Figure 7). The sampling took place before new reed sprouts inhibited the sampling. It was carried out on foot and using a small boat. A one-meter strip of reed at the sea front was sampled, covering, altogether, about five kilometers of reed belts in the Warnow estuary.

During Kiel Week 2023, Hamburg Port Anniversary 2023, Warnemünde Week and Hanse Sail 2023, additional, alternative approaches to estimating the floating macro-litter emission to the harbor water were applied. One approach was a visual screening of the litter pollution on the floor. Two students recorded the macro-litter on the floor over several hours by walking over large parts of the festival areas. It was assumed that macro-litter that is closer than one meter to the waterfront ends up as harbor water. The results were extrapolated to the entire festival area, for the entire duration, and recalculated into emissions per visitor. Another approach was based on the total number of visitors and the total amount of officially collected waste weight by the city. The waste production in grams per visitor was calculated. This amount was recalculated into the number of litter items using the average weight of observed litter items.

To acquire an impression of past litter pollution during events, for Rostock and Kiel newspaper articles that were accessible via the Internet were analyzed. Additionally, the waste reports and management concepts of both cities and their development were analyzed.

To enable a quantification of the role of harbor events on macro-litter pollution in the Baltic Sea region, information from the Internet (search engine) and literature was reviewed. Data of over 50 events were compiled in a table, containing name and type of event, time, duration and frequency, number of local inhabitants and visitors, number of ships involved, geographical location and setting of the harbor, as well as costs and waste management concepts. For the 11 largest events, all necessary data could be compiled. For about 20 smaller events (e.g., River Harbour festival Turku, Ship day Helsinki, Archipelago Festival Karlskrona, Hajkutter Festival Nysted, Sail Aland, Haff Sail Ueckermünde, Hafentage Barth), as well as music festivals taking place in the harbor (e.g., Klaipėda Castle Jazz Festival), the number of visitors was partly estimated from publicly available photos.

2.4. Model Setup and Assumptions

Exemplary model simulations were carried out for Rostock harbor, covering the entire Warnow estuary, including the coastal parts of the western Baltic Sea. The model simulations involved two steps: first, a 3D hydrodynamic model calculated hindcast simulations for the years 2009 and 2010; second, the results were used for an offline Lagrangian particle-tracking approach. For the former, the general estuarine transport model (GETM) [24,25] with the General Ocean Turbulence Model (GOTM) [26] was used as the turbulence closure model. Previous studies with GETM/GOTM covered the entire Baltic Sea, and this enabled a coupling of the estuary to the Baltic Sea dynamic, which is imperative to reflecting the estuarine circulation properly.

The study area is numerically discretized on a structured grid with a horizontal resolution of 20 m and a vertical resolution of 25 terrain-following sigma layers. This very high spatial model resolution, implemented in a previous study [27], reflects the harbor infrastructure and bathymetry in detail and provided the precondition for sufficiently realistic model simulations. The meteorological forcing is calculated from the output of a reanalysis product of the German Weather Service (COSMO-REA6) with a temporal resolution of one hour and a spatial resolution of 6 km. Discharge data of the river Warnow were included as daily mean values. Details on boundary conditions, especially the exchange with the Baltic Sea, are provided in Lange et al. [27]. This includes a model validation based on salinity and temperature data. The results show that the model is very able to represent the field data in detail, and for the existing estuarine circulation.

The main output parameters were staggered horizontal current velocities on an Arakawa C-grid, horizontal eddy viscosity calculated using a Smagorinsky parameterization and bottom shear stress based on a quadratic drag, stored with five-minute resolution each. These were used as forcing inputs for the particle-tracking model ocean parcels [28]. Diffusion was considered using the Milstein scheme (first order). Particles were allowed to beach in coastal sections characterized by reeds and beaches. The model approach did not allow us to take into account the remobilization of litter that was previously beached.

2.5. Model Scenario Simulations

The model and Lagrangian plastic transport simulations covered the Hanse Sail in 2009 and in 2010. The years 2009 and 2010 were chosen because of contrasting weather conditions and high plastic emissions. The aim was to acquire an insight into transport and deposition patterns. The results were used for the planning of the field studies in 2023. The model simulations were not repeated for the year 2023 because of a lack of sufficiently highly resolved wind data. Further, the prevailing wind directions were sufficiently represented by the year 2009.

The simulations focused on floating macro-litter, mainly plastic. The group of floating polymers includes, for example, low- and high-density polyethylene (PE, 0.915–0.97 g/cm^3 density) and polypropylene (PP, 0.89–0.92 g/cm^3 density). These two polymers alone account for 36% (PE) and 21% (PP) of the global total of non-fiber plastics production and are commonly used for packaging, e.g., plastic bags, plastic films, and bottles. Other important floating polymers are cigarette filters (cellulose acetate; ~0.94 g/cm^3 density) and polystyrene objects and pieces (e.g., flower pots, yoghurt cups; 0.95–1.1 g/cm^3 density). All these polymers accounted for over 95% of all observed floating plastic particles during our studies. All these polymers show a similar behavior in the water, and it is assumed that floating plastic is transported passively within the upper 50 cm of the surface water layer. Wind-driven transport of particles floating above the water surface is not taken into account. The same is true for sinking plastic polymers. The simulations started with the beginning of the Hanse Sail and ended after 10 days.

3. Results

3.1. Hanse Sail Rostock—Floating Litter (Plastic) Particle Composition

During Hanse Sail 2017, floating litter along the festival water was collected on two Hanse Sail days. Altogether, 232 pieces of plastic were found: 33% cigarette butts, 16% food packages, 8% drinking cups, 5% plastic straws, 3% bottle caps and 3% bags, as well as 29% of other plastic pieces. This screening provided an initial insight but did not cover the entire Hanse Sail duration.

To acquire an improved insight into littering during the entire Hanse Sail duration, in 2019, a more detailed approach than in 2017 was applied. The full data are provided in Appendix A. The amount of collected floating particles was 1492 (502 on Thursday evening, 411 on Friday and 579 on Sunday/Monday). The share of plastic was above 90%; among them, 33% cigarette butts, 18% plastic bags, 10% food packages, 4% confetti, 2% cups, 3% caps, 2% bottles, 1% tableware and 1% firework pieces (Figure 2).

Figure 2. The pie chart shows the relative share of floating macro-litter item types. It is based on the 1492 particles collected in the Rostock harbor area during the Hanse Sail festival in 2019. The category "Other" indicates other plastic items. The photos indicate potential pollution pathways to the harbor water, namely, sea-gulls and inappropriate waste collection (data in Appendix A).

To acquire an insight into the total harbor pollution with floating litter, the monitoring of the Hanse Sail 2018 focused on the entire water surface area of the city harbor (Figure 3a). After the event, floating litter was collected, involving 14 boats (Figure 3b). Altogether, 1333 particles (plastic and non-plastic) with a total weight of 12.1 kg were picked-up from the water surface. Consequently, the average weight of the observed floating particles in the harbor in 2018 was 9 g per particle. The weight of single particles was not documented; therefore, additional statistical information cannot be provided. Over 90% of the particles were macro-litter, with a size above 25 mm. The share of plastic particles was about 85%, with 37% and 41%, respectively, polyethylene and polypropylene particles greatly dominating the plastic fraction. Among the plastic particles were 21% cigarette butts, 37% plastic food packages and cutlery, 10% drinking cups, 4% plastic straw, 2% plastic bottles and 1% bottle caps. A total of 27% were plastic confetti. The item categorization was slightly different compared to 2019.

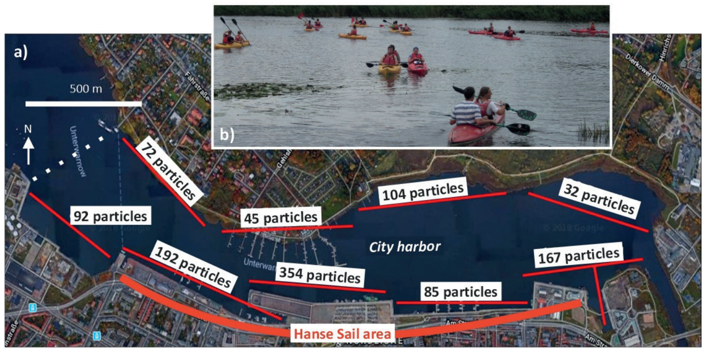


Figure 3. (**a**) Floating litter particles found on the water surface in different parts of the city harbor in Rostock after the Hanse Sail 2018 (data: Appendix B). The thick red line indicates the 2.2 km extent of the Hanse Sail activities along the south coast; the dotted white line indicates the boundary of the city harbor (map: GoogleMaps). (**b**) Photo taken during the public sampling activity.

The results show that plastic particles were always dominating and that cigarette butts were the most important floating item. The shares of all other items vary and depend on conditions and locations. The amount of confetti—and, in 2019, the high amount of advertisement plastic bags by one company—indicate that careless and/or accidental pollution plays an important role. Even seagulls can cause litter emissions to the sea if waste systems are overfilled or not adequately secured/covered (Figure 2).

3.2. Hanse Sail Rostock—Floating Litter (Plastic) Spatial Distribution

During the Hanse Sail 2018, the focus was on spatial pollution patterns. Wind from a westerly direction dominated most of the time [23] and favored litter accumulation in and around the city harbor. It can be assumed that the sampling after the Hanse Sail in and around the city harbor caught the vast majority of particles (Figure 3, Appendix B). The observed spatial pattern of litter particles shows litter along all shores around the harbor, with highest concentrations being directly in front of the Hanse Sail festival waterfront. Of the 1333 particles found, 190 particles present in the datasheets could not be spatially allocated and are lacking in Figure 3. The city harbor has a water surface area of about 1.4 km^2. The pollution of the city harbor surface water with macro-litter (including plastics) after the Hanse Sail 2018 was about 950 particles/km^2, and the pollution with macro-plastics alone was about 810 particles/km^2. These numbers include the front of the reed belts.

3.3. Hanse Sail Rostock—Floating Litter (Plastic) Emissions

The sampling methodologies and the data allowed for calculations of floating litter emissions to the city harbor during the Hanse Sail. The 1333 floating macro-litter particles found after the Hanse Sail in 2018 serve as a basis. It is assumed that the Hanse Sail had 1 million visitors (including locals, showman, salespersons); that 10% of the emitted litter to the harbor had left the city harbor area; that the survey covered only 50% of the harbor water surface area; that small particles, such as cigarette butts, that contribute over 30% of the floating litter (Figure 2), were not found; and that 25% of the found litter was already in the water before the Hanse Sail. Based on those assumptions, the emission is 3 particles per 1000 visitors or 3000 particles in total. In 2019, altogether, 1492 particles were found. The sampling was restricted to the harbor water near the festival area, but all particles, even very small ones, were collected. Following a similar calculation approach as for 2018, but taking into account the differences, we receive an emission of 3.7 particles per 1000 visitors or 3700 particles in total. The data suggest that close to 90% of it is plastics. The results of 2019 confirm the calculations of 2018 but have a weaker database.

During the Hanse Sail 2023, after the COVID-19 pandemic, macro-litter monitoring during and after the event was again carried out. Because of the different concept, the Hanse Sail 2023 had only half the amount of visitors compared to Hanse Sails before 2020. At the beginning of the Hanse Sail 2023, the amount of litter floating in the water along 2.2 km harbor walls was visually estimated, from about 2 m distance, to be about 150 pieces, but not removed (Figure 4b,c). The amount did not increase during the Hanse Sail; on the contrary, later lower numbers were estimated because of wind- and current-driven litter transport towards the open harbor water. As a consequence, after the Hanse Sail, a survey of the open water and fronts of reed belts in the harbor was carried out, similarly to that in 2018, but with only one boat and only for selected areas. Only 19 pieces were found, of which 14 were plastic pieces; among them were three food/sweet packets, three plastic cigarette box packaging, two small bags and only one cigarette butt. The macro-litter emission calculations are based on 500,000 visitors and the assumptions that 10% of the emitted litter to the harbor has left the city harbor area; that the survey covered only 20% of the harbor water surface area (including reed belt front); and that small particles, such as cigarette butts, were not found. A total of 15% of the found litter was assumed to be already in the water before the Hanse Sail because the cleaning did not cover the entire area. For 2023, this results in emissions of 0.24 particles per 1000 visitors or only 120 particles in total. The model simulations were used to evaluate our observed spatial pollution pattern, to refine the emission calculations, and to optimize the sampling campaign 2023. Despite that, we estimate the range of uncertainty for the calculated emissions to be at least +/−100%. However, this uncertainty estimation cannot be statistically validated. Even when taking into account the fact that the data basis is limited, it seems that a strong drop in the amount of emission took place between 2018/2019 and 2023.

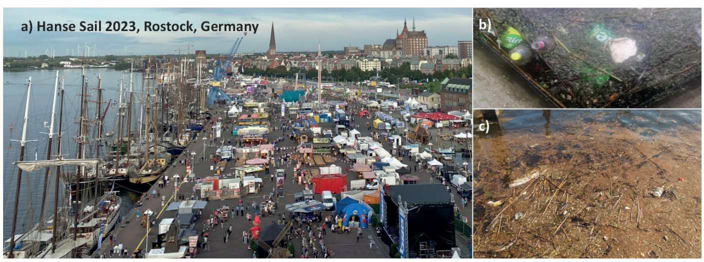


Figure 4. (**a**) The Hanse Sail in Rostock, Germany 2023. (**b**,**c**) Floating litter trapped between ships in Alter Stadthafen at the beginning of the Hanse Sail 2023.

Alternative calculations for the Hanse Sail and during other harbor events, using the total waste amount, the number of visitors and emission shares to the sea based on expert guesses, resulted in an unrealistically high total litter emissions to the sea (see Section 2.3). Calculations based on the observed litter in the festival area close to the water front ended up with very low total floating emissions in the harbor water. In both complementary approaches, the subjectivity and methodological weaknesses could not be improved sufficiently. Further, the two alternative macro-litter emission calculation approaches did not provide results that could be verified by observing floating litter concentration on the harbor water surface. As a consequence, the results were not used.

The total waste collected during the Hanse Sail 2023 by the City of Rostock was about 50 tons and the total number of visitors was 500,000 visitors. This means that every visitor generated about 100 g of waste. During Kiel Week 2022, altogether, 208 tons of waste were collected. Consequently, each of the about 3 million visitors produced 69 g of waste. During the Klaipeda Sea Festival, about 47 tons of waste were collected. Assuming 500,000 visitors, we end up with 94 g of waste generated per visitor. All numbers are based on personal communications by the cities. The amount of waste per visitor is comparable between the festivals, considering the uncertainties of the data. Taking the data of Hanse Sail 2018, where 12.1 kg floating litter were collected in the harbor, and assuming a total waste generation of about 60 tons, about 0.02% of all waste (in weight) produced during the event ends up floating in the harbor water.

3.4. Changes in Waste Management

The literature survey was meant to answer the question of why the person-specific emission of floating litter during Hanse Sail in 2023 was less than 10% compared to Hanse Sails before 2020. Data provided by the city of Rostock indicate that during Hanse Sail 2023, about 50 t of waste was generated, less than for Hanse Sails before 2020. This reduction in waste generation could be due to the lower number of visitors in 2023. Another important aspect is that the Hanse Sail concept has changed [29]. The number of stalls and drinks stands and their concentration at the sea wall, as well as the density of visitors along the coastline, were reduced. The modified concept enabled a better implementation of the waste management strategy, avoided extreme densities of visitors and is certainly another factor in the reduced litter emissions to the harbor.

Because of known littering problems, the city implemented an improved waste management system in recent Hanse Sails, including a deposit system for cups, the mandatory use of degradable tableware, free waste deposit containers for all ships, reusable fence fasteners, low-emission fireworks, nightly ground cleaning and an optimized waste bin distribution and emptying system [30].

The waste management approach during Kiel Week is comparable. The Kiel Week received the Platinum Level Certification of the Clean Regatta Program [31]. The 20 criteria include the elimination of single-use items (e.g., elimination of single-use water bottles, plastic straw, bags, dinnerware, water refill stations) and responsible waste management (e.g., green team, proper waste bin placement and signage paperless event management). This means that about 150 garbage workers take care of 1100 waste bins with capacities between 120 und 5000 L [15]. The Kiel Week aims for a sustainable events certification according to ISO 20121 [32].

Several waste management activities in Rostock and Kiel result from the European Union's policies and their implementation, for example, their ban on single-use plastic items like plastic plates, cutlery, straws, balloon sticks and cotton buds, which entered into force in 2021 [33]. In Germany, a deposit for plastic bottles has existed since 2003, which will be expanded in 2024. Further, in Germany, many types of plastic bags have been prohibited since 2022. Improved waste management systems can, at least partly, explain the strong reduction of floating litter that was observed during Hanse Sails between 2017 and 2019 and in 2023 as well. Our data do not allow for the assessment of the role of changes in perception and awareness of litter in the environment and changes in the littering behavior of visitors.

3.5. Hanse Sail Rostock—Litter Transport and Deposition Simulations

The first model simulations were carried out to support the design of the sampling campaign in 2023. Later model simulations used our calculated macro-litter emission values and were carried out with the aim to assess litter transport and deposition, as well as to quantify the litter export to the open Baltic Sea.

Figures 5 and 6 show the transport of hypothetical floating litter emitted to the sea during different Hanse Sails in August. It was assumed that 3000 floating macro-litter particles were emitted during the entire event, as calculated for the year 2018 (Section 3.3). For these scenario simulations, the weather conditions during the Hanse Sails in 2009 and 2010 were applied. Both years show contrasting wind directions and wind speeds temporally exceeding 7 m/s (4 Beaufort; moderate breeze). For the summer season, the wind velocities in 2009 and 2010, where above the average, were expected to show significant transport distances and representative spatial depiction patterns.

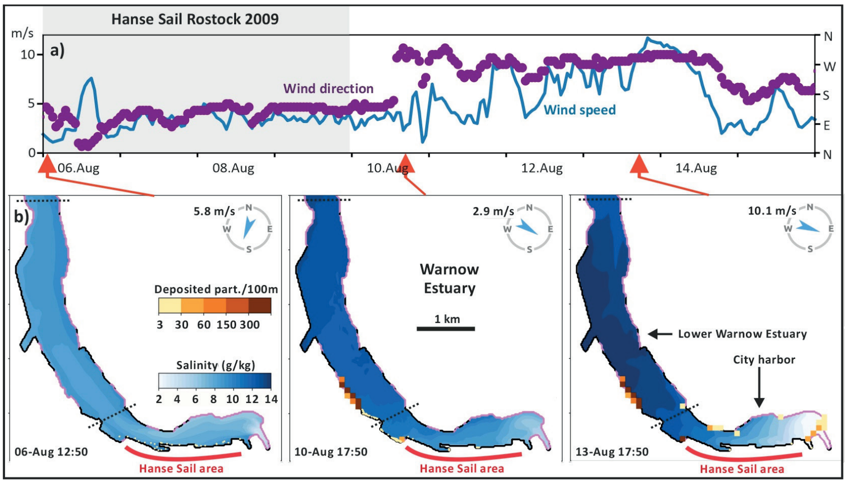


Figure 5. (**a**) Wind speed and direction during Hanse Sail 2009 that lasted from 6 to 9 August. The red arrows indicate the date and time of figure series (**b**). (**b**) The model simulation of floating macro-litter and the litter deposition along the shoreline for three dates. It is assumed that, altogether, 3000 particles were emitted during the event. Purple coastlines indicate accumulating shorelines; black colors indicate shorelines; the dashed line indicates the boundary of the city harbor. The model simulation movie shows the dynamic transport behavior in detail (Supplementary Material).

The model suggests that during Hanse Sail in 2009 (Figure 5), the gentle breeze (about 4 m/s) from easterly directions caused a floating litter transport along the coast towards the west. The model assumes that most litter is beached or trapped in reed belts about 3 km west of the Hanse Sail location. In the days after the Hanse Sail, which lasted from 6 to 9 August 2009, the wind speed increased and changed to southwesterly directions. The resulting currents transported several particles back towards the east and caused an accumulation in the eastern part of the city harbor.

During the Hanse Sail 2010, between 5 and 8 August (Figure 6), the gentle breeze from northwest to southwest scattered the floating particles in the southern city harbor area, were quay walls and hard coastal protection constructions do not allow for beaching. The simulation suggests some particle accumulations at beaches and reed belts on the northern coast, opposite the Hanse Sail location. However, changing wind directions after the Hanse Sail caused a transport of up to 7 km to the north, where the particles were trapped and beached. With a southerly wind with speeds of 5 m/s, particles crossed the about-500-m-wide bays and reached the northern shoreline opposite the Hanse Sail festival area within a few hours.

At the end of the Hanse Sail 2009, 42% of all emitted particles were still in the city harbor area, and 58% were further transported into the lower Warnow estuary area. The boundaries of the harbor areas are indicated in Figures 5 and 6. In 2010, 88% remained in the city harbor and only 12% were in the lower Warnow estuary area. The Hanse Sails 2009 and 2010 represent situations with contrasting and comparatively strong winds. In Rostock, wind-directions between northwest and southwest are most common, and the conditions during Hanse Sail 2010 can be regarded as representative of a typical situation. Therefore, detailed field studies and sampling campaigns with a focus on the amount and composition of litter emissions in harbors from the land, as well as studies on litter pollution and deposition, could focus on the Hanse Sail coast line and the city harbor area. This means that our sampling approaches were reasonable and suitable. The pollution patterns observed in 2018 are in agreement with the model results.

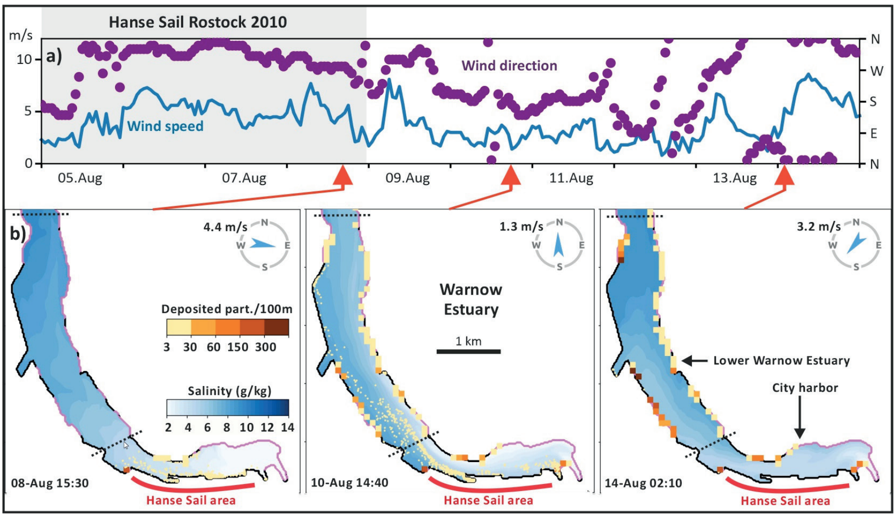


Figure 6. (**a**) Wind speed and direction during Hanse Sail 2010, which lasted from 5 to 8 August. The red arrows indicate the date and time of figure series (**b**). (**b**) The model simulation of floating macro-litter and the litter deposition along the shoreline for three dates. It is assumed that, altogether, 3000 particles were emitted during the event. Purple coastlines indicate accumulating shorelines; black colors indicate shorelines; the dashed line indicates the boundary of the city harbor. The model simulation movie shows the dynamic transport behavior in detail (Supplementary Material).

The model simulations cover a further six days after the Hanse Sails, until practically all floating particles were beached. In this final situation, in 2009, 28% of all particles were beached in the city harbor area and 72% in the lower Warnow estuary area. In 2010, 17% were beached in the city harbor area, 76% in the lower Warnow estuary and 6% in the estuary close to the Baltic Sea. This implies a period of significant transport after the Hanse Sails took place, but only within 7 km of the festival area (see Supplementary Material).

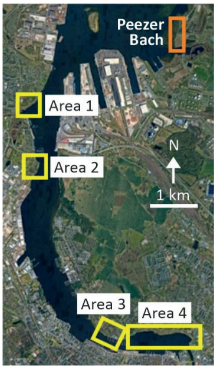
Only in 2010 were about 6% of the macro-litter particles transported further north into the northern part of the estuary, and 0.4% reached the open Baltic Sea in a distance of 11 km from the Hanse Sail festival area. We can conclude that Hanse Sails are not relevant to open Baltic Sea pollution with floating litter.

However, the dynamic model movies (Supplementary Material) visually indicate that near-surface transport comprises a complex interaction between external forces from the Baltic Sea, estuarine circulation, harbor morphometry and wind shelter effects, and it can hardly be predicted without a model. Under certain conditions, the temporary transport of macro-litter particles into the Baltic Sea cannot be excluded.

3.6. Coastal Litter Accumulations in the Warnow Estuary

The annual macro-litter data gathered during the Citizen Science project, “Natur- & Erlebnisraum Warnow-Ästuar” (NABU Regionalverband Mittleres Mecklenburg e.V.), between 2018 and 2020 at the remote beach and flat coast near Peezer Bach (Figure 7) shows a pollution of between 3533 particles (2018) and 5671 particles (2019) per 100 m. The weight of the collected particles is between 236 kg (2018) and 35 kg (2020). In all years, plastic particles have a share between 96% and 98%. A detailed look into the item types found can potentially indicate emission pathways and water-bound transport. The share of cotton buds (hygienic article) is between 1.7% and 2.7%, which indicates that untreated sewage water, released during sewage overflow events or from ships, plays a role in the pollution of this coastal strip. However, these cotton buds were not necessarily released in the city harbor. Most particles indicate the adjacent harbor as the major pollution source, pointing towards a retention of macro-litter particles within few kilometers of the emission point. Disposable cutlery, plates and drinking straws have a higher likelihood of emission during Hanse Sails. The total amount of these particle types varies between 13 (2020) and 31 (2018) and results in a share between 0.25% and 0.28% of the total number of particles. The numbers are relatively low and do not indicate significant waterborne transport from the city harbor to the Peezer Bach coastline. The Peezer Bach is similar to the Warnow mouth to the Baltic Sea, located in a distance of 11 km from the city harbor. Altogether, the data support the model simulation results and do not indicate long-distance litter transport. They indicate a retention of macro-litter particles within a few kilometers of the emission point.

About 7 km of the Warnow estuary coastline is covered by reed belts. Alongside beaches and flat coasts, we considered these reed belts as traps for macro-litter and implemented this trap function in our model. Consequently, four reed areas (covering most of the reed belts) were studied in spring 2023—a season when the reed belts are still accessible and floating macro litter is still highly visible (Figure 7). Apart from reed area 3, which was less accessible, all other reed belts showed a comparable floating litter density between 0.036 and 0.056 particles/m². A total of 83% of the litter found was made of plastic. Reed area 4 in the city harbor, opposite of the Hanse Sail festival area, did not show higher pollution compared to areas 1 and 2. Nor did special item types, such as plastic straws (emitted before the prohibition) or cutlery, point to the Hanse Sail festival as a significant pollution source. However, a weakness of reed belt analyses is that floating litter is overgrown by vegetation within weeks. The increasing density causes the sedimentation of many litter particles. The result is a reduced floating litter pollution density and changes in the particle composition. The trap function of the reed belts was highly visible in the field, but quantification was not possible with our simple approach. Further, because of bio-fouling, it is doubtful that floating litter emitted during the previous Hanse Sail would still be detectable months later.



Item type	Area 1	Area 2	Area 3	Area 4	Total %
Plastic packaging	13	11	3	22	23%
Plastic, unidentified	7	13		24	21%
Plastic bag		6		13	9%
Styrofoam		8		7	7%
Single-use cup	2	3		7	6%
Plastic bottle			1	11	6%
Bottle cap		8		1	4%
Plastic cutlery		4			2%
Reusable cup		1	1		1%
Lollypop stick		1		1	1%
Plastic straw				2	1%
Paper or tissu	2	6		4	6%
Glass bottle		6	1	11	8%
Other	4	4	1	5	7%
Total	**28**	**71**	**7**	**108**	**214**
Sampled area (m^2)	500	2000	1000	2500	6000
Items/m^2	**0.056**	**0.036**	**0.007**	**0.043**	**0.036**

Figure 7. Floating macro-litter quantity and item types found in a 1 m strip at the front of four major reed belts covering a distance of five kilometers. The colors indicate item groups. Additionally, the flat coast near Peezer Bach is indicated, which is where citizen science clean-up data collection activities took place (map based on Google Maps).

3.7. Quantification of Baltic Harbor Festival Emissions

The Internet research resulted in over 50 Baltic coastal harbor and sailing festivals, several with a focus on music. The 11 largest events, as well as grouped smaller festivals, are documented in Table 1. The aim is to provide a rough estimation of the quantitative relevance of all harbor and sailing events to the pollution of the Baltic Sea with litter. The quantifications are based on two scenarios: scenario 1 assumes that the emission data of 0.24 litter particles per 1000 persons, as observed during Hanse Sail 2023, can be transferred to all events in the Baltic Sea region; scenario 2 is based on an emission of 3 litter particles per 1000 persons, as observed in earlier Hanse Sails. Based on our data, it can be assumed that about 85% of the litter particles are plastics.

Table 1. Estimated Baltic-wide annual macro-litter emissions resulting from harbor and sailing festivals. The most recent visitor numbers, mainly for 2023, were used. Scenario 1 assumes an emission of 0.24 litter particles per 1000 visitors based on calculations for Hanse Sail 2023. Scenario 2 is based on an emission of 3 litter particles per 1000 visitors as calculated for Hanse Sail 2018.

					Emissions	
Festival	**City**	**Country**	**Visitors**	**Days**	**Scenario 1**	**Scenario 2**
Hanse Sail Rostock	Rostock	Germany	500,000	4	120	1500
Warnemünde Week	Rostock	Germany	650,000	9	156	1950
Travemünde Week	Travemünde	Germany	500,000	10	120	1500
Kiel Week	Kiel	Germany	3,800,000	9	912	11,400
River Harbour Festival	Turku	Finland	550,000	3	132	1650
Baltic Herring Market	Helsinki	Finland	80,000	7	19	240
Maritime Festival	Kotka	Finland	200,000	4	48	600
Maritime days	Tallinn	Estonia	130,000	4	31	390
Sea Festival	Klaipeda	Lithuania	500,000	3	120	1500
Baltic Sail	Gdansk	Poland	3,700,000	4	888	11,100
Tall Ships Races	Szczecin	Poland	2,000,000	4	480	6000
Total of smaller events			6,000,000		1440	18,000
		Sum	18,610,000		4466	**55,830**

Scenario 2 suggests that even at the largest festivals (Kiel Week, Baltic Sail Gdansk), the annual emissions are below 12,000 particles. The Baltic-wide total of about 56,000 particles per year seems a realistic estimation since, very likely, not all events have implemented comprehensive waste management approaches. Assuming emissions of 3.7 particles per 1000 visitors, as calculated for Hanse Sail 2019, we receive total floating macro-litter emissions in the Baltic region close to 70,000, but we consider our data of 2019 to be less comprehensive and reliable with respect to calculating emissions compared to the data of 2018. Scenario 1, with an emission of about 4500 particles per year, reflects a situation that, very likely, will be reached during the coming years, assuming that improved waste management efforts will be implemented everywhere. Our estimated range of uncertainty for the calculated Baltic Sea region emissions is about ±300%. However, this uncertainty estimation cannot be statistically validated.

4. Discussion

4.1. Assessment of Approach and Methods

It is well known that field studies on macro-litter, e.g., on beaches, show a very high spatiotemporal variability, and the methodological weaknesses are well known [34–36]. Macro-litter sampling of the water surface and of festival areas have additional weaknesses. Sampling on the water surface is disturbed by wind-driven transport and pollution patchiness. Only the covered sampling area can be estimated, and extrapolation to the entire harbor water area is required. However, our model simulations suggest that samplings along the coastline by boat catch most of the litter. Samplings in the festival areas are permanently disturbed by visitors, and the time of the day affects the results. Knowing all these uncertainties, we tried to combine different approaches and addressed the emission problem, in particular, from different perspectives.

For the model simulations, we used an advanced spatially highly resolved 3D flow model that is very well adapted to the Warnow estuary [27]. The model simulations assumed that macro-litter was transported passively with the near surface layer. Direct wind-driven transport of particles drifting on the water surface (e.g., styrofoam) was neglected because it can easily be estimated based on the prevailing wind conditions. The simulations assumed that beaches and reed belts had sink functions and trapped the litter permanently. This view was supported by our observations and the literature (e.g., [37]). We further assumed that hard substrate harbor walls reflect the litter. This is a simplification because the litter sampling campaigns did show that, especially during higher water levels and higher waves, some litter was accumulated further up at stone dikes, but this shore type does not play a quantitatively important role and has negligible influence on the results. Further, we observed that litter was trapped between ships. This causes a temporary delay until the litter is subject to transport with currents. Since the quantity of particles is in the order of 10–50, this has limited consequences for the general transport and beaching pattern. Small-scale structures along the shore, such as single ships and landing stages in marinas, were not represented by the model.

The macro-litter emission scenarios used for the model simulations were based on calculations for the year 2018. However, many of the 150 ships, taking part in the Hanse Sail, e.g., 2023, transport visitors several times per day between city harbor and the Baltic Sea. The emissions from boats were not included in the simulations.

The calculations of the total annual macro-litter emissions for the entire Baltic Sea resulting from harbor events should meet the right order of magnitude, but they cannot be regarded as reliable data because of three weaknesses: The extrapolations are based on the results of the Hanse Sails in Rostock and assume that all other events have similar person-specific emissions and implemented comparable waste management strategies. It is uncertain as to whether we found all relevant events and estimated the correct numbers of visitors. The number of visitors, provided by different sources for the same event and year, varies by 50% depending on the estimation approach and the definition of a visitor (e.g., [29]). Last but not least, the decision about what is considered as a harbor event and to what extent emissions to the harbor area are possible includes subjectivity.

4.2. The Role of Festivals for Baltic Sea Litter Pollution

Publications that allow for a comparison with our results, to our knowledge, do not exist. However, during Kiel Week 2018, a report stated [38] that the emission of macro-litter to the harbor water increased by 20 times during the Kiel Week and that about 75% of the particles were made from plastic. As a consequence of the observed large amounts of cigarette butts floating in the harbor, during Kiel Week 2019, 96 large standing ashtrays were placed in the festival area and 20,000 mobile ash trays were distributed [39]. Together with additional waste emission reduction measures, the harbor water pollution during the event was reduced. For 2019, for two harbor areas in Kiel, between 300 and 400 particles of floating macro-litter were reported [39]. Compared to the Hanse Sail, the Kiel Week has a higher number of visitors, but the city harbor has very similar in size and structure. Applying a similar calculation approach to that use for the Hanse Sails, we receive a total of about 1300 particles and an emission of about 0.4 particles per 1000 visitors. These values are slightly above our calculations for the Hanse Sail 2023 and indicate that our calculated person-specific litter emissions are realistic.

In 2023, the Kiel Week reported 3.8 million visitors. The well-established waste management system removed more waste than ever—52 t during the first two days alone [40]. The steadily improved waste collection and removal systems employed during the sailing events in Kiel and Rostock are certainly a result of an improved awareness of litter in the environment. This improved awareness of litter as a problem has very likely positively affected the littering behavior of visitors during in recent decades and caused the public cleaning activities of volunteers (e.g., [41,42]). For example, in both cities, there are campaigns run by volunteers to remove the floating litter during and/or after the events (e.g., [22,39,43]). The removal of the majority of floating litter alone largely ensures that its transport to, a pollution of, the open Baltic Sea is prevented.

An estimated 1.2 million visitors attended the opening hours of the Kiel Week 2023 [44]. This unexpectedly large number temporarily exceeded the waste collection and cleaning system. Consequences included large amounts of litter on the festival floor, causing a risk of harbor water pollution. Temporarily exceeded waste collection capacities increase the risk of accidental pollution by wind, rain or sea-gulls, and seem to play a significant role not only in Rostock and Kiel. This is possibly the reason for the very high amounts of floating macro-litter observed in port areas of the Island of Mallorca.

On the Island of Mallorca, floating sea bins were applied and collected 15,899 particles and 336 kg of floating litter during the summer months [45]. In Kiel, floating sea bins were successfully applied to trap floating litter during Kiel Week as well, albeit without data collection, analyses and scientific evaluation. In harbors, floating litter often accumulates between boats and in corners. Sea bins can serve as a useful removal measure and compensate for temporary short-comings in the waste collection and removal system. However, various other cost-efficient technical measures exist to reduce floating litter in harbors [46,47].

Schwarz et al. [48] review the transport and accumulation of litter in seas and point out that what is observed floating in the sea is only 1% of the calculated litter emission from land to the sea. It is assumed that sediments and coastlines serve as efficient sinks. Estuarine filters account for about 88% of the global coastline, and it is estimated that about 57% of river water and 71% of sediment discharge to the oceans pass through estuarine filters [49]. Model simulations of the Waitematā Estuary in New Zealand, for example, indicate that more than 80% of the emitted macro-litter is kept back in the estuary [50]. A strong retention of macro-litter is supported by several recent studies (e.g., [51–53]). This is firmly in agreement with our model results, which suggest a practically complete retention of all macro-litter particles that are emitted during the Hanse Sail to the Warnow estuary. Since the situation of Kiel and its estuary, the Kieler Förde, is comparable, it can be assumed that emitted litter during Kiel Weeks remains in the estuary as well. Having a look at all other investigated harbor festivals in the Baltic Sea Region, most harbors are not directly located on the open sea. Therefore, we estimate that between 60% and 90% of the macro-litter emitted during harbor events in the Baltic Sea region remains in the harbor areas or the surrounding coastlines and does not enter the open Baltic Sea. However, this needs to be explored in detail.

For Hanse Sails before 2020, we calculated total floating macro-litter emissions of 3000 particles, and for Hanse Sail 2023, only about 120. During earlier macro- and meso-litter coastline monitoring at five locations in the Warnow estuary (10 samplings), over 2300 particles were found and classified. Additionally, the emission of selected macro-litter items was calculated [11]. The Warnow river enters the estuary near the city and has an annual mean water discharge of 16.5 m^3/s and a catchment area of 3280 km^2 [54]. The calculations in Gonzales et al. [7] suggest that the Warnow river alone emits 100,000 particles of macro-litter annually to the Warnow estuary. Combined literature data [7,11] suggest an annual macro-litter emission above 500,000 particles to the entire Warnow estuary. However, this total emission estimation has a high uncertainty. Against this background, the Hanse Sails contribute less than 1% to the annual total macro-litter emissions to the Warnow estuary and are only of local importance for the Rostock city harbor. This very low share partly results from the short duration of the event (only four days), as well as the limited directly affected coastline of about 2 km (Hanse Sail festival area) compared to the over 35 km total estuary coastline. Marine litter concentrations on the sea-floor near the festival areas show a relatively low level of pollution as well and support our results [55]. On the other hand, in earlier investigations of dredged sediments from the Warnow estuary shipping channels, altogether, 778 particles were found. A total of 26% belonged to the categories of plastic caps, packets/wrappers, cutlery/trays/straw and bottles and indicate residents, tourists or festival visitors as likely emission sources [11]. However, the data cannot be related to a defined period in time or an area. Since many particles were originally floating, the data confirm that floating particles are, after some time, sinking and are removed from the water surface.

Published calculations suggest that the largest rivers entering the Baltic Sea, namely, the Odra, Vistula, Nemunas, Daugava and Neva, each emit above 500,000 floating macro-litter particles (>25 mm) per year to the Baltic Sea. This would result in total riverine macro-litter emissions to the Baltic Sea of about 40–100 million particles/year [7]. Following this approach, and adding all other emission pathways for macro-litter to the Baltic Sea, one would certainly end up with 100 million particles/year or more. Taking this number, the emissions from harbor and sailing festivals of about 50,000 particles annually would be only 0.05% of the annual riverine inputs to the Baltic Sea.

5. Conclusions

The awareness of litter as a major problem in the marine environment has increased in recent decades. This has caused an ongoing improvement of waste collection and removals systems. This is highly visible in Germany. As a consequence, today, the litter emissions to the harbor surface water during harbor and sailing festivals, such as the Hanse Sail in Rostock, are of minor importance to Baltic Sea marine litter pollution. The calculated emissions are about 3 particles/1000 visitors or even less, and they cause, despite large numbers of visitors, maximal emissions of below 12,000 particles for the largest festivals (Kiel Week, Baltic Sail Gdansk). With respect to the marine litter pollution of entire estuaries, as well as on a Baltic Sea region scale, the share is below 1% of the total emissions. Harbor surface water cleaning efforts after events, as well as efficient retention in estuaries and coastal waters, ensure that, if at all, only small shares enter the open sea. Therefore, harbor festivals only contribute to a local pollution problem. However, it seems that with improved waste strategies, the importance of accidental and/or uncontrolled pollution (e.g., fireworks during New Year's Eve or harbor parties) increases. Comprehensive inventories considering all macro-litter emission pathways in estuaries are still lacking. Further, our approach to quantifying litter retention, taking into account harbor size, morphometry, spatial orientation and distance to the open sea, as well as the dominant wind conditions, would be important. Our model simulations do not show a relevant floating macro-litter export to the open sea but indicate that the estuary serves as an efficient trap.

Supplementary Materials: Movies showing all particle-tracking simulations of near surface marine macro-litter transport in Rostock (Warnow Estuary) can be downloaded from: https://doi.org/10.5281/zenodo.10220575.

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Appendix A

HanseSail 2019 (Rostock, Germany): Floating macro-litter sampling was conducted on Thursday and Friday evening and on Sunday and Monday morning with a landing net used from the harbor wall. On Monday morning, landing nets were also used from a boat in the estuary. A week before, the whole area was cleaned, and the litter was removed to ensure a clean harbor for the HanseSail (see Figure 2).

Codes			Master List of Categories of Litter Items								OSPAR					
Par_id	TSG_ML ...eral- Code	...SPAR-Code	General name	Level 1 - Materials	...re	...ach	...floor	...ating	...cro	...odsam	OSPAR-Name	OSPAR-categories	Thursday litter 08.08.2019	Friday litter 09.08.2019	Litter from Saturday, Sunday and Monday 10-12.08.2019	Total litter pieces
27	G27	64	Cigarette butts and filters	Artificial polymer materials		x	x			x	Cigarette bu	Plastic • Polystyrene	81	170	248	499
4	G4	3	Small plastic bags, e.g. freezer bags incl. pieces	Artificial polymer materials		x				x	Small plasti	Plastic • Polystyrene	26	33	88	147
30	G30	19	Crisp packets/sweet wrappers	Artificial polymer materials		x				x	Crisp/sweet	Plastic • Polystyrene	30	41	74	145
81	G81		Polystyrene pieces 0 - 2.5 cm	Artificial polymer materials		x				x			120		20	140
			plastic bag coepto gmbh Oskar Jäger str. 173 in 50	Artificial polymer materials								Plastic • Polystyrene	114	3		117
			confetti	Artificial polymer materials								Plastic • Polystyrene		60		60
25	G25		Tobacco pouches/plastic cigarette box packaging	Artificial polymer materials		x				x				18	23	41
21	G21	15	Plastic caps/lids drinks	Artificial polymer materials		x				x	Caps/lids	Plastic • Polystyrene	17	15	6	38
76	G76	46	Plastic/polystyrene pieces 2,5 cm > < 50 cm	Artificial polymer materials		x					Plastic/poly	Plastic • Polystyrene	33			33
6	G6	4	Bottles	Artificial polymer materials	x		x	x			Drinks (bott	Plastic • Polystyrene	9	4	12	25
20	G20		Plastic caps and lids	Artificial polymer materials			x						9	12	4	25
33	G33	21	Cups and cup lids	Artificial polymer materials	x	x				x	Cups	Plastic • Polystyrene	6		17	23
125	G125	49	Balloons and balloon sticks	Rubber	x	x	x	x		x	Balloons, in	Rubber	5	7	9	21
			firework plastic piecces	Artificial polymer materials								Plastic • Polystyrene	4	4	10	18
3	G3	2	Shopping Bags incl. pieces	Artificial polymer materials		x				x	Bags (e.g. s	Plastic • Polystyrene			14	14
82	G82		Polystyrene pieces 2.5 cm > < 50 cm	Artificial polymer materials		x		x		x				14		14
156	G156		Paper fragments	Paper/Cardboard		x				x			8	5		13
175	G175	78	Cans (beverage)	Metal	x	x	x	x		x	Drink cans	Metal	1		12	13
34	G34	22	Cutlery and trays	Artificial polymer materials		x				x	Cutlery/tray	Plastic • Polystyrene		4	6	10
96	G96	99	Sanitary towels/panty liners/backing strips	Artificial polymer materials		x	x			x	Sanitary tov	Sanitary waste	4	6		10
32	G32	20	Toys and party poppers	Artificial polymer materials	x	x				x	Toys & part	Plastic • Polystyrene		1	7	8
200	G200	91	Bottles incl. pieces	Glass/ceramics	x	x	x			x	Bottles	Glass	6	2		8
10	G10	6	Food containers incl. fast food containers	Artificial polymer materials	x	x	x			x	Food contai	Plastic • Polystyrene	3		4	7
178	G178	77	Bottle caps, lids & pull tabs	Metal	x	x				x	Bottle caps	Metal	6	1		7
177	G177	81	Foil wrappers, aluminium foil	Metal		x				x	Foil wrappe	Metal	4	2		6
147	G147	60	Paper bags	Paper/Cardboard		x				x	Bags	Paper • Cardboard	1		3	4
153	G153	65	Cups, food trays, food wrappers, drink containers	Paper/Cardboard	x	x				x	Cups	Paper • Cardboard	2		2	4
155	G155		Tubes for fireworks	Paper/Cardboard		x				x			1	1	2	4
158	G158	67	Other paper items	Paper/Cardboard		x	x	x		x	Other paper	Paper • Cardboard			4	4
26	G26	16	Cigarette lighters	Artificial polymer materials	x	x				x	Cigarette lig	Plastic • Polystyrene	1	1	1	3
75	G75	117	Plastic/polystyrene pieces 0 - 2.5 cm	Artificial polymer materials		x					Plastic/poly	Plastic • Polystyrene		3		3
95	G95	98	Cotton bud sticks	Artificial polymer materials	x	x	x			x	Cotton bud	Sanitary waste	3			3
148	G148	61	Cardboard (boxes & fragments)	Paper/Cardboard	x	x	x	x		x	Cardboard	Paper • Cardboard			3	3
154	G154	66	Newspapers & magazines	Paper/Cardboard		x		x		x	Newspapers	Paper • Cardboard			3	3
1	G1	1	4/6-pack yokes, six-pack rings	Artificial polymer materials	x	x				x	4/6-pack yo	Plastic • Polystyrene	2			2
49	G49	31	Rope (diameter more than 1 cm)	Artificial polymer materials	x	x				x	Rope (diam	Plastic • Polystyrene		2		2
11	G11	7	Beach use related cosmetic bottles and containers	Artificial polymer materials		x				x	Cosmetics (	Plastic • Polystyrene			1	1
12	G12	7	Other cosmetics bottles & containers	Artificial polymer materials	x	x				x	Cosmetics (	Plastic • Polystyrene	1			1
38	G38		Cover/packaging	Artificial polymer materials				x							1	1
40	G40	25	Gloves (washing up)	Artificial polymer materials	x	x				x	Gloves (typi	Plastic • Polystyrene		1		1
41	G41	113	Gloves (industrial/professional rubber gloves)	Artificial polymer materials	x	x				x	Gloves (indu	Plastic • Polystyrene		1		1
65	G65	38	Buckets	Artificial polymer materials		x				x	Buckets	Plastic • Polystyrene			1	1
87	G87		Masking tape	Artificial polymer materials		x				x			1			1
93	G93		Cable ties	Artificial polymer materials		x	x			x			1			1
97	G97	101	Toilet fresheners	Artificial polymer materials		x				x	Toilet freshe	Sanitary waste	1			1
100	G100	103	Containers / tubes	Artificial polymer materials		x				x	Containers/t	Medical waste	1			1
101	G101	121	Dog faeces bag	Artificial polymer materials	x	x				x	Bagged dog	Faeces			1	1
135	G135		Clothing (clothes, shoes)	Cloth/textile				x					1			1
165	G165	72	Ice-cream sticks, chip forks, chopsticks, toothpicks	Processed/worked wood	x	x				x	Ice lolly stic	Wood (machined)			1	1
			travel ticket; bus, train etc	Paper/Cardboard								Paper • Cardboard			1	1
			Barrier tape, red-whit; yellow-black. Etc.	Artificial polymer materials								Plastic • Polystyrene			1	1
2	G2		Bags	Artificial polymer materials	x		x	x								0
												Total	502	411	579	1492

Appendix B

HanseSail 2018 (Rostock-Germany): Citizen science sampling of floating litter at the water surface of the Warnow estuary after the Hanse Sail on 13 August. “Bereich” indicates the collection areas in Figure 3. “Partikel Größenklassen” indicate the particle size classes. The German item names follow OSPAR [21].

	Bereich A			Bereich B			Bereich 3			Bereich 4			Bereich 5			Bereich 6			Bereich 7			Bereich 8			Bereich 9			Land		
Summe	**92**			**192**			**72**			**167**			**45**			**356**			**32**			**103**			**85**			**190**		
Partikel Größenklasse (mm)	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**	**<5**	**<25**	**>25**
Plastikverpackung			22			52			28			22			9			98			20			33	5		15			22
Konfetti			1			45			19		9	1			6			130			0			0	3		24			4
Zigarettenfilter			16			14			11			121			1			9			0			2			6			5
Becher (PP Material)			7			15			1			0			3			15			0			15			3			28
Taschentuch			7			13			1			2			0			19			0			1			0			28
Styropor	1		3		1	5		1	5	1		1			7	2	6	9			0	2		0			4	6	3	2
Etikett Ikea			1			2			0			1			0			1			0			0			4			36
Tüte Plastik (PE+PA)			4			12			2			0			1			11			0			5			4			2
Strohalme (PP)			6			7			1			0			3			6			0			0			3			6
Papp-/Papierverpackung			7			0			0			0			0			16			0			0			0			4
Plastikbruchstücke			0			3			1			2			0			2			0			6			0	5		6
Plastikflasche			0			1			0			0			3			4			3			11			1			0
Folie			2			5			0			1			1			2			2			6			3			0
aufblasbarer Werbebanner (PE)			0			0			0			0			2			2			2			5			0			1
Tickets/Bons			2			0			0			0			0			7			0			0			0			2
Tüte Papier			2			4			0			1			0			2			0			0			0			0
Plastikdeckel			0			1			0			0			2			1			0			1			1			3
Dose			0			1			0			0			1			1			0			1			0			5
Baustoff (PU+PP)			0			1			0			0			0			2			0			1			0			4
Plastikbesteck			0			0			0			0			0			0			0			0			0			7
Holz/Holzbesteck			2			1			0			2			1			0			0			0			0			0
Glasflasche			0			0			0			0			1			1			0			3			0			0
Feuerzeug			0			2			1			0			0			0			2			0			0			0
Eisbecher			2			1			0			0			0			0			0			0			1			1
Taschentücherverpackung			0			1			1			0			0			3			0			0			0			0
Kronkorken			0			0			0			0			0			0			0			0			0			5
Fastfood Verpackung (PS)			1			0			0			1			1			0			0			0			1			0
Tesaband			0			1			0			0			0			2			0			0			1			0
to go Becher			0			1			0			0			1			0			0			0			2			0
Alufolie			1			0			0			1			0			1			0			0			0			1
Hygieneartikel			0			0			0			0			0			2			0			2			0			0
Luftballon (PA)			0			0			0			0			0			1			1			2			0			0
Plastikteller (PP)			2			0			0			0			0			0			0			0			0			1
Feuerwerkskörper			0			1			0			0			0			0			0			1			0			0
Kugelschreiber			0			0			0			0			1			0			0			0			0			1
Tetrapack			0			0			0			0			0			0			0			1			1			0
Gummihandschuh			0			0			0			0			0			0			1			0			1			0
Standschild 820			0			0			0			0			0			0			0			0			0			2
Plane			0			0			0			0			1			0			0			0			0			0
Schwamm			1			0			0			0			0			0			0			0			0			0
Textil			0			0			0			0			0			0			1			0			0			0
Blumentopf			0			1			0			0			0			0			0			0			0			0
Segelbedarf			0			1			0			0			0			0			0			0			0			0
Zigarettenschachtel			0			0			0			1			0			0			0			0			0			0
Glas			1			0			0			0			0			0			0			0			0			0
Tube			1			0			0			0			0			0			0			0			0			0
Drat			0			0			0			0			0			1			0			0			0			0
Angelzubehör			0			0			0			0			0			0			0			1			0			0
DKB Sitzkissen			0			0			0			0			0			0			0			1			0			0
Ball			0			0			0			0			0			0			0			1			0			0
PA Schnur			0			0			0			0			0			0			0			1			0			0
Fahne			0			0			0			0			0			0			0			1			0			0
Seil			0			0			0			0			0			0			0			0			1			0
Absperrband			0			0			0			0			0			0			0			0			1			0
Eimer			0			0			0			0			0			0			0			0			0			0
Butterbrotpapier			0			0			0			0			0			0			0			0			0			0

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PAPER IV

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RESEARCH PAPER

Replacing Single-Use Plastics (SUPs) in Coastal Festivals: A Critical Evaluation of Bio-Based, Biodegradable and Compostable Tableware, Regulatory Policies and Public Awareness

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Abstract Single-use plastic (SUP) tableware is one of the top ten items found on beaches worldwide. Bio-based, biodegradable and compostable tableware have emerged as a popular alternative to replace SUPs, however, often used without deep consideration to disposal needs and environmental impact, which are key aspects to ensure litter reduction. This study critically evaluated the usage of six bio-based tableware materials at coastal festivals, examined the gaps between policy regulations and waste management in Germany, Lithuania, Chile and Tunisia, assessed the social perception, awareness and acceptance towards material alternatives, and investigated the materials disintegration under real environments: estuarine water and an industrial composting facility. Our policy analysis revealed that whilst the majority of policies are designed to phase out conventional SUPs, the available infrastructure in the study areas is not equipped to handle alternative materials. Our public survey revealed a general lack of awareness regarding degradability, disposal requirements and ecological footprint of the different materials, indicating knowledge gaps and confusion in the public which could result in improper disposal and littering. Finally, the disintegration experiments demonstrated that only tableware made of palm leaves, cardboard, and sugar cane bagasse fully disintegrated in estuarine water over 1 year, while only PLA tableware fully disintegrated in industrial compost within 12 days, demonstrating that disintegration is highly environment-specific. Our findings bring together important aspects that have not been analyzed in conjunction before and highlight research gaps that become relevant in the revision of the International Plastics Treaty.

Highlights Discrepancy between policy goals and waste infrastructure, alternative tableware materials cannot be correctly treated.
The public perceived polylactic acid (PLA) tableware to have more negative effects than non-plastic tableware.
General misinformation in society regarding correct disposal of bio-based materials, likely to increase littering behavior.
Bio-based tableware lacks clear labelling and fails to disintegrate in the short-term.
73–84% of respondents are willing to pay for an alternative material, preferring reusable options.

Keywords Bio-based tableware · Litter · Degradability · Waste management · Social events · International plastic treaty

Introduction

Plastic pollution in the coastal and marine environment is a global problem and single-use plastics (SUPs), including cutlery, cups, plates and containers, are among the top ten items found on beaches (Ocean Conservancy 2022). These items are commonly used for takeaway food and drinks at festivals and social events. Tourism exerts significant pressure on coastal areas through high visitor numbers and increased waste generation (Gormsen 1997; Smith et al. 2023), and is one of the main sources of litter (Galgani et al. 2011). In fact, coastal festivals attract large numbers of visitors over short periods, which puts a strain on waste management systems. While precise estimates are limited, events could generate 0.3–3.6 kg of waste per person per day (Cierjacks et al. 2012; Martinho et al. 2018), which is up to five times higher than the global average waste generated

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under normal conditions (0.74 kg per person per day) (Kaza et al. 2018).

Finding replacements for single use plastics are of global importance and bio-based materials have become a popular alternative. However, few studies have critically evaluated the policy regulation of these materials, the infrastructure needed for their handling, their disintegration in real environments, or the social dimension in terms of awareness and acceptance. These aspects are detrimental to the effective reduction of plastic pollution and preventing the creation of new pollutants.

Bio-based materials (which can be biodegradable, compostable or none) encompass a wide range of options. On one hand, there are bio-plastics which can be derived from biomass [e.g., polylactic acid (PLA), polyhydroxyalkanoate (PHA)] or fossil fuels [e.g., polybutylene adipate-co-terephthalate (PBAT), polycaprolactone (PCL)]. On the other hand, there are other bio-based materials partly or wholly derived from biomass (EN 16575), such as wood, sugar cane bagasse, palm leaves and cardboard, and even seaweed (Carina et al. 2021; Yap et al. 2023) which are also used to manufacture tableware. It is important to note, however, that both biomass and fossil fuel based materials can be biodegradable, compostable or neither (Niaounakis 2013) and their degradability depends on factors like temperature, moisture, pH, and medium (soil, sand, seawater, compost) (Haider et al. 2019; Kliem et al. 2020; Rudnik 2019b).

Bio-based plastics, as well as other biomass-based materials have been argued to reduce fossil fuels reliance, greenhouse gas (GHGs) emissions and lower carbon footprint especially when using agricultural leftovers and ensuring appropriate disposal (Moshood et al. 2022; Nandakumar et al. 2021; Rosenboom et al. 2022; Serrano-Aguirre and Prieto 2024). However, other studies have suggested a higher ecological footprint from the use of land, feedstock, water, energy, acidification, eutrophication and GHGs emissions (Brizga et al. 2020; Manfra et al. 2021; Mastrolia et al. 2022; Rosenboom et al. 2022). Still, most life cycle assessment studies (Rosenboom et al. 2022; Van Roijen and Miller 2022) ignore the potential impact of these materials as pollutants in the coastal environment. Various certification standards assess the degradability of plastics and bio-plastic materials in aqueous environments (ISO 14851:2019, ISO 14852:2021), marine waters (ISO 19679:2020, ISO 23977-1:2020, ISO 23977-2:2020, ISO 22403:2020-04 and ASTM D6691) and sediments (ISO 18830:2016, ISO 22404:2019). However, most of them only assess bio-/plastics and their potential to degrade at laboratory conditions. ISO 22766 (2020) is the only standard assessing the degradation of plastics under real marine environment conditions, however there is none assessing this process in freshwater or estuarine systems. As a result, there are several knowledge gaps regarding the degradation behavior of bio-based materials in real environments, and uncertainties exist regarding the infrastructure needed for disposal, as inconsistent labelling fails to specify disposal needs and the rate or the extent of degradation (Rudnik 2013). Some studies have shown the presence of harmful pesticides, per- and polyfluoroalkyl substances (PFAS) and heavy metals in bio-based materials (BEUC 2021; Bouma et al. 2024; Geueke et al. 2018) which could leak into the environment if littered.

Most recently, the United Nations International Plastics Treaty (INC-5.1) (UNEP 2025) emphasized the importance to assess the lifecycle of plastics, bio-plastics and alternatives named as “non-plastic substitutes”. Currently, the policies regulating bio-based, biodegradable and compostable materials are scarce. In the European Union (EU), the SUPs Directive (DIR 2019/904) banned disposable tableware, straws, stirrers, takeaway food containers, and expanded polystyrene drinking cups, among others. While the Packaging Directive (DIR 1994/62/EC) promotes reusable packaging, deposit return systems, and labeling for compostable and biodegradable packaging. Furthermore, a communication on the Policy Framework for Bio-based, Biodegradable and Compostable Plastics (COM 2022/682), although not legally binding, defines the production, marketing, disposal and treatment of these materials. However, these policies focus mainly on bio-plastics, thus, it remains unclear how other bio-based materials (i.e., sugar cane, palm leaves, etc.) are regulated. The framework also highlights the need for more research into material properties, their behavior in real natural environments and consumers’ awareness.

In effect, people’s awareness of bio-based alternatives and disposal behavior has not been widely studied, and evaluating their perception is key to ensure success in the implementation of mitigation measures. Confusion and misinformation in regards to material properties and disposal requirements could result in improper waste disposal (Ansink et al. 2022) and potentially increase littering (UNEP 2015). Since these items are expanding globally, it becomes necessary to assess whether these materials could be a good alternative at sites of different socio-economic contexts.

In this study, six bio-based tableware materials are evaluated for their feasibility to replace SUPs at coastal festivals to answer the question: “do bio-based materials contribute to reducing litter pollution?”. The study aims to (i) ascertain the existence of any discrepancies between policy goals for SUP reduction and waste infrastructure available, (ii) assess the usage of SUP and bio-based tableware at coastal festivals, (iii) assess public perception, awareness and acceptance of alternative tableware materials across sites of different socio-economic development, and (iv) evaluate tableware disintegration in two real environments. This critical evaluation shall provide an insight into the potential

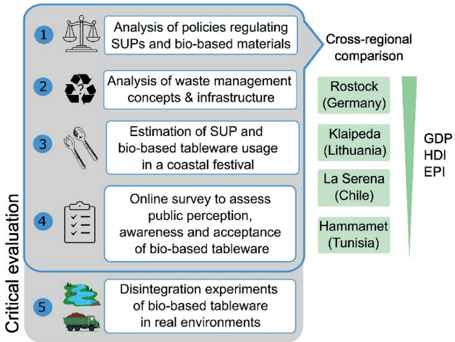


Fig. 1 Methodological concept of the critical evaluation of alternative materials to replace single-use plastic (SUP) tableware at coastal festivals, composed of five main sections. Sections 1–4 (outlined in blue) are part of a cross-region comparison, while Section 5 was carried out in an exemplary estuary system and an industrial composting site

and risk of these materials in replacing SUPs and highlight research gaps that become relevant in the revision of the International Plastics Treaty.

Methodology

The methodology encompasses four main aspects, (i) an analysis of policies and waste concepts for the management of single-use plastics (SUPs) and bio-based tableware, (ii) a quantification of conventional plastic and bio-based tableware usage in an exemplary coastal festival, (iii) an online survey to assess the perception, awareness and acceptance of people to bio-based tableware and (iv) disintegration experiments in coastal waters and at an industrial composting facility (Fig. 1).

Study Areas

Four coastal areas were chosen based on (1) high tourism activity, (2) important coastal festivals and (3) contrasting socio-economic and environmental profiles (i.e. GDP, HDI and EPI) (Fig. 2; Table 1). Gross Domestic Product (GDP) was used to compare economic disparities potentially impacting the availability of waste management infrastructure. Human Development Index (HDI) (UNDP 2024) was used to assess educational access and developmental disparities. Environmental Performance Index (EPI), including indicators such as waste management and pollution (Block et al. 2024), aided in evaluating environmental commitment and progress across these aspects. According to this, Germany had the highest GDP, HDI and EPI, representing a site of high economic prosperity, high infrastructural development and strong environmental commitment. Chile

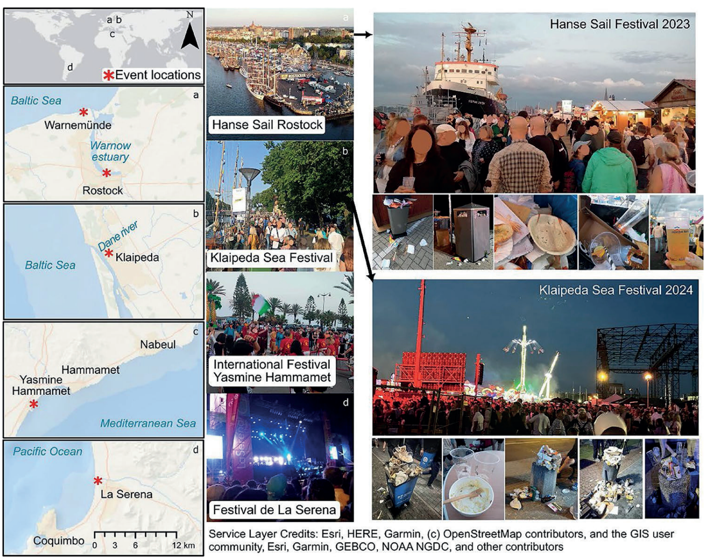


Fig. 2 Study areas and event locations: **a** Hanse Sail (Germany); **b** Klaipeda Sea Festival (Lithuania); **c** International Festival Yasmine Hammamet (Tunisia) and **d** Festival de La Serena (Chile). On the right, close-up photos from Hanse Sail and Klaipeda Sea festivals with examples of litter-prone items. Photos courtesy of: Sylvain Riondet, Emna Jedidi, Paola Forni, Viktorija Sabaliauskaite, Jonas Gintaukas and Camila Escobar

Table 1 Socio-economic characteristics of the study areas, based on gross domestic product (GDP) of the country per capita, human development index (HDI) where <0.55: low, 0.56–0.70: moderate, 0.71–0.79: high, and 0.80–1.0: very high, and environmental performance index (EPI), where 0 is the lowest and 100 is the highest score

Study area	Countries' Gross Domestic Product (GDP) per capita in million US$	Human Development Index (HDI) (0–1)	Environmental Performance Index™ (EPI) (0–100)	Local coastal events	Visitors per event
Rostock, Germany	54,343 (2023)[a]	0.922 (very high) (Mecklenburg-Vorpommen state)[b]	74.5 (Country no. 2 in Global West, 2024)[c]	Hanse Sail (August 10th–13th 2023) Warnemünde Week (1st week July)	500,000 (2023) 1.5 million for both events (2019)[e]
Klaipeda, Lithuania	27,786 (2023)[a]	0.880 (very high) (Klaipeda county)[b]	64.1 (Country no. 6 in Eastern Europe, 2024)[c]	Klaipeda Sea Festival (last week of July)	ca. 500,000 (2019)[f]
La Serena, Chile	17,068 (2023)[a]	0.838 (very high) (Coquimbo region)[b]	49.6 (Country no. 15 in Latin America & Caribbean, 2024)[c]	Festival de La Serena (February 1st–2nd, 2019)	25,000 (2019)[g]
Hammamet, Tunisia	3,978 (2023)[a]	0.719 (High) (Nord East Tunisia)[b]	45.3 (Country no. 6 in Greater Middle East, 2024)[c]	International Carnival of Yasmine Hammamet (March 17th–20th 2023)	ca. 30,000 (2019)[h]

References: [a]World Bank (2025), [b]Global Data Lab (2022), [c]Block et al. (2024), [d]Hanse Sail (2023), [e]Welt (2019a, b), [f]LRT (2019), [g]Municipalidad La Serena (2019), [h]RTCI (2019)

The number of visitors per event is based on reported data by the event organizers or media

followed Germany in terms of GDP sharing similarities with Lithuania in HDI and EPI, both representing areas with moderate economic level and environmental commitment. Finally, Tunisia had a lower GDP, HDI and EPI, thus, represents a site with lower economic level which may face challenges in the implementation of policies and infrastructure.

Rostock, Germany, is a highly touristic destination with 210,795 inhabitants. In 2023, it received 130 cruise ships having 419,000 passengers (Hansestadt Rostock 2024). The Hanse Sail and Warnemünde Week are the most important coastal festivals (Table 1). Both locations are sites with a high number of restaurants, cafés and takeaway stalls during festivals. Although there are no studies assessing littering behavior during these events, litter has been observed at the Warnow estuary after the Hanse Sail event, with between 232 and 1492 floating items in 2017 and 2019, respectively, majority being plastics (Schernewski et al. 2024).

Klaipeda, Lithuania's major coastal city, has 155,501 inhabitants and received 946,427 visitors in 2022 (Official Statistics Portal Lithuania 2022). The Klaipeda Sea Festival is the most popular event at the city, occurring at the harbour area (Table 1). Here, various restaurants, cafés and takeaway stalls exist. There are no studies assessing littering during this event, however based on own observations, SUPs are still used and littering is common (Fig. 2).

La Serena, Chile, has 267,400 inhabitants and its neighboring city, Coquimbo, has 275,644 inhabitants (BCN 2025a, b). The entire region received 643,639 visitors in 2023 (INE 2025a). Beaches are highly urbanized with residential buildings, restaurants, bars and additional takeaway stalls during the summer. La Serena hosts various music festivals, like Festival de La Serena (Municipalidad La Serena 2019) (Fig. 2; Table 1). There are no studies assessing littering during events in the city, which often occur near the beach, however there is evidence that high visitor numbers at the beach leads to littering. At beach Cuatro Esquinas, litter abundance was 1393 items over a 100 m transect in 2022 during the summer. Top litter items were cigarette butts, crisp packets/sweet wrappers, paper cups, paper food trays, paper drink containers and paper wrappers and wooden ice cream sticks (Escobar-Sánchez et al. unpublished). Based on our observations, SUPs are commonly used for takeaway during the summer.

Hammamet, Tunisia, has 83,000 inhabitants (personal communication, Hammamet municipality, November 2021) and attracted around 2.5 million visitors in 2024 (African Manager 2024). Along the beach promenade are restaurants, cafés and takeaway stalls. A popular event is the International Carnival of Yasmine Hammamet (Fig. 2; Table 1). About 32% of the litter found at beaches in Tunisia corresponds to SUPs (Haseler et al. 2025). In Hammamet, abundances of beach litter were 1022 items per 100 m in 2021. Among the top litter items were plastic caps/lids, crisp/sweet packets, plastic bags, cotton bud sticks, food containers, cups and lids, straws and stirrers (Haseler et al. 2025). Based on our observations, SUPs are commonly used for takeaway.

Analysis of Policies and Waste Management Infrastructure

To identify key challenges and opportunities in the replacement of single-use plastic (SUP) tableware, relevant policies in each country were revised. The policy documents were sourced from official government websites and complemented by the Chatham House (2025) database and local experts. It was assessed whether these policies (1) recommended the replacement of SUPs by biodegradable and compostable items, and (2) outlined specific disposal and waste infrastructure requirements for their treatment. Concurrently, municipal waste management plans were examined to determine the collection and treatment infrastructure available for plastics and bio-based tableware. The objectives outlined in the policies were compared to the infrastructure available to identify discrepancies between SUP reduction goals and management.

Estimation of Tableware Usage at Coastal Festivals

The usage of SUP and bio-based tableware was estimated using Hanse Sail festival as example, to give an insight for infrastructural needs for waste management. First, a screening was carried out to assess the number of food and drink stalls and the type of tableware sold (SUP, reusable or bio-based). Then, a sub-sample of stands (44 stands, 27% of the total) were randomly selected for an in-depth assessment on the number and type of items used during the busiest event hours: 12:00–13:00, 16:00–20:00 and 20:00–00:00, for a total of 11 h. Here, the number of buyers and the number and type of tableware obtained was counted over a period of 15 min per stall. The total number of tableware items was classified into reusable (i.e., returnable cups), recyclable with deposit (i.e. plastic bottles), disposable plastic, disposable bio-based, and other waste (i.e. aluminium foil, tissue paper). The weight of total disposed tableware was estimated as the proportion of all disposable tableware from the total number of tableware used, multiplied by the weight of each item, based on manufacturer data (Supplementary data S1). Tableware usage was extrapolated to other study areas considering the waste generated per visitor.

Online Survey To Assess Public Perception, Awareness and Acceptance of Alternative Tableware

An online survey of 25 questions was designed to assess public perception, awareness and acceptance of alternative tableware materials. The survey was available in five languages and started with an introduction outlining the study purpose (Fig. 3). Then, six different tableware alternatives were presented along with conventional single-use polystyrene. Subsequently, five criteria (degradability, recyclability, ecological footprint, additives and/or harmful chemicals,

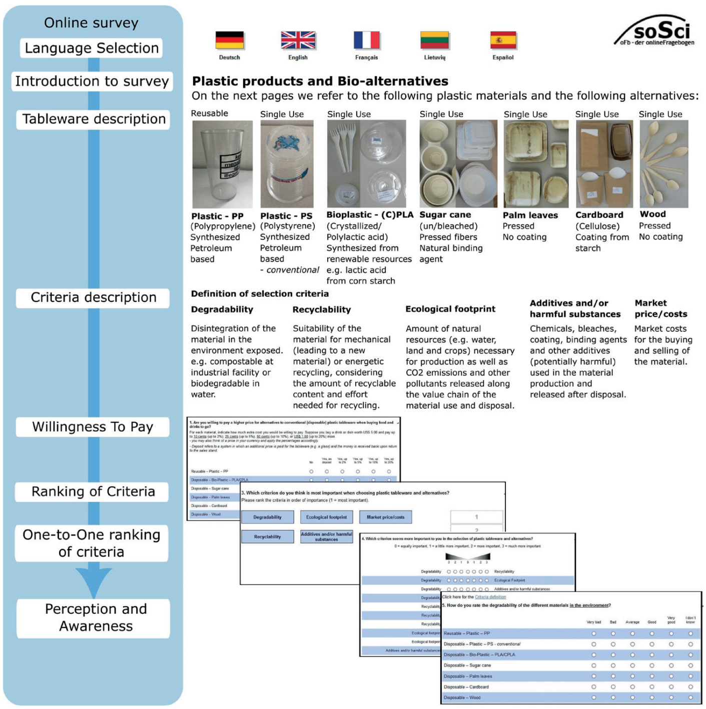


Fig. 3 Survey introduction, materials and criteria description as well as main questions of the survey to evaluate willingness-to-pay, perception, awareness and acceptance of alternative materials to replace single-use plastic (SUP) tableware

and price/market costs) were presented to assess material preferences and perception (defined in Fig. 3). The survey contained *Likert* scale, multiple choice, and ranking questions and finalized with socio-demographic questions. Main questions included:

- Are you willing to pay a higher price for alternatives to conventional (disposable) plastic tableware when buying food and drinks to go?
- What criterion do you think is most important when choosing plastic tableware and alternatives?
- How do you rate the degradability/ compostability/ mechanical recyclability/ energetic recyclability/ presence of additives and chemicals from the different materials? (Each criterion was asked separately).
- In your knowledge, where should the materials be disposed of after use?

The survey was distributed in the four study areas, per email and social media, as well as leaflets and posters with a QR code placed around the city (only in Klaipeda and La Serena). A complete version of the survey is available in the supplementary data (S2). The number of needed responses was calculated based on population size at each study area, with a 95% confidence level and 5% margin of error, following the formula below. Where n' is the sample size of a known population, n is the sample size of an infinite population, N is the population size, z is the critical value for the confidence level, σ is the standard deviation and CI is the confidence interval. Based on the population size of each study area (Table 1), the required minimum answers were 383 per site (Conroy 2018).

$$n' = \frac{n}{1 + \frac{z^2 \times \sigma(1-\sigma)}{CI^2 \times N}}$$

Disintegration Experiments of Bio-Based Tableware in Real Environments

The disintegration of bio-based tableware materials, namely PLA, cardboard, sugar cane bagasse, palm leaves and wood, was tested at the Warnow estuary (Fig. 4A) and at an industrial composting facility (Fig. 4B). This allowed comparison between a coastal environment, where items may be littered during festivals (as observed in Schernewski et al. 2024) and a composting site, following disposal requirements according to policy recommendations. Table 2 provides an overview on the studied items and materials, which represent the materials replacing conventional plastic tableware at the exemplary event Hanse Sail, in Rostock (Germany), except for polystyrene (PS) which was used as negative control material. Since we only assess weight differences and visual characteristics, we refer here to disintegration, defined as the fragmentation and loss of visible material (EN 13432; ISO 22766), instead of biodegradability or compostability, which follow specific definitions and methods (Rudnik 2013; ISO 17088).

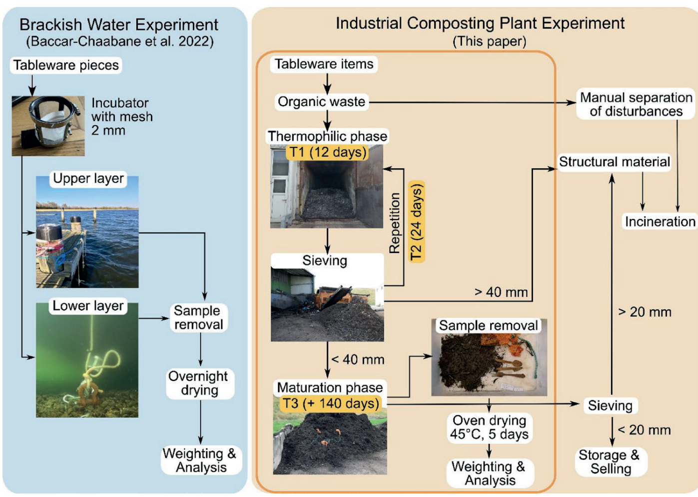
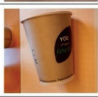
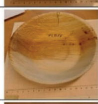


Fig. 4 **a** Experiment sites in brackish water at the Warnow estuary in the upper and lower water layers (Baccar Chaabane et al. 2022). **b** Flowchart of the composting process at the industrial composting facility in Rostock, Germany. Outlined in orange the treatments tested: T1—rotting phase in the chamber for 12 days, T2—extended rotting phase for 24 days and T3—rotting and maturation phase for a total of 152 days

Table 2 Characteristics of tableware materials used in the disintegration experiments

Material	Tableware items used	Label	Origin	Bio-based?
Recycled PS (rPS)		NA	Petroleum based Polystyrene	No
Polylactic Acid (PLA)		Completely compostable	Synthesized from renewable resource, i.e. maize	Yes
Cardboard not coated (C)		Biodegradable and compostable	Cellulose	Yes
Cardboard coated with starch (CC)		100% biodegradable	Cellulose and Starch	Yes
Sugar cane bagasse unbleached (SCU)		100% compostable	Sugar cane, pressed fibers	Yes
Sugar cane bagasse bleached (SCB)		100% compostable	Sugar cane	Yes
Palm leaves (PL)		NA	Areca palm fruit sheath pressed	Yes
Wood (W)		NA	Birch wood, pressed	Yes

The materials represent those used to replace conventional plastic tableware at the exemplary event Hanse sail, in Rostock (Germany), except for polystyrene (PS) which was used as negative control

Disintegration in Coastal Waters

In situ experiments were conducted at the Warnow estuary, a brackish water environment (Fig. 4A). This location was selected due to its proximity to the city harbor, where the Hanse Sail festival occurs. The estuary has an average depth of 5.6 m and bottom salinity of 5–18 PSU (Lange et al. 2020). Testing sites were chosen to represent diverse conditions. A total of 12 incubators were placed per site, in the upper and lower water column layer. Temperature (°C), pH, salinity (‰) and dissolved oxygen (mg l^{-1}) were measured at each site using a water quality probe (Intellical CDC401 conductivity probe, Hach company). Disintegration (%) was calculated as the difference in dry weight before and after the experiment, complemented by visual characteristics. For detailed methodology, see Baccar Chaabane et al. 2022.

A majority of standards assessing degradability of plastics and other materials in freshwater and marine environments consider laboratory conditions (Supplementary data S3). ISO 22766 (2020) is only one standard that assesses the disintegration of plastics under real marine environment conditions, which states that >90% visual disintegration should occur within 3 years. Since this study is limited to 1 year, we consider tableware items that do not reach 90% disintegration over this period as “not degradable”.

Disintegration in an Industrial Composting Facility

Disintegration was tested in an industrial composting facility which follows a standardized procedure according to the German Biowaste Ordinance (BioAbfV 1998): 12-day aerobic thermophilic phase inside a 50–60 m^3 container box without mixing at 55–65 °C, followed by a maturation phase to dry compost outdoors (Fig. 4B).

Three replicates ($n=3$) of each tableware material were placed in a 50 × 38 cm polyethylene/polypropylene plastic sack (5 L volume) with a 5 × 10 mm mesh size, filled with ca. 5 L of organic waste. The sack facilitated contact with the organic waste while preventing item loss. The samples were exposed to three treatments: 12-day thermophilic phase (T1), 24-day extended thermophilic phase (T2), and 12-day thermophilic phase followed by a prolonged maturation phase of 140 days (T3). A set of three sacks per material ($N=35$) were allocated to each treatment. Each item was weighed, measured and photographed before and after treatment. Disintegration (%) was determined by the change in dry weight before and after, along with visual inspection for surface changes, fragmentation, color alterations and biofilm formation. The experiment ran from August 3rd to December 1st, 2021.

International standards dictate that biodegradable plastics must disintegrate by at least 90% within 12 weeks in industrial composting (EN 13432, ISO 17088) and by 81% in home composting (EN 13432). In the absence of standards addressing non-plastic substituents, we apply these thresholds to our tableware materials. The industrial composting site follows the voluntary Compost Quality Assurance (BGK 2024), and thus requires that remnants be <20 mm size. Materials exceeding this size are considered nuisances and removed for incineration (Fig. 4B). Thus, if the tableware items did not reach the required level of disintegration, we consider them as “not compostable”.

Results

Policy Context and Current Waste Management Systems for SUP and Bio-Based Tableware

Study areas count with different policies regulating plastic packaging, organic waste and bio-based materials, with different level of comprehensiveness (Fig. 5). Here only the most important policies are described. The legally binding UN International Plastics Treaty (INC-5.1) (UNEP 2025), currently still in development, aims at ending plastic pollution in the marine and coastal environment following the principles of circular economy. In its latest draft, it includes bio-based, biodegradable and compostable plastics as well as "non-plastic substitutes", stating that it shall be ensured that these alternatives are environmentally sound and safe in replacing conventional plastics, taking into consideration their entire life cycle. This policy instrument will be detrimental in reducing plastic pollution and regulating bio-based materials once it enters into force.

Currently, there are few policies regulating plastic manufacturing, usage and disposal, and even less regulating bio-based alternatives. One of these policies is the European Union (EU) Single-Use Plastics Directive (DIR 2019/904) which targets litter-prone materials made of plastic, expanded polystyrene and oxo-degradable plastic, but also bio-plastics, suggesting that there is no guarantee that they will degrade if littered (DIR 2019/904). In 2022, the EU Commission released a communication on the Policy Framework for Bio-based, Biodegradable and Compostable Plastics (COM 2022/682), although not legally binding, defining the production, marketing, disposal and treatment of bio-plastics, emphasizing that generic claims of "bio-based", "biodegradable" and "compostable" plastics should not be made and clear labelling of bio-based content, disposal and treatment should be considered. It also states that bio-based plastics "should not be considered a solution for inappropriate waste management or littering", and biodegradable options should only be used when reduction, reuse or recycling of plastics is not possible. While compostable plastics are only justified when the environmental benefits are higher than other alternatives, without affecting compost quality, and where collection and treatment exist (COM 2022/682). Although these policies seem to be a stepping stone towards the regulation of conventional plastics, they do not address other bio-based materials, thus it remains unclear how these should be treated.

In Germany, the Packaging Act (VerpackG 2019) regulates packaging waste, promotes recycling, establishes an extended producer responsibility (EPR) system and encourages eco-design. It defines that bio-plastics should be disposed with plastic waste, while certified biodegradable plastics may be disposed with organic waste. For other biodegradable and compostable materials, the same applies (Umweltbundesamt 2023). The German Single-Use Plastics Ordinance (EWKVerbortsV 2021) banned plastic tableware, however with an exception to "materials made from natural polymers that have not been chemically modified". In 2019, Rostock's environmental department mandated the use of reusable or compostable/biodegradable options at public events, except where wastewater discharge is restricted, in which case single-use materials are allowed if they can be mechanically or energetically recycled (AbfS §2 (2) 2023). On Warnemünde beach, only reusable or biodegradable tableware is allowed (e.g., sugar cane, palm leaves, etc.) and bio-plastics like PLA and crystallized PLA are prohibited (Strandsatzung, §8 2021). Compostable packaging and tableware are classified as organic waste and must be disposed of accordingly (AbfS §3 (8) 2023). Event organizers must adhere to these regulations and the city can deny permissions for non-compliance (AbfS §2 (2), 3 2023) (Fig. 5). Despite these measures, enforcement remains challenging due to a lack of clear legal basis for punishing violations (Municipality of Rostock, personal communication, July 2024). Rostock has an efficient waste collection system where plastics, metals, paper and glass are separately collected and recycled, organic waste is composted, and residual waste is incinerated (Table 3). The policies provide a good baseline for management, however in practice bio-based tableware often complicates industrial composting, and mixed waste from coastal festivals hinders separate treatment (Stadtentsorgung Rostock, personal communication, February 2022).

In Lithuania, the Law on the Management of Packaging and Packaging Waste (2001/IX-517) mandates EPR for packaging materials, requiring plastic fractions to be recycled and biodegradable fractions to be composted. The law categorizes disposable plates, cups, sandwich bags, and aluminum foil as packaging waste but excludes disposable cutlery. The packaging shall have an appropriate and certified labelling to identify its material of origin. Producers and importers failing to meet collection, recycling, and reuse face pollution taxes (1999/VIII-1183) (Fig. 5). Klaipeda has underground bring-points for separate waste collection of plastic, paper, aluminum, glass and organic waste (EEA 2022). Despite this, Lithuania's plastic recycling rates reached only 1.9% from materials collected at source and 17.5% from post-collection sorting in 2020 (KRATC 2023). Although separate collection of organic waste is mandated since 2023, food waste still ends up in landfills or incinerators due to insufficient public engagement and lack of infrastructure. Klaipeda's seven composting sites handle only garden waste, encouraging home composting as a solution to the limited capacity (Table 3) (EEA 2022; KRATC 2023).

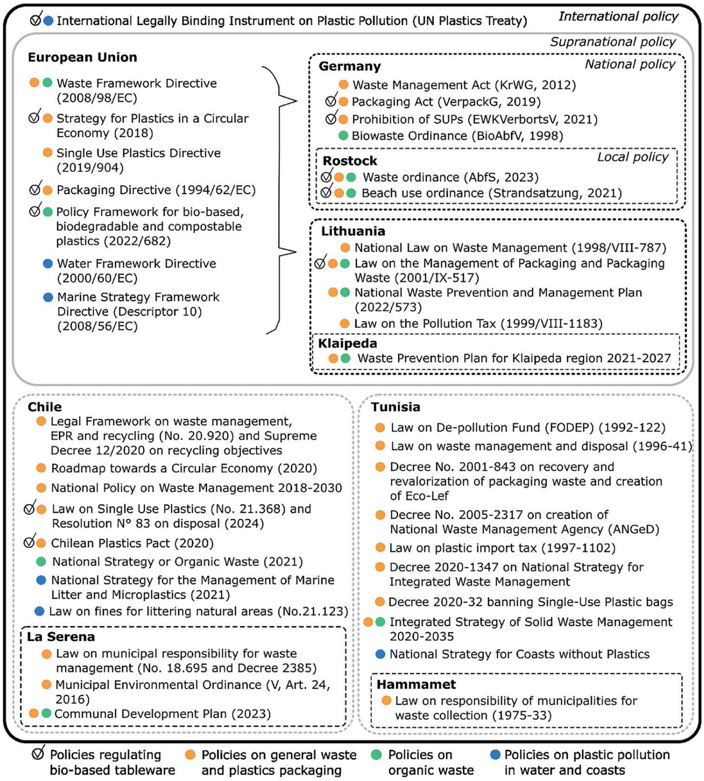


Fig. 5 International, supranational, regional and local policy instruments on general waste, plastic waste, organic waste and bio-based tableware. For details on each policy instrument, please refer to the references

In Chile, the National Strategy for Marine Litter and Microplastics aims to prevent 40% of litter from entering aquatic ecosystems by 2030 through EPR, SUP bans and stakeholder collaboration (MMA 2021a). The Law on SUPs (Law No. 21368) bans single-use containers for in-house dining and mandates the use of reusable alternatives. For takeaway, the law mandates the use of non-plastic or "certified plastic" containers made from at least 20% renewable and compostable materials that degrade within 180 days, either in a home composting system (up to 30 °C) or in an industrial composting system (40–70 °C). The items shall include a label and consumers should get clear information for correct disposal (Resolution 83, 2024). However, industrial composting in the country is scarce. The National Strategy on Organic Waste seeks to increase composting to 66% by 2040, emphasizing home composting (MMA 2021b) (Fig. 5). In La Serena, mixed waste collection is prevalent, with bring-points ("puntos limpios" and "puntos verdes") for paper, aluminum, glass, and plastics (Diario La Región 2013). However, recycling rates are low (4%), and most waste is landfilled or dumped. Although the region counts with 9 dumpsites (INE 2025b), the only sanitary landfill is currently collapsed (SUBDERE 2018). In December 2024, segregate waste collection for plastic and paper/cardboard packaging started in some areas of the city (Municipalidad La Serena 2025). However, with 64% of recycling facilities located in the capital region, logistic and financial challenges hinder waste segregation and recycling efforts due to high transport costs and low market value for plastics (Fundación Chile 2020). The Communal Development Plan envisions constructing a municipal treatment and recycling plant and a composting site by 2028 (Municipalidad La Serena 2023). Consequently, the promotion of bio-based tableware in Chile, particularly in La Serena, is misaligned with the available infrastructure (Table 3).

In Tunisia, the National Strategy "Littoral Sans Plastique" aims to achieve a "plastic-free coastline", through the improvement of waste infrastructure in coastal cities,

Table 3 Waste management infrastructure and treatment of Single-Use plastics (SUPs) and bio-based tableware at the study areas

	Rostock (Germany)	Klaipeda (Lithuania)	La Serena (Chile)	Hammamet (Tunisia)
Waste collection in events and festivals	Predominantly mixed collection, small scale segregation of materials for plastic, glass and paper	Mixed collection	Mixed collection	Mixed collection
Treatment facilities available	Mechanical recycling facilities exist in Rostock for plastic, paper/cardboard, metal, glass Industrial composting plant MBT—Mechanical Biological Treatment	Sorting facility for recyclables MBT—Mechanical Biological Treatment Seven composting facilities (for garden waste only)	No recycling facility in the region. Materials for recycling are transported to the capital city (Santiago de Chile) where recycling occurs at a small scale No composting facility	Partial recycling of plastic containers (Eco-lef) No composting facility
Disposal and treatment of plastic	Plastic bin (door-to-door system) Mechanical recycling	Bring-points for plastics Mechanical recycling or Waste to Energy	Bring-points for plastics (only washed and dried) Not possible for mixed materials Transported to capital city for recycling	No segregate waste collection at source Waste pickers take recyclables to export for recycling
Current treatment of plastic tableware at events	Predominantly Waste to Energy, separately collected plastic is recycled	Waste to Energy	Landfill	Landfill
Disposal and treatment of paper and cardboard	Paper bin (door-to-door system) Due to food rests, it should be disposed in residual waste	Bring-points for paper and cardboard Due to food rests, it should be disposed in residual waste	Bring-points for paper and cardboard Due to food rests, it is not accepted in bring-points for recycling	No separate collection available No separate collection available
Current treatment of cardboard tableware at events	Waste to Energy	Waste to Energy	Landfill	Landfill
Disposal of bio-based tableware	Organic waste bin	No information	No information	No separate collection available
Current treatment of bio-based tableware	Incineration plant	Incineration or Landfill	Landfill	Landfill

circular economy concepts, incentive-based regulatory instruments and awareness raising (World Bank 2022). Law No. 96-41 (1996) mandates waste disposal, reuse and valorization, and Art. 131 of the Tunisian Constitution (2014) delegated this task to municipalities (Chaabane 2020). Currently, waste is collected mixed, with 70% landfilled, 21% openly dumped, and only 4% recycled (Ministere des Affaires Locales et de lÉnvironnement 2019). Despite 63% being organic waste, only 1–2% is treated due to infrastructural gaps (Chaabane 2020). The Integrated Strategy of Solid Waste Management 2020–2035 aims to increase material recycling by 20%, enhance waste recovery by 40% through composting or energy production, and reduce landfilling by 60% (Ministere des Affaires Locales et de lÉnvironnement 2021) (Fig. 5). The Eco-Lef system recovers plastic containers made of polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP) and aluminum (Chaabane et al. 2019); however, performance has declined (Heinrich Böll Stiftung 2020). In this sense, packaging recycling is still premature. In Hammamet, waste management involves both public and private sectors. Waste segregation at source is not effective, and most waste ends up in landfills or dumpsites (Chaabane 2020). The informal sector collects recyclable materials from waste containers or landfills. Organic waste comprises a large proportion of the waste; however, it is not segregated (Municipality of Hammamet, personal communication, November 2021). To our knowledge, there are no national or local policies regulating the use of bio-based, biodegradable or compostable tableware (Table 3).

Quantification of Single-Use Plastic and Bio-Based Tableware Usage at a Coastal Festival

A total of 162 stands (47% drink stands, 53% food stands) were present at the event. During the in-depth assessment, 44 stands were analyzed (27% of total stands), and 715 consumers and 1365 items were counted. From the total items observed, 10% of were single-use plastic, 21% were reusable plastic, 35% were disposable bio-based materials, like cardboard, palm leaves, sugar cane and wood, 31% other waste (e.g., aluminum foil and tissues) and 3% were recyclable items with a deposit (e.g., plastic bottles, glass bottles or cans). Thus, 45% of tableware used was disposable (Fig. 6). The consumption varied per time of day, with 2.22 items per client in the forenoon, 1.73 items per client in the afternoon and 1.91 items per client in the evening. The weighted average tableware usage per client was 1.91.

Here we focus on estimations based on approximate waste weight, according to the item weight, based on manufacturer details (Supplementary data S1). Considering SUP, bio-based and other disposable waste, 1043 items (ca. 4.3 kg) were disposed during the in-depth (11 h) assessment. Extrapolating these values for the entire event (500,000 visitors): 729,718 items or 3.0 tons of consumer waste was generated, corresponding to 16% SUP, 42% bio-based tableware and 43% other waste (e.g., tissues). Thus, 1.8 tons of tableware waste was produced. According to the waste management company, ca. 21 tons of waste were disposed in total during the Hanse Sail in 2023, which includes waste disposed by stands, from consumers, sailing boats and other waste produced during the event (Stadtentsorgung Rostock, personal communication, March 2021). Based on our estimations, the amount of tableware waste represented 9% of the total waste disposed.

Due to the fact that Rostock city and Hanse Sail already have implemented measures to reduce SUPs, majorly replaced by reusable PP cups, the context at Hanse Sail can be considered an improved waste management scenario. According to this, it was estimated that at Hanse Sail ca. 1.8 tons of disposable tableware were generated, equivalent to 3.6 g per visitor, with 16% corresponding to SUP and 42% to bio-based items. In contrast, in a Business-As-Usual scenario we assumed that all tableware used was SUPs, hence 67% SUPs and 33% other waste (e.g. tissues), leading to 2.6 tons of SUP tableware waste. We extrapolated these results to other festivals to provide an insight on tableware usage for waste management (Table 4). Item number was calculated considering a weight of 2–8 g SUP item and 4–29 g bio-based item, based on manufacturer details (Supplementary data S1). In this sense, study areas would need to manage 0.13–3.0 tons of SUP tableware in the Business-As-Usual scenario, or 0.01–0.5 tons of SUP tableware and 0.04–1.3 tons of bio-based tableware in an improved waste management scenario (Table 4).

Social Perception, Awareness and Acceptance of Bio-Based Tableware as Alternative To SUPs

The final survey version, targeting all study areas, obtained 369 valid responses (451 total responses, 82 incomplete responses discarded). From the total of valid answers, 28% were from Germany, 30% from Lithuania, 25% from Chile and 17% from Tunisia. While the intended sample size of

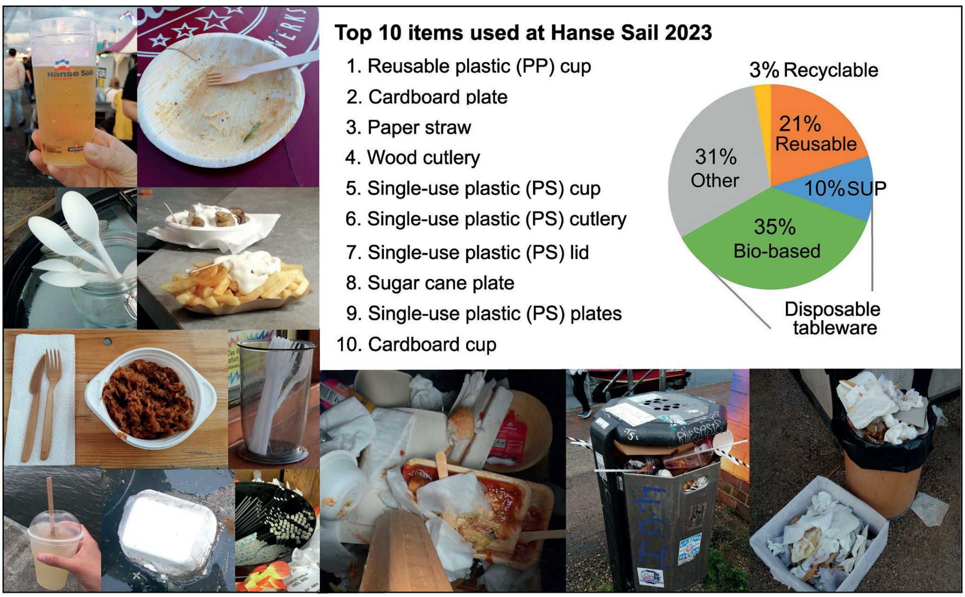


Fig. 6 Top tableware items used by food and drink stands during the Hanse Sail 2023, in Rostock (Germany), and the proportion of Single-Use Plastic (SUP), reusable and bio-based tableware materials, as well as recyclable and other waste. The proportion of disposable tableware was 45%, corresponding to SUP and bio-based items

383 responses per site was not achieved, the dataset still provides valuable insights into public awareness across the four sites. However, the reduced sample size leads to a larger margin of error and limits the statistical power of between-site comparisons. Given the sample sizes obtained per city, the margin of error at a 95% confidence level ranged from $\pm 9.17\%$ to $\pm 12.0\%$ (above the ideal $\pm 5\%$), suggesting that results should be interpreted with caution, particularly in the case of La Serena and Hammamet.

Scientists (28%), end-users (47%), and public administration (11%) were the most represented stakeholder groups, in contrast to waste management (3%), tourism (4%), NGOs (3%) and other (3%). The majority of respondents were aged between 20 and 39 (53%) and 40–59 (31%), and 59% identified as female, 36% as male and 2% as non-binary. Most respondents held a bachelor's (21%) or master's (36%) degree. Moreover, 53% of respondents reported rarely using SUP tableware (1–4 times per year), while 24% use it occasionally (1–2 times a month) and 11% never use it. The pattern was similar across stakeholder groups and countries (Supplementary data S4 and S5).

The assessment on willingness to pay for alternative materials to conventional (disposable) plastic tableware revealed that 73–83% of respondents were significantly more willing to pay than not (Pearsons Chi square test, $p=0.01$). A significant difference in the willingness-to-pay (WTP) for different materials was identified (Kruskal-Wallis test, $\alpha=0.05$ at $p<0.0001$). Respondents exhibited a significantly higher WTP for reusable polypropylene (PP) in comparison to cardboard ($p<0.0001$), palm leaves, sugar cane, and wood ($p<0.0001$) (post hoc Dunn's test, $\alpha=0.05$ at $p=0.0381$). In contrast, a greater WTP for palm leaves ($p<0.0001$), sugar cane ($p=0.0002$), and wood ($p=0.0005$) was observed in comparison to PLA. There was no significant difference in the WTP between reusable PP and PLA, nor between palm leaves, sugar cane, cardboard and wood. As shown in Fig. 7, between 8% and 24% of respondents expressed a WTP an additional expense of 2% or 5% for alternative materials. However, only 5–15% of respondents indicated a WTP an additional 10% or 20%. The majority of respondents (78%) indicated "ecological reasons" as their motivation for paying a higher price.

Comparing responses between different study areas, respondents at all areas were more willing to pay for an alternative material (ca. 70–80%) than not at all. Considering separate WTP levels, respondents from Rostock (65%) and Klaipeda (51%) showed highest WTP for reusable PP, while in La Serena and Hammamet, respondents were both willing to pay for reusable PP (34%) and PLA (24%) (Fig. 7). WTP an additional 2% or 5% fee for alternative materials was similar across sites (Rostock: 1–29%, Klaipeda: 8–31%, La Serena: 13–21% and Hammamet: 10–24%) and between materials. WTP an additional 10% or 20% fee followed the same pattern but it was lower for all materials and sites (Fig. 8). At all sites, the main reason for paying a higher price was "ecological".

Stakeholder groups with most answers, namely public administration, scientists and end-users, were compared. Although the three groups were not equally distributed, and the number of answers is too low to derive accurate statistics, we present here exploratory insights into the results. All groups were more willing to pay for any alternative (79–80%), than not at all (20–21%). Considering separate willingness to pay levels, the three groups reported a higher preference to pay a deposit fee for reusable PP (47–57%) (Supplementary data S6). WTP an additional 2% or 5% fee for alternative materials was similar across stakeholder groups with similar WTP for sugar cane, palm leaves, cardboard and wood. WTP an additional 10% or 20% fee followed the same pattern but it was lower for all materials

Table 4 Estimation of SUP and alternative tableware generation in coastal festivals in the different study areas based on a Business-As-Usual scenario considering only SUP usage and an improved management scenario considering 16% SUP and 42% alternative materials

Event and location	Event duration	Number of visitors	Total waste collected during event	Total number of SUP tableware items used (Business as Usual)	Total number of SUP tableware (Improved Waste Management, 16% SUP)	Total number of Bio-based tableware (Improved Waste Management, 42% Bio-based)
Hanse Sail (Rostock)	4 days	500,000 (2023)	21 tons[a]	2.6 tons (325,500–1.3 million items)	0.5 tons (62,500–250,000 items)	1.3 tons (45,000–325,000 items)
Klaipeda Sea Festival (Klaipeda)	3 days	ca. 500,000 (2023)	20–30 tons (mean = 25 tons)[b]	3.0 tons (375,000-1.5 million items)	0.3 tons (37,500–150,000 items)	0.9 tons (31,000–225,000 items)
Festival de La Serena (La Serena)	2 days	25,000 (2019)	No data	0.13 tons (15,000–65,000 items)	0.01 tons (1,250 −5,000 items)	0.04 tons (1,400–10,000 items)
International Carnival of Yasmine Hammamet (Hammamet)	4 days	ca. 30,000 (2019)	No data	0.16 tons (20,000–78,000 items)	0.02 tons (2,500–10,000 items)	0.05 tons (1,700–12,500 items)

For Hanse Sail and Klaipeda Sea Festival, estimations derive from waste collected values. For the other two events, estimations are based on visitor numbers and values from Hanse Sail as reference

References: [a] Stadtentsorgung Rostock (2024) (personal communication), [b] Ecoservice (2023)

(Supplementary data S6). For all stakeholder groups, the main reason for paying a higher price was "ecological".

Regarding the relevance of criteria when choosing an alternative material to conventional plastic tableware, significant differences were observed (Chi Square test, Bonferroni correction, $\alpha = 0.05$, $p < 0.0001$). Ecological footprint (30%) was ranked significantly most important, (Pairwise comparison tests with Benjamini and Hochberg correction, $p < 0.05$), while market costs (51%) were ranked significantly least important ($p < 0.05$) (Fig. 8B). Furthermore, significant differences were observed in the reported importance of criteria in the one-to-one comparison (Chi square test with Bonferroni correction, $\alpha = 0.05$, $p < 0.0001$). Degradability was reported significantly less important than ecological footprint (Pairwise comparison tests, Benjamini and Hochberg correction, $p < 0.0001$), and significantly more important than market price ($p < 0.0001$). Recyclability was considered significantly more important than market price ($p < 0.0001$). Ecological footprint and the presence of additives were reported significantly more important than market price (both $p < 0.0001$) (Fig. 8A). In contrast, degradability and recyclability, degradability and additives, recyclability and ecological footprint, recyclability and additives, and ecological footprint and additives were considered equally important when compared to one another. The ranking of criteria was similar between stakeholder groups and between countries ($p > 0.05$) (Fig. 8A). In regards to the one-to-one comparison of criteria, stakeholders showed similar evaluations as well (Supplementary data S7).

The assessment of the awareness and perception on the potential impact (positive and negative) of each material in regards to degradability, compostability, mechanical and energetic recyclability, and presence of additives and chemicals, revealed that for degradability (Pearson's Chi Square test, $\alpha = 0.05$, at $p = 0.003$), mechanical recyclability ($p = 0.0002$) and presence of additives ($p = 0.0467$) a significantly higher number of "I do not know" answers obtained compared to other concepts.

In general, PP, PS and PLA were more negatively perceived for most concepts, in contrast to sugar cane (SC), palm leaves (PL), cardboard (C) and wood (W) which were perceived more favorably (Fig. 9). Degradability, compostability, energetic recyclability, the presence of additives and harmful substances, and ecological footprint were in general perceived more positively for SC, PL, C and W than for PLA, reusable PP and disposable PS tableware. In contrast, mechanical recyclability was perceived similar

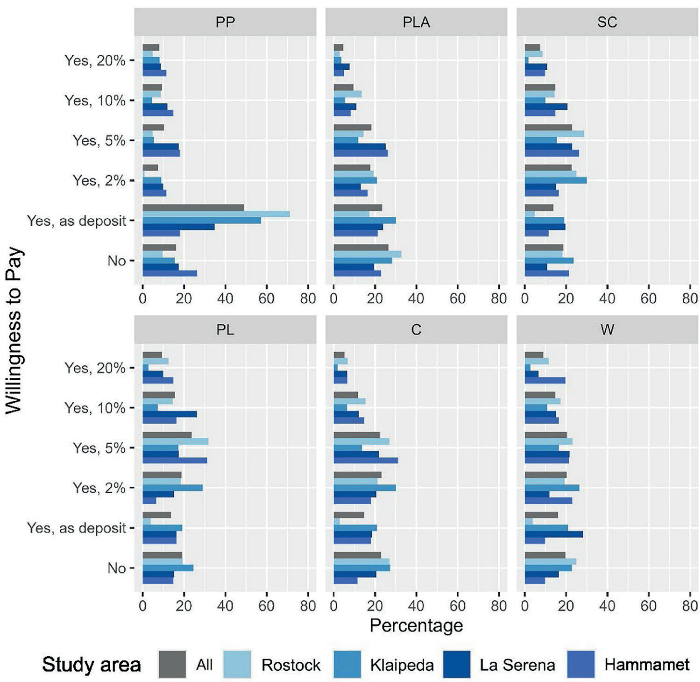


Fig. 7 Willingness to Pay for alternative materials to replace SUP tableware namely reusable Polypropylene (PP), Polystyrene (PS), Polylactide Acid (PLA), sugar cane bagasse (SC), palm leaves (PL), cardboard (C) and wood (W), based on all answers (367) and per study area: Rostock (104), Klaipeda (110), La Serena (92), Hammamet (61). For the results based on stakeholder groups, see Supplementary data (S6)

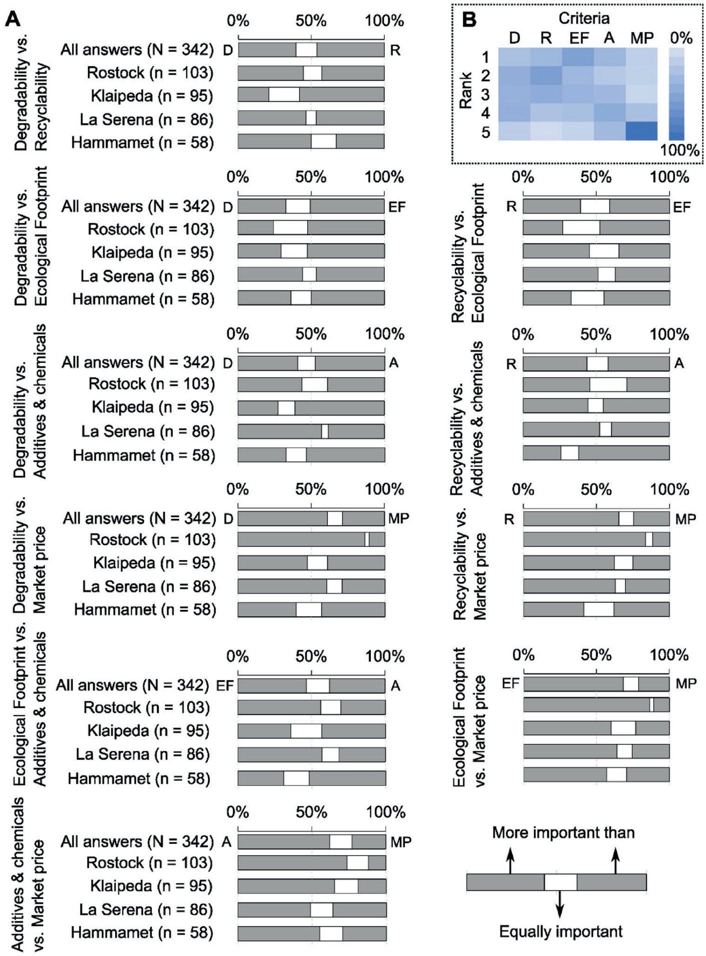


Fig. 8 **a** One-to-one comparison on the importance of criteria for the selection of alternative tableware materials from all respondents (342) and per country: Rostock (103), Klaipeda (95), La Serena (86), Hammamet (58). Here, D = Degradability, R = Recyclability, EF = Ecological footprint, A = Additives and chemicals, and MP = Market price. **b** Ranking of the importance of criteria, according to the percentage of answers (0–100%) from all respondents. Results separated per stakeholder group available in the Supplementary data as S7

and rather positive across all materials. The perception of materials across the stakeholder groups was found to be very similar. Scientists expressed slightly more negative perceptions regarding mechanical recyclability for SC, PL, C and W. Energetic recyclability of PP, PS and PLA was perceived slightly more negatively by end-users. Lastly, a higher proportion of "I do not know" answers were reported by end-users (Fig. 9). The perception of materials across different study areas was also similar (Supplementary data S8). Respondents from Rostock perceived mechanical recycling of PLA, SC, PL, C and W more negatively, and the presence of additives in SC, PL, C and W more positively than respondents from other sites. Respondents from Hammamet perceived both mechanical and energetic recyclability of all materials more positively. Lastly, a higher proportion of "I do not know" answers were reported for Klaipeda, La Serena and Hammamet (Supplementary data S8).

The assessment of public awareness regarding the disposal of materials showed that 59% of respondents think PLA should be disposed in the plastic bin, while only 14% assigned this waste to organic. Between 45% and 62% think sugar cane, palm leaves and wood are to be disposed in the organic bin. Moreover, 10–17% assigned alternative materials to be disposed in residual waste. Finally, between 3%

and 12% recognizes not to know where to dispose alternative materials, especially wood (Fig. 10). The answers were similar across stakeholder groups, however, a lower proportion of public administrators indicated PLA to be disposed in the plastic bin and a higher proportion reported wood to be disposed in the organic bin, in contrast to scientists and end-users (Supplementary data S9). Comparing study areas, a higher proportion of respondents from Rostock assigned alternative materials to residual waste (19–37%) in comparison to respondents from other sites. In Hammamet, PLA was assigned to plastic waste by 14% of respondents, in contrast to 59–67% at other sites. Lastly, the proportion of "I do not know" answers were higher in Hammamet (Supplementary data S10).

Disintegration of Bio-Based Tableware in Estuarine Water and at an Industrial Composting Facility

Items were exposed to the brackish water of the Warnow estuary at three locations for an average of 365 days. Water temperature ranged between 5 °C during winter to 19 °C during summer, with very low differences (up to 1 °C) between upper and lower layers. Salinity was between 5.9 and 13.2‰, with differences of 0.06–3.7‰ between the upper and lower layers. pH was between 7.05 and 8.7 constant throughout the year. Dissolved oxygen was 7.9–12.1 mg l^{-1} with differences of 0.04–1.7 mg l^{-1} between layers and slightly lower during the summer.

In coastal brackish water, sugar cane (SC), palm leaves (PL), and starch-coated cardboard (CC), were the only materials achieving disintegration after 1 year, with rates of 0.2–0.5% d^{-1}, 0.1–0.6% d^{-1}, and 0.1–0.7% d^{-1} (Fig. 11), and final disintegration of 66–100%, 32–100% and 32–100%, respectively. Conversely, wood (W), (crystallized) polylactic acid (CPLA/PLA) and polystyrene (PS) showed no disintegration over nearly 1 year. Disintegration rates for SC, PL and CC varied minimally between estuary locations, with differences of 0.1–0.2% d^{-1}. Lower layers generally showed lower disintegration (10–69% less than upper layers) (Baccar Chaabane et al. 2022). The materials

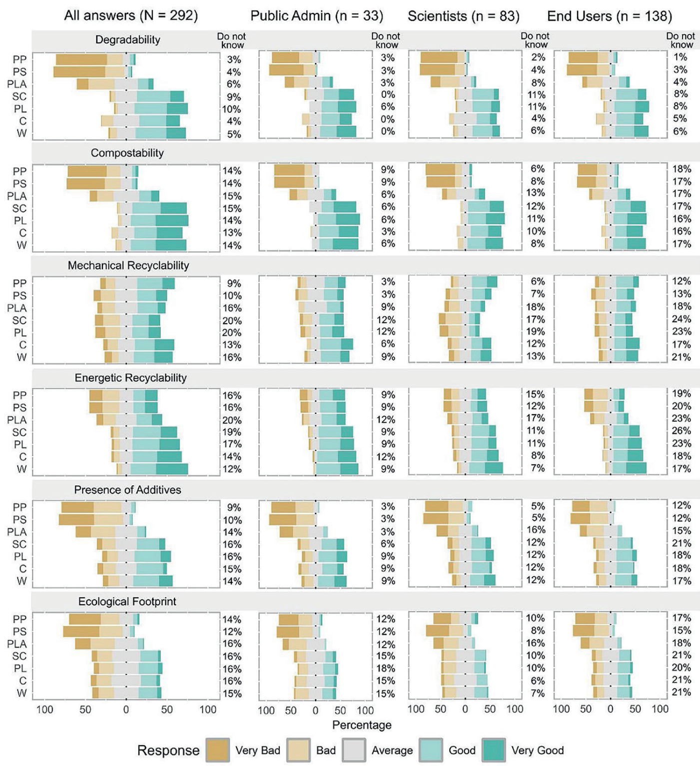


Fig. 9 Perception on degradability, compostability, mechanical and energetic recyclability, presence of additives and ecological footprint of alternative materials to replace SUP tableware, namely reusable Polypropylene (PP), Polystyrene (PS), Polylactide Acid (PLA), sugar cane bagasse (SC), palm leaves (PL), cardboard (C) and wood (W), considering all answers (N=292) and per stakeholder group. Results from the test survey not included, since definitions of the criteria were adapted. Survey results separated per study area, available in the Supplementary data as S8

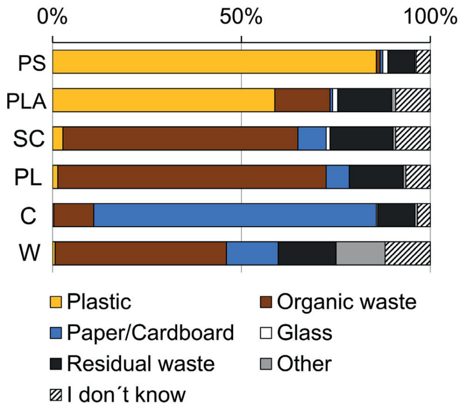


Fig. 10 Awareness on the correct disposal requirement for the alternative materials to replace SUP tableware ($n=294$), namely polystyrene (PS), Polylactide Acid (PLA), sugar cane bagasse (SC), palm leaves (PL), cardboard (C) and wood (W). Survey results separated per stakeholder group and study area in Supplementary data as S9 and S10

displayed signs of disintegration, such as surface roughening, holes, cracks, color changes and biofilm formation (see Baccar Chaabane et al. 2022). According to the ISO 22766 standard, >90% of visual disintegration should occur within ≤3 years. The low number of replicates did not allow for statistical analyses, however the slow disintegration rate and the fact that only three materials fully disintegrated within 1 year is of concern.

At the industrial composting facility, PLA was the only material achieving disintegration within the EN 13432 standard, with highest disintegration rate in all treatments: 7.7% d^{-1} in T1, 3.8% d^{-1} in T2 and 0.6% d^{-1} in T3, and a final disintegration of 91–92% at all treatments, leaving only a powder residue (Figs. 11 and 12). Lower disintegration rates were observed for palm leaves (PL), coated cardboard (CC) and wood (W) at all treatments, with 0.1–0.5% d^{-1}, 0.1–0.4% d^{-1} and 0.0–0.3% d^{-1}, respectively, and reaching 32%, 18% and 7% final disintegration at T3 (152 days). For sugar cane unbleached (SCU), a higher disintegration was observed at T1 (1.0% d^{-1}) vs. T2 (0.2% d^{-1}), while for uncoated cardboard (C) a higher disintegration was observed at T2 (1.6% d^{-1}) vs. T1 (0.6% d^{-1}) or T3 (0.1% d^{-1}) (Figs. 11 and 12). Materials also displayed signs of surface roughening, holes, cracks, color changes and biofilm formation (Fig. 12). Although organic residues attached to the items (even after drying and cleaning) likely influenced dry weight results, the low level of disintegration in nearly all materials suggests that conditions to be labelled as "biodegradable" or "compostable" were not met, and cardboard (un-/coated),

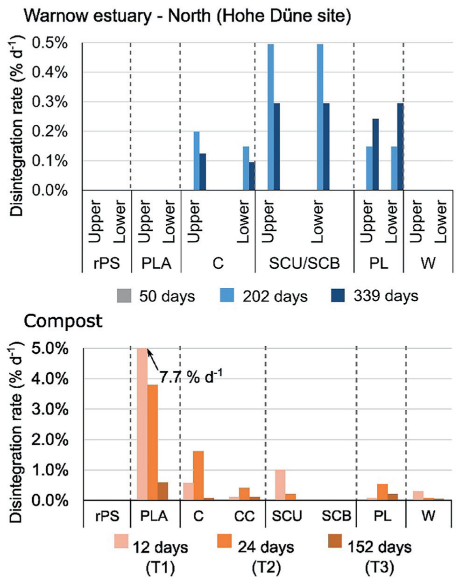


Fig. 11 Disintegration rate for the different materials, namely recycled polystyrene (rPS), polylactic acid (PLA), cardboard (C), cardboard coated with starch (CC), sugar cane bagasse unbleached (SCU), sugar cane bagasse (SC), palm leaves (PL) and wood (W), presented as the difference in weight before and after experiment period (% d^{-1}) in a brackish estuary system (here Hohe Düne, for other sites see Baccar Chaabane et al. 2022) and in compost

sugar cane (un-/bleached), palm leaves and wood did not reach <20 mm in size, thus are subject to incineration.

Discussion

Discrepancy between Policy Goals and Waste Management Infrastructure: Implications for Plastic Litter Pollution

The issue of reducing SUP pollution has been identified as a key concern in all study areas, as evidenced by the implementation of national strategies and policies aimed at addressing marine litter. Despite the existence of policy instruments for the reduction of plastic waste in all areas, with many aiming for a replacement (Fig. 5), the policy analysis revealed that the regulation of bio-based materials, and specifically tableware, is still in early stages, and there is a lack of translation towards waste management infrastructure (Table 3).

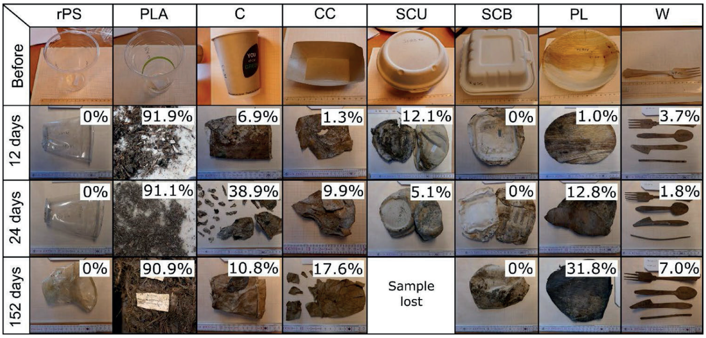


Fig. 12 Total disintegration of tableware items at the industrial composting site, after each treatment: T1 (12 days in rotting phase), T2 (24 days in rotting phase) and T3 (rotting + maturation phase, 152 days), namely recycled polystyrene (rPS), polylactic acid (PLA), cardboard (C), cardboard coated with starch (CC), sugar cane bagasse unbleached (SCU), sugar cane bagasse bleached (SCB), palm leaves (PL) and wood (W). Here only one exemplary replicate per sample material is shown

At Hanse Sail, considering an "improved management" scenario with two regulatory policies to replace SUPs with biodegradable and compostable materials, we estimated 0.5 tons of SUPs and 1.3 tons of bio-based tableware waste would be generated. Despite Rostock's (Germany) higher economic prosperity, infrastructural development and robust environmental commitment (Table 1), the majority of waste at social events is collected mixed, and tableware made of plastic and bio-based materials is incinerated, despite the presence of an efficient waste management infrastructure (Table 3).

At Klaipeda, an estimated 3.0 tons of SUP waste would be generated during a "business-as-usual" scenario, while at an "improved management" scenario 0.3 tons of SUP and 0.9 tons of bio-based tableware would be generated. Despite Klaipeda (Lithuania) being classified as a site exhibiting moderate socio-economic and environmental performance, segregation at source and material recycling remains inadequate. The absence of industrial composting facilities (Sect. 3.1) suggests that the waste generated during a coastal festival would most likely be incinerated or landfilled.

The waste management in La Serena and Hammamet is further challenged by the fact that these sites still rely on landfill sites for the disposal of waste; and recycling as well as composting in both regions is negligible (Table 3). In La Serena (Chile), a site characterized by moderate socio-economic and environmental performance (Table 1), waste segregation at source is insufficient and recycling is highly centralized (Table 3). In the Chilean Law on SUPs, the explicit recommendation is made for the utilization of "certified" compostable tableware materials to replace SUP tableware, with the aim of reducing plastic tableware pollution from coastal zones. At La Serena, an estimated 0.13 tons of SUP waste would be generated in a "business-as-usual" scenario, and 0.01 tons of SUP and 0.04 tons of bio-based tableware waste in an "improved management" scenario. Despite the comparatively low quantities, La Serena's inability to provide segregated waste collection, an industrial composting site, or recycling facilities in the immediate vicinity indicates that, at present, these materials cannot be treated in accordance with the policy. Moreover, the fact that the city is dependent on a landfill site that has reached capacity poses a significant challenge in terms of the management of disposable waste.

Finally, Hammamet (Tunisia) was the site with lowest socio-economic and environmental prosperity in our study (Table 1). Despite the existence of various national-level policies, policies at the municipal level are limited, and the translation of these policies for waste management is hampered by a lack of resources and expertise (Chaabane 2020) (Table 3). Here, approximately 0.16 ton of SUP waste would be generated in a "business-as-usual" scenario, and 0.02 tons of SUP and 0.05 tons of bio-based tableware waste in an "improved management" scenario. Despite the lower quantity of waste than at other sites, the waste segregation at source in Hammamet is restricted to plastic bottles alone (Eco-Lef system). There is no treatment facility for organic waste, and consequently, all waste is landfilled. In this regard, the prevailing infrastructure is inadequate in addressing SUP items and is incapable of handling biodegradable or compostable tableware.

In none of our study areas were policies aligned with the waste infrastructure available and this discrepancy indicates a risk of not solving the reliance of SUPs, but instead creating a new litter item by introducing materials that cannot be properly managed. To our knowledge, there is no policy addressing bio-based materials in the study areas other than "bio-plastics", thus the COM 2022/682 and the Law on SUPs in Chile are the closer examples to policy instrument addressing bio-based, biodegradable and compostable materials. However, based on our study, none of the requirements stipulated in the COM 2022/682 or the Chilean Law on SUPs are followed, since adequate collection and treatment does not occur, none of the items used in this study were accompanied by a label specifying their material of origin, type of treatment or disposal requirements. Finally, the fact that bio-based tableware is still aimed for single-use, does not align with the requirement to prioritize reuse, and use biodegradable options only in situations where the reduction, reuse or recycling of plastics is not possible (COM 2022/682).

Insufficient Disintegration of Bio-Based Tableware in Real Environments

The results of the disintegration experiment in estuarine water (Baccar Chaabane et al. 2022) demonstrated that tableware composed of sugar cane bagasse, palm leaves and cardboard disintegrated by >90% within 1 year, which is within the requirements set in standard ISO 22766. Although this study was limited to 1 year, and a second year of exposure (as set by ISO 22766) would possibly lead to higher disintegration in other materials, the slow disintegration rate is already a matter of concern. To date, few studies have tested the disintegration and degradability of bio-based tableware materials in real environments, with the majority of studies focusing on bio-plastics (Folino et al. 2020; Rudnik 2019b; Zhang et al. 2017). In this study, only PLA is a bio-plastic, and did not disintegrate after 1 year in water. The higher disintegration observed for the upper water column layers in the Warnow estuary remains unclear and may depend on various physical, chemical and biological parameters (Moncmanová 2007; Serrano-Aguirre and Prieto 2024). A study identified sunlight conditions as a contributing factor to PLA disintegration (Beltrán-Sanahuja et al. 2020). However, the exposure of PLA samples to brackish water for 1 year in this study did not result in any observable effects. Further research is necessary to provide reliable conclusions on the effects of salinity, pH, sunlight, temperature and oxygen availability in estuarine systems. Nevertheless, our results showed that the disintegration of PLA and wood in estuarine water was negligible, thus, if these items are littered into coastal waters, they may persist as pollutants for a long time.

The disintegration of bio-based tableware in the industrial compost was also insufficient. While four out of six materials used in this study were labelled as “compostable”, our disintegration experiments demonstrated that only PLA tableware disintegrated by >90% within 12 days, while all other items exhibited remarkably low disintegration rates. We did not find other studies assessing the disintegration of bio-based materials in industrial compost; thus, we revised studies carried out in other environments. Consistent with the findings of this study, a previous investigation found a 90% degradation of PLA after 36 days in anaerobic digestion (Hegde et al. 2019) and 85% after 70 days in sludge (Yagi et al. 2013). Another study established observed a 52% disintegration of food bowls from a hybrid fiber of sugar cane bagasse and bamboo after 60 days in soil (Liu et al. 2020). Similar results were observed for a plate made of tapioca starch and sugar cane bagasse, which reached 56% disintegration in soil after 2 weeks (Wahid et al. 2019). In the present study, sugar cane bagasse (un-/bleached) (labelled as 100% compostable) fully disintegrated in brackish water, however disintegration in the industrial composting site was negligible (0–12.1%). A study conducted by Wahid et al. (2019) demonstrated that plates made of tapioca starch and oil palm fiber exhibited 61% disintegration in soil after 2 weeks. In the present study, plates and bowls made of areca palm sheath fully disintegrated in brackish water, but only disintegrated 1– 32% in the industrial composting site. Cardboard has shown rather low disintegration due to high lignin content (Venelampi et al. 2003), however, no studies were found on the disintegration of cardboard tableware in the environment.

The fact that the majority of the tableware items did not disintegrate during the 12-day aerobic thermophilic phase at 55–65 °C, nor after a prolonged maturation phase of 152 days, indicates that these materials may pose a problem in home composting systems operating at lower temperatures. In most industrial compost facilities, organic waste has only about 2–4 weeks to rot. An extension of this process is usually not economically viable. In this sense, regardless of whether tableware waste at coastal festivals is segregated at source and composted as recommended by policy regulations, problems of insufficient disintegration arise. Due to this, most if not all materials are subject to incineration or landfill. The low level of disintegration of PLA and wood in water, and cardboard (un-/coated), sugar cane (un-/bleached), palm leaves and wood in compost suggests that conditions set in the standards EN 13,432 and ISO 17,088 were not met. Our study suggest that the conditions tested to grant standards may not accurately reflect real environmental conditions, which has also been argued by Haider et al. (2019).

Social Misperception and Lack of Awareness on the Environmental Impact and Disposal of Bio-Based Tableware

Society plays a significant role in the implementation of policies, and thus evaluating their perception becomes crucial. The survey results indicated that the general public held a more positive perception of bio-based materials, such as sugar cane, palm leaves, cardboard and wood, in comparison to PLA and reusable PP. In general, degradability and compostability were perceived more positively for sugar cane, palm leaves, cardboard and wood than for PLA. The perception of degradability is in line for sugar cane, palm leaves and cardboard, however, wood did in fact not disintegrate in water nor compost. Similarly, PLA which was perceived negatively for compostability was in fact the only material that disintegrated by >90%.

Mechanical recyclability was perceived similar and rather positive across all materials. However, this process works best for materials that retain their properties throughout multiple recycling cycles. PS losses quality after four recycling rounds (Pin et al. 2023), whereas paper after 25 times (Procarton 2021). A study suggested that palm leaves could be mechanically recycled; however due to a loss in quality, they could only be used as secondary material (Faiad et al. 2022). Energetic recyclability was perceived more positively for sugar cane, palm leaves, cardboard and wood. Incineration is most effective for materials with high energy content, relatively low moisture content and a composition dominated by carbon, hydrogen and oxygen, since combustion of nitrogen, sulfur and chlorine components may lead to toxic gases (Rosenboom et al. 2022). The composition of bio-plastics and other bio-based materials is not fully disclosed, and the potential for air pollution resulting from the presence of additives and chemicals cannot be ignored.

In this regard, the presence of additives and harmful substances was perceived more negatively for PP, PS and PLA than for sugar cane, palm leaves, cardboard and wood. A recent study reported that plastics contain approximately 16,000 different chemicals and additives, including plasticizers, stabilizers, flame retardants, etc. (Wagner et al. 2024). A study assessing the presence of additives from plastic tableware during use, disposal and recycling, found that the release of these additives can occur in contact with food as well as with the environment (Hahladakis et al. 2018). However, the presence of harmful chemicals has also been reported for sugar cane, palm leaves cardboard and wood. Various studies have found the presence of pesticides, per- and polyfluoroalkyl substances (PFAS), fluorotelomer alcohol and heavy metals (BEUC 2021; Bouma et al. 2024; Geueke et al. 2018).

The ecological footprint was perceived negatively for reusable PP, PS and PLA, and positively for sugar cane, palm leaves, cardboard and wood. The ranking of criteria, as well as the one-to-one comparison of criteria in our survey, suggested ecological footprint as the most important criterion for selection of a SUP alternative. The majority of life-cycle assessment studies have been conducted on bioplastics, suggesting they could potentially lead to lower reliance on fossil fuels, lower greenhouse gas (GHGs) emissions, and lower carbon footprint (Moshood et al. 2022; Nandakumar et al. 2021; Rosenboom et al. 2022; Serrano-Aguirre and Prieto 2024). But other studies have suggested a higher ecological footprint from the use of land, feedstock, water, energy, acidification, eutrophication and GHGs emissions (Brizga et al. 2020; Manfra et al. 2021; Mastrolia et al. 2022; Rosenboom et al. 2022). With regard to other bio-based materials, the ecological footprint may also be high. Research has indicated that the carbon footprint of palm leaves is significant, primarily due to the material transport from Asia and the energy source used for production (Korbelyiova et al. 2021). Similarly, cardboard plates also showed a high carbon footprint mainly associated to plastic coating (Korbelyiova et al. 2021). No peer-reviewed studies were found assessing the ecological footprint of sugar cane and wood tableware. Even though only 0.02% of the global agricultural area is used for bio-plastic production (European Bioplastics, 2018), this material is already exerting pressure on water scarcity, species extinction, desertification and the loss of natural habitats in certain regions (Heinrich Böll Stiftung 2019). Overall, the biased perception in favor of sugar cane, palm leaves, cardboard and wood and against PLA does not align with the disintegration observed in water and compost (Figs. 9 and 11) nor the potential environmental impact of the materials.

Market costs were seen as the least important criterion for selection of alternative materials. The survey results indicated that around 10–25% of respondents were willing to pay a higher price for alternatives and ca. 50% preferred a deposit system for reusable PP, with similar results across countries. However, consumers seem to lack knowledge about the potential environmental impact and disposal of the materials. As demonstrated by Ansink et al. (2022) consumers are often confused and misinformed regarding the correct disposal of bio-plastic items. In their study, people were invited to consume a beverage in a bio-plastic cup and subsequently dispose of it in one of three different bins. Although the material of the cup was described, 90% consumers disposed the cup wrongly together with plastic waste. In the present study, about 60% of respondents indicated that PLA is to be disposed of in the plastic bin, when in fact it should be composted. In addition, 45–62% of respondents suggested other bio-based materials to be disposed of in the organic bin, when in fact the infrastructure is not equipped to cope with the slow decomposition. None of the tableware in this study contained information regarding disposal requirements. The lack of knowledge regarding correct disposal which was similar across countries and stakeholder groups, suggests that this lack of information is not confined to any particular social group or geographical region, regardless of economic prosperity, educational access and environmental performance. In this sense, despite the willingness to use different alternatives, the absence of information in the packaging can potentially increase littering as argued in other studies (Filho et al. 2021; Haider et al. 2019). Thus, it is essential to assess the awareness and perception of society to evaluate the effectiveness of future of policies.

Improving Waste Management at Coastal Festivals

Coastal festivals can exert a variety of pressures on the coastal zone, including noise pollution, changes to beach geomorphology, trampling on dune vegetation (Andriolo and Gonçalves 2023) and litter pollution (Abdulredha et al. 2018; Gomes et al. 2007; Mateu-Sbert et al. 2013; Schernewski et al. 2024). All study areas are subject to litter pollution, and coastal festivals likely contribute to this problem.

There are few studies assessing the waste generation and littering behavior at coastal festivals (Cierjacks et al. 2012), thus further research on quantities and types of waste generated are needed to derive mitigation measures. Still, various studies have shown that it is possible to make festivals more sustainable, by including a higher number of bins, material segregation, reduce unnecessary waste or introducing reusable options (Bianchini and Rossi 2021; Martinho et al. 2018; Šuškevičė and Kruopienė 2021). A good example was seen in Portugal where deposit systems, reusable mugs and cutlery were implemented. Here, waste segregation achieved a rate of 47%, and 67% of attendees showed awareness and participated in some form of waste prevention measure (Martinho et al. 2018). The success of waste prevention initiatives will depend on the commitment of festival attendees, consumer behavior, awareness, perceived efficacy, convenience of the measure, outreach communication and participation (Hottle et al. 2015). Moreover, it becomes important to assess the knowledge of different stakeholder groups and combat misconceptions, in case they exist, in order to derive measures that do not lead to greenwashing. The replacement of SUPs for another disposable product, labelled as “biodegradable” or “compostable” has been demonstrated to lower perceived responsibility and increase littering behavior (Ansink et al. 2022; Filho et al. 2022; Nazareth et al. 2022).

A study assessed the ecological footprint of disposal mechanisms for different waste types generated during a festival, and examined seven waste management scenarios. Their results found that scenarios considering recycling and composting of different waste materials (i.e. PP, PET, PE, aluminum, PLA, organic, paper and cardboard) had lower CO_2 emissions and energy consumption than scenarios were landfill disposal or only composting was considered (Hottle et al. 2015). In light of their results and this study, a combination of reusable PP and PLA, ensuring segregated collection and composting, could be a potential alternative to reducing the use of disposable conventional plastic. However, at all our study areas, segregate collection and securing an adequate treatment for materials is one of the main challenges. While the collection of segregated materials is possible, the problem arises when PLA tableware is littered in coastal waters, where they have shown negligible disintegration.

Deposit systems have the potential to address this issue, offering the convenience of single usage while prioritizing reuse. These systems use reusable tableware, such as cups or bowls made of hard plastic, glass or other materials, and are available for nominal fee which is typically incorporated into the cost of the beverage or meal. After usage and return, the deposited fee is returned to the customer. The system ensures the removal of single-use items from the market and allows a sense of environmental engagement and loyalty among the tourism sector. However, whether reusable options are environmentally better than disposable ones, will depend on factors like reuse cycles, washing settings, material type, consumer behavior and potential littering into the environment (Pålsson and Olsson 2023). Some studies indicate lower CO_2 emissions and global warming potential from reusable tableware (Camps-Posino et al. 2021; Yadav et al. 2024), while other studies suggest single-use bio-plastics to be more environmentally friendly (Genovesi et al. 2022). Other studies suggest a minimum usage between 10 (Garrido and del Alvarez 2007) and 150 times (Cottafava et al. 2021) for reusable cups to be more environmentally friendly than single-use options. It is evident that further research is required in this domain to reach definitive conclusions.

Assessment of the Methods and Future Research

The assessment of tableware usage at Hanse Sail was based on a screening of all stands and deep analysis duringnoon, afternoon and evening to assess for variations in usage, however, it is possible that important fluctuations of consumption were missed. The Hanse Sail 2023 was subject to rain and wind, which may have resulted in lower visitor numbers and tableware usage. Moreover, our estimations may differ from waste bin analyses. Future studies could make a comparison between both methods to assess tableware usage and waste after each day of the event.

With regard to the social survey, the distribution of answers across different stakeholder groups was limited by the number of responses available, and it is a weakness of the results. Similarly, the limited number of responses from the waste management sector (9), tourism (12) and NGOs (8) did not allow for comprehensive analysis. The survey also included questions directed at sellers; however, these had to be discarded due to an insufficient number of responses. Despite the fact that the intended sample size of 383 responses per site was not achieved, the final dataset of

369 valid responses provides valuable insights into public awareness across the four sites. The reduced sample size, however, gives rise to a larger margin of error and limits the statistical power of between-site comparisons. Despite these limitations, the survey offers exploratory insights into public awareness of material disposal in distinct socioeconomic contexts, and as part of a mixed-methods approach, it complements the broader analysis presented in this study. Nevertheless, further research including a larger sample size for different stakeholder groups would be beneficial to assess differences in perception based on professional background.

More studies are required assessing the degradation of bio-based, biodegradable and compostable tableware, also non-plastics, in real environments. This study only considered physical changes; however, future studies should consider factors like CO_2 production and assimilation. Moreover, this study did not test disintegration of used tableware and wetness could play an important role to accelerate it. Finally, there is only one standard assessing disintegration of bio-plastics under real field conditions (ISO 22766:2020) which states $>90\%$ of visual disintegration should occur over ≤ 3 years. Our experiment in estuarine water was limited to 1 year, thus further research should consider longer testing periods. Nonetheless, the results obtained provide valuable insights into the presence or absence of materials after a designated period of time, facilitating the assessment of their potential to persist as pollutants in the environment. In the composting site, a comparative approach would be appropriate using larger mesh sizes to allow more exchange with the organic material. Nevertheless, the fact that some materials disintegrated completely, in contrast to others, indicates that the majority of items were not compostable even after 152 days. In the case that alternative non-plastic tableware usage keeps expanding, standards to assess degradability under real field conditions are urgently needed.

Conclusion

Single-use plastic tableware, being among the top ten most found items on beaches worldwide, has been banned in the European Union and may be within the items soon to be banned at an international level through the International Plastic Treaty. Concomitant with this decision, there has been a surge in the popularity of biodegradable, compostable and bio-based alternatives in the market, which are being promoted as a solution to plastic pollution. The findings of this study demonstrate that the adoption of different bio-based materials is faced by challenges concerning their disintegration in water and compost, in addition to their potential environmental impacts, posing various barriers in the study areas analyzed.

First, biodegradability and compostability in real environments cannot be guaranteed. The degradability for which bio-based materials are advertised for, is seen to contribute to lower plastic pollution, circular economy and diverging from fossil fuels reliance. However, this and other studies have demonstrated that disintegration depends on material properties and the environment they are exposed to. While bio-plastics like PLA could disintegrate quickly in compost, this does not occur in brackish water and very few studies have tested this process with other bio-based materials in real water environments. Secondly, the discrepancy between policy ambitions and waste management realities hinders effective circular economy practices. The disposal of bio-based tableware is often problematic due to inadequate infrastructure, with the majority of such items being incinerated or landfilled. In essence, these items are designed for single-use, and if they are discarded in coastal areas, they can contribute to pollution due to their low disintegration. Third, the lack of information regarding material properties, environmental impacts and disposal requirements can resulted in misperception and confusion among various societal groups, as it was observed in our results.

To address the challenge of single-use plastics (SUPs) and litter pollution in coastal areas, it is crucial to strengthen waste management infrastructure, especially with regard to segregated collection and recycling in touristic areas. To this end, policymakers and governments must ensure sufficient funding for the establishment of separate collection systems and adequate treatment of alternative materials, in order to fulfil the goals set out in policy plans. Furthermore, businesses must test the degradation of materials under real field conditions and assess potential negative environmental externalities throughout the entire life cycle, as recommended by the International Plastic Treaty. They must also provide transparent information on the origin of materials and additives, as well as clear labelling on disposal requirements, to inform the public and ensure correct disposal. Finally, society must be educated to differentiate between the terms “bio-based”, “biodegradable”, “compostable” and “eco-friendly”. Based on the current challenges and knowledge gaps highlighted in this study, bio-based materials cannot be considered an effective solution for reducing marine litter pollution. As set out in the EU Plastics Strategy (COM/2018) and the International Plastic Treaty, prohibiting unnecessary materials and prioritizing reuse is the most sustainable alternative to SUPs and the most effective way to avoid litter. Implementing deposit systems for reusable polypropylene (PP) and disposable PLA tableware could be a suitable way to make coastal festivals more sustainable, however the risk of PLA being littered into coastal waters remains a concern. Further research is therefore needed to assess the degradability of bio-plastic and non-plastic substituents under real environments, in order to evaluate the impact of these materials in the coastal and marine environment.

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Data Availability The original contributions presented in the study are included in the article as well as in the Supplementary Data.

Declarations

Conflict of interest The authors declare no conflict of interest.

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PAPER V

Beach and tourism ecolabels: Can they effectively reduce beach litter? An assessment of ecolabel awarding criteria, measures effectiveness and implementation challenges

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Abstract

Tourism is a major contributor to coastal litter pollution globally. There is an urgent need to address the impact of mass tourism, however identifying effective, context-specific measures to reduce litter remains challenging. This study evaluated 142 beach and tourism ecolabels against a list of 43 litter reduction measures to assess their suitability as tools for beach litter reduction. A total of 24 ecolabels addressed litter, applicable in different countries. Ecolabels only included 7–53% of measures to reduce beach litter, with only two exceeding 50%. Benefits and challenges of ecolabel implementation were assessed taking Morocco, Tunisia and Egypt as case study areas, considering state of pollution, current ecolabel implementation, and ecolabel acceptance by managers and beachgoers. Moroccan beaches showed lower pollution levels, which coincides with national efforts on beach litter reduction programs and Blue Flag implementation, mandated by the government. Nevertheless, limited temporal data restricts definitive conclusions. Since ecolabels are not specifically

designed to reduce beach litter, they present several limitations: they fail to address seasonal changes in litter accumulation and limit strategies to high seasons only. We recommend ecolabels should 1) integrate effective and context-specific measures informed by local litter data, 2) include litter thresholds in line with international legislation to assess litter reduction over time, 3) include short-term, low-effort actions as well as long-term policy strategies, and 4) engage stakeholders with different backgrounds in ecolabel implementation.

Keywords: plastics, mitigation measures, MCA, Clean Coast Index, Blue Flag

Statements and Declarations

Declaration of interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Informed consent

Verbal informed consent was obtained prior to the interview and surveys regarding participation and publication of the results.

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Data Availability

The original contributions presented in the study are included in the article as well as in the Supplementary data and in the Zenodo Data Repository.

Author´s contribution

Conceptualization GES, PH, GS; Methodology GES, JW, ER, MH, PH, GS; Field work GES, JW, ER, MH, LE, LBA, GH, FM; Data Analysis GES, JW, ER, MH; Writing GES, JW; Review & Editing GES, JW, ER, MH, LE, LBA, GH, FM, PH, GS; Visualization GES; Supervision GES, PH, GS.

1. Introduction

Tourism has been identified as a significant source of litter pollution in coastal areas worldwide [1,2]. High visitor numbers, particularly in summer, result in greater waste production, with some touristic destinations generating two-thirds of their total waste in summer alone [3]. If appropriate waste management systems are not in place, these higher quantities of waste could leak into the environment as litter, observed to increase up to 4.7 times during high season [1]. Coastal tourism is one of the main economies at the coastal zone, representing 40 – 52% of the global tourism sector, contributing to 3.2% of the global GDP [4]. Thus, keeping beaches and sea clean is important both environmentally and economically, since litter can impact local economies which depend on the good status of coastal and marine habitats [5]. In the Mediterranean Sea, litter pollution has resulted in the loss of up to 268 million Euros per year [6].

With the aim to reduce beach litter pollution globally, various policies and management strategies have been implemented worldwide. For example, the Marine Strategy Framework Directive (MSFD) [7] provides a legal framework to achieve a Good Environmental Status (GES) in European coastal and marine waters, setting a threshold of 20 litter items per 100 m beach [8]. The Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast (IMAP), adopted a threshold of 130 items per 100m, of which only 16% of monitored beaches remained below [9]. Remaining below this threshold is a challenge for most European beaches and may be even more difficult for non-EU countries. In contrast to the northern Mediterranean, the southern Mediterranean faces various political and social challenges which have impacted economic growth and sustainable development [10] and thereby also pose challenges to waste management and litter reduction.

Research on strategies to reduce litter remains general, suggesting circular economy principles, awareness raising campaigns and the need for public legislation [11,12]. Few studies have assessed implementation costs, effort and effectiveness, and suitability of litter-reduction measures based on context [13–15], and there is a lack of studies analyzing the acceptance of these measures by managers and users.

Ecolabels, also known as awards or certifications, recognize sustainable efforts of the tourism sector providing a “quality symbol” for fulfilling management objectives [16], helping them stand out from competitors and attract tourists to “environmentally-friendly” establishments or destinations [16,17]. It has been argued that ecolabels could support the sustainable management of beaches, as a framework to implement measures and showcase mismanagement (i.e. through the loss of the ecolabel) [16]. Due to challenges in policy implementation, countries could potentially benefit from ecolabel implementation, motivating the engagement of the private sector in litter reduction. However, due to “green” demand, many self-declared ecolabels have emerged as a marketing tool without meeting environmental requirements; a phenomenon known as “greenwashing”, causing confusion and mistrust [18] and casting doubt on their effectiveness to address environmental problems, such as litter pollution.

In coastal areas, the Blue Flag founded in 1985, was the first ecolabel for sustainable tourism management [19]. Studies have assessed the impact of Blue Flag in the motivation to visit beaches [20,21] and in their sustainable management [19,22,23]. One study assessed ecolabels effectiveness to address sustainability issues in Latin America, finding that ecolabels had a limited effect, complying on average with 33% of sustainable development and Integrated Coastal Zone Management (ICZM) goals. Ecolabels had a greater focus on providing amenities and ensuring visitor satisfaction than on continuous monitoring and management [24]. In this sense, there is to our knowledge no scientific evidence confirming that the implementation of an ecolabel effectively helps reduce beach litter over time.

In view of this research gap, the present study aims to evaluate the effectiveness of beach and tourism ecolabels to reduce beach litter. For this, i) a global compilation of ecolabels is carried out and analysed, and ii) ecolabel criteria are compared to a list of measures to reduce beach litter, to assess their effectiveness for this purpose. In order to assess the benefits and weaknesses of ecolabel implementation, we take a closer look at three countries of North Africa; Morocco, Tunisia and Egypt, where coastal tourism is highly relevant and litter pollution is high, and thus could potentially benefit from ecolabel implementation. These countries also present weak policies, thereby requiring different approaches to address litter pollution. The following questions are addressed: i) what ecolabels address the coastal zone and show the highest potential for reducing beach macrolitter?, ii) what is the current state of beach macrolitter pollution in North Africa?, iii) what is the current situation of ecolabels in the study areas, and which ecolabels are most suitable for implementation? and iv) what is the acceptance of ecolabels by beach/hotel managers and beachgoers?

2. Methodology

The effectiveness of ecolabels to reduce litter needs to consider existing state of pollution, the effort required for implementation, the effectiveness of ecolabels for litter reduction and their suitability to be implemented per individual context. For this reason, a mixed-methods approach was applied to assess each of these aspects (Fig. 1). The approach included i) a global compilation of ecolabels and Multi-Criteria Analysis, following [24], to assess their compliance with and effectiveness of measures to reduce beach macrolitter, ii) an assessment of seasonal trends of macrolitter pollution using monitoring and literature data, and iii) an assessment of ecolabel implementation in the study area, through spatial mapping of ecolabeled beaches and hotels, and interviews/surveys to stakeholders and beachgoers, to assess ecolabel knowledge and acceptance. It is important to note that although there are slight differences between ecolabels, awards and certifications in terms of implementation process and requirements [16], for ease of reading we refer to them all as “ecolabels”.

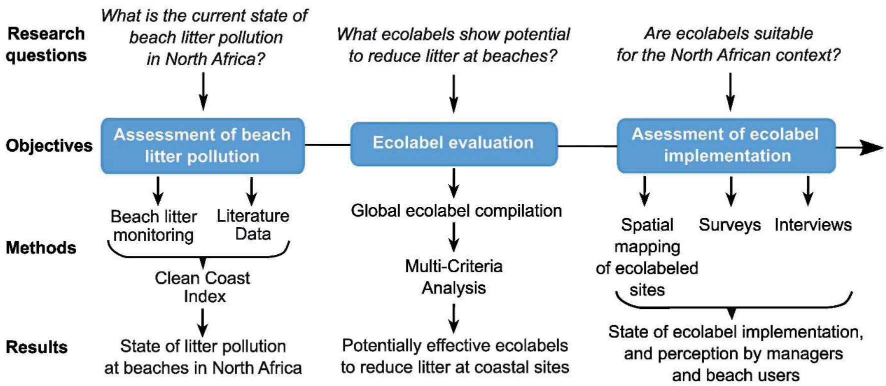

Fig. 1 Methods used to evaluate the potential of ecolabels to reduce macrolitter at beaches

2.1 Study area

The Mediterranean Sea is a semi-enclosed basin with a population of around 520 million people, with 61% living on the southern and eastern shores [25]. Tourism is the most important economic sector in the region, attracting almost a third of the global international tourists [26] and generating US$300 billion annually [6]. In the southern Mediterranean, Morocco, Tunisia and Egypt are the African countries that received the most international tourist arrivals, with over 38 million visits recorded in 2023 [27], and therefore were the countries selected for this study.

Morocco borders the Atlantic Ocean and the Mediterranean Sea. The latter has a coastline length of 512 km [28] and 65% of the total population live near the coast [29]. The largest coastal city on the Mediterranean is Tangier, with 1.3 million inhabitants. Main touristic sites include Tangier, Tetouan, Al Hoceima and Saidia (Fig. 2). Morocco is among the top 20 countries worldwide for mismanaged plastic. Projections until 2025 estimated 0.11–0.29 million metric tons of plastic will enter the ocean each year [30]. A recent study found higher levels of plastic pollution on Moroccan Mediterranean beaches than on Atlantic beaches [31], highlighting the importance to address litter in the region.

Tunisia´s coastline is 1,148 km and has over 12 million inhabitants, ca. 80% live at the coast [29,32]. Touristic sites are located at the Gulf of Hammamet (Fig. 2). Tourists in Tunisia generate up to three times more solid waste per capita per day (2.6 kg) than residents (1 kg), which intensifies the potential of pollution during the high season [33]. Tunisia is among the countries with the highest plastic waste generation in Africa. Around 60% of plastic is mismanaged, with projections for 2025 estimating 0.07–0.18 million metric tons of plastic entering the ocean annually [30]. In 2025, the Ministry of Environment announced a national beach cleaning program, targeting 133 beaches with a total budget of 1.8 million TND per year (ca. US$620,000) [34].

Egypt has a 2,450 km coastline and a population of 111 million, with around 22 million living near the coast [30]. Major coastal cities in the Mediterranean coast include Alexandria (population 5.6 million) and Port Said (population 778,000) [35]. Smaller tourist towns are Marsa Matruh and El Alamein (Fig. 2). Egypt is Africa´s highest plastic waste generator [36] and among the top 20 countries worldwide for mismanaged plastic, with projections for 2025 estimating 0.30–0.78 million metric tons of plastic entering the ocean annually [30].

A study assessing beach litter levels in the North African Mediterranean countries found extremely high levels of pollution, with tourism, recreation and nearby local activities being the main pollution sources [37]. This likely results in economic losses for the tourism industry, estimated at US$16.6 million in Tunisia [38], and US$13.6 million in Morocco [39].

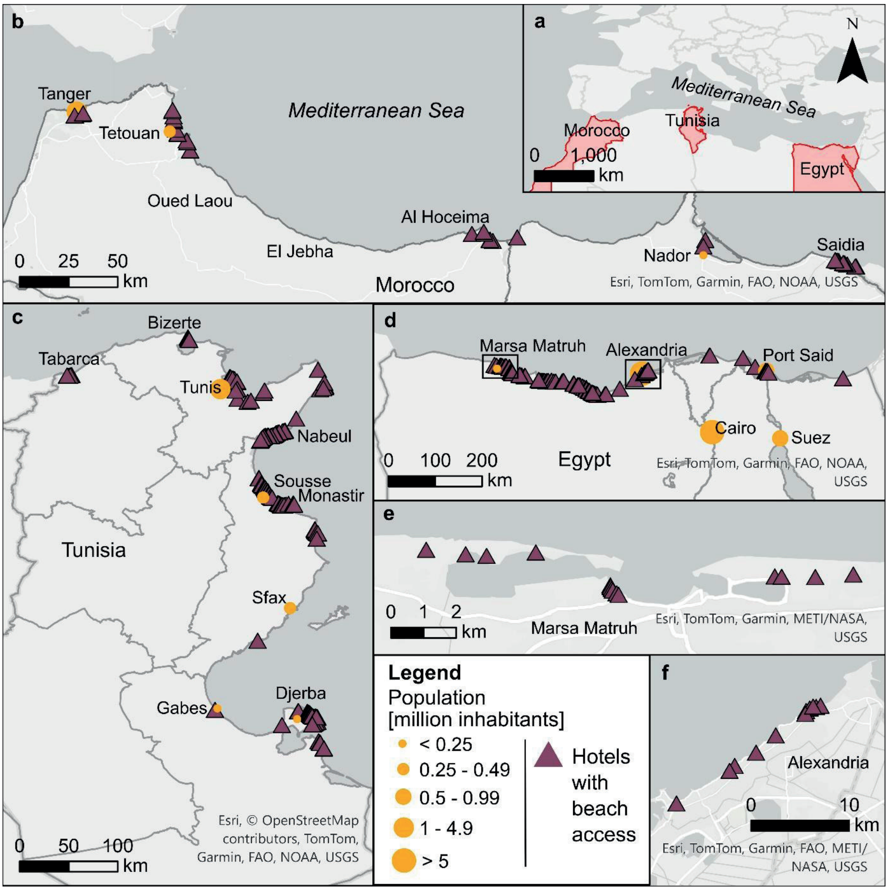

Fig. 2 Map of the study area in North Africa (a) highlighting the largest coastal cities in the Mediterranean coastline of Morocco (b), Tunisia (c) and Egypt (d), and a close-up of Marsa Matruh (e) and Alexandria (f), as well as hotels with beach access at each site

2.1 Global ecolabel evaluation: Multi-Criteria-Analysis and effectiveness of measures

The potential of ecolabels to reduce beach litter was assessed following the methodology in Fig. 3, comprising a global compilation of tourism ecolabels, a multi-criteria analysis (MCA) to those not applicable at the coastal zone, expert assessments to rate the effectiveness of litter reduction measures, and a scoring system to evaluate ecolabel compliance with rated measures.

A compilation was conducted up to February 2025 across international/regional/national scales and tourism sectors (hotels/companies/destinations/beaches). Ecolabels were identified via Google/Bing using “tourism ecolabel” and “tourism eco-certification” as keywords and through the Ecolabel Index, Global Ecolabel Network (GEN), and Global Sustainable Tourism Council (GSTC). Data on costs, validity, and waste/litter measures were extracted from ecolabel´s standards or requested by email. Ecolabels were excluded if standards were not public, absent from Perinorm [40], or providers did not respond to inquiries.

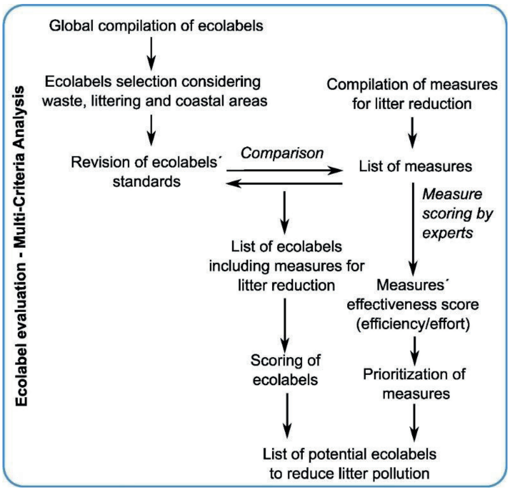

Fig. 3 Methodology of the multi-criteria analysis (MCA) for the evaluation of ecolabels to assess their effectiveness and potential to reduce beach macrolitter

Ecolabels were analyzed for: 1) consideration of beach/sea, 2) consideration of coastal litter, 3) waste management measures (e.g., wastewater or general waste reduction), 4) tourism sector targeted, 5) geographical scope, 6) alignment with global standards (e.g., ISO, GSTC), 7) validity, and 8) costs. Ecolabels outside the study area were reviewed for comparison.

Litter reduction measures were compiled from various sources (e.g., UNEP, Act4Litter, WWF, GSTC, Barcelona Convention, see Supplementary data S1) and grouped into eight categories: 1) clean-ups, 2) litter avoidance, 3) waste reduction, 4) alternatives, 5) management, policy and infrastructure, 6) monitoring, 7) stakeholder involvement, and 8) awareness and capacity building. Since some measures are more effective at reducing beach litter, 21 stakeholders rated efficiency vs. effort (cost/time). Experts’ backgrounds were marine litter (5), environmental engineering (5), other environmental fields (3), and 8 were from other sectors (harbor, tourism, wastewater). Measures were rated on a 0–4 Likert scale, with 0 = not at all efficient/effortful, 4 = highly efficient/effortful. The effectiveness score was taken as the ratio of modes for efficiency (impact) and effort (cost and time) (Eq. 1) [41]. Stakeholder evaluation assigned weights to measures considered most effective. Ecolabels applying top-rated measures were deemed most effective for beach macrolitter reduction.

Effectiveness score = Efficiency mode/Effort mode (Eq. 1)

Ecolabel criteria were compared against measures using a binary scoring: 1 = compliance, 0 = non-compliance. Measures not applicable (NA) (e.g., beach-specific actions for accommodation ecolabels) were excluded from the total. To avoid double scoring, only the strongest measure per category was counted (e.g., "eliminating" single-use plastics over "reducing"). Final scores show each ecolabel's compliance with litter measures and relative effectiveness.

2.2 Assessment of macrolitter pollution in North African countries

Between 2021 and 2023, beach macrolitter (> 25 mm) monitoring was conducted along the Mediterranean coasts of Morocco, Tunisia and Egypt using modified 10 m transects. General results were published in [37]. Here we present litter abundances individually per beach. As this was the first large-scale monitoring effort in Tunisia and Egypt and it focused on low season to avoid tourist interference, a literature review was undertaken to complement data on macrolitter abundance (items m^{-2}) for other seasons. Macrolitter abundance was taken as the median values per beach type and season over the years to assess seasonal and spatial pollution patterns. The sites were then classified as remote, semi-rural, semi-urban, urban or touristic [37,42,43]. Additionally, the Clean Coast Index (CCI, Eq. 2) which estimates beach cleanliness, was calculated for high (spring and summer) and low (autumn and winter) seasons, separately per site. The CCI calculates pollution levels (items m^{-2}) and multiplies this by a coefficient (K = 20), providing scores ranging from 0 to 20+ across five categories (0–2: very clean; 2–5: clean; 5–10: moderate; 10–20: dirty; and 20+: extremely dirty) (CCI) [44].

*CCI = (Total number of items / Area of beach) * K (Eq. 2)*

2.3 Spatial mapping of beaches and ecolabeled sites

To evaluate the implementation of ecolabels, sandy beaches were mapped using ArcGIS Pro v3.3.5 and categorized as tourist, urban, semi-urban, semi-rural or remote based on the definitions by [37,42]. Rocky shores, cliffs, and hard structures were excluded. Hotels were extracted at a buffer zone of 300 m from the coastline using data from the Humanitarian OpenStreetMap [45–47]. Each site was validated via Google Maps to add missing entries and exclude hotels lacking direct beach access. Both datasets are available in Zenodo [48,49]. Ecolabeled beaches and hotels were identified through local tourism authorities and ecolabel websites [50–55]. The proportion of ecolabeled versus non-ecolabeled sites was then compared.

2.4 Assessing potential of ecolabel implementation in North Africa

Semi-structured opportunistic interviews included 39 quantitative/qualitative questions on beach/hotel operations and waste management, as well as benefits and challenges of ecolabel implementation. Twelve beach managers and three hotel managers from the study area were interviewed, however only three were interviewed regarding ecolabels. Interviews were conducted in person with the support of local Arabic or French speakers and lasted 30–45 minutes. The results were qualitatively summarized. Key questions on ecolabels were (full list in Supplementary data S2):

1. Have you used tourism ecolabels? If not, do you think ecolabels could be useful to reduce beach litter in your region?
2. What was or what would be a motivation for you to implement an ecolabel (e.g., sustainable development, marketing, image, tourist demand, etc.)?
3. What are the challenges of implementing ecolabels for you?

A survey for local and internationals beachgoers included 29 questions on litter perception, beach wrack, litter reduction preferences, ecolabels, and ecosystem services. The survey was distributed at the beach in English, Arabic and French, and respondents had 30–45 minutes to complete it. Here, only responses related to litter and ecolabels are presented (Robbe et al. unpublished):

1. Would you prefer to visit a beach with an environmental label over a beach without one?
2. Which environmental labels for tourism and beaches have you heard of?
3. Which waste reduction measures at beaches would you personally accept? Which ones do you think are most effective?

3. Results

3.1 Multi-Criteria Analysis

3.1.1 Ecolabels covering coastal areas and addressing litter reduction

A total of 142 active ecolabels were found, 92 addressing waste management. The complete dataset is available in Zenodo [56]. A total of 34 consider beaches/sea, 30 address coastal litter/waste. Six ecolabels were excluded (lacking public standards), leaving 24 for analysis. Among these, 10 ecolabels are globally applicable; 14 are region-specific: 5 in Europe, 2 in North America, 4 in South America, and one each in Central America, Oceania, and Africa, respectively. Twelve are national, and two have continental coverage.

Eighteen ecolabels directly address beach litter. Green Destination Award/Certified address environmental littering in general. Four (EarthCheck Certified, EarthCheck for Destinations, Istanbul Environment Friendly City Award, and Seychelles Sustainable Tourism Label) do not mention litter directly but address coastal waste pollution. Litter monitoring is required by five (Bandera Azul Ecológica, NTE INEN 2631, NTS-TS-001-2, Seaside Award Wales and Stoke Surf awards), and recommended by Blue Flag. Eleven ecolabels were evaluated at our site-specific context, while others were reviewed for global context (Fig. 4).

Ecolabels varied in scope: 18 are mono-sectoral, 6 are multi-sectoral. Covered sectors include beaches (14), accommodation (9), destinations (9), marinas (7), tourist boats (4), and restaurants (2) (Fig. 4). Number of criteria ranged from 5 to 291, encompassing environmental, social, economic, and cultural dimensions. Ten ecolabels lack global recognition; others align with Global Sustainable Tourism Council (GSTC). Certification costs range from free (e.g., Blue Flag in Morocco) to US$12,000 annually, and validity spans 1-5 years, with most granted for one year (Supplementary data S3).

	Beaches													Destinations					Accomodations						
	Bandera azul ecológica	Bandera ecoplayas	Blue Flag	ISO 13009	IRAM 42100	NMX-AA-120-SCFI-2006	NTE INEN 2631	NTS-TS-001-2	Seaside Award - England	Seaside Award - Northern Ireland	Seaside Award - Wales	Green Destinations - Quality Coast Award	White Flag	Green Destinations Award	Green Destinations Certified	Istanbul Environment Friendly City Award	NTS-TS-001-1	EarthCheck (destinations)	Earth Check Certified (companies)	Certified Sea Turtle Friendly	NMX-AA-171-SCFI-2014	Pacific Sustainable Tourism Label	Seychelles Sustainable Tourism Label	Stoke (surf)	
Accomodations													X						X	X	X	X	X	X	**9**
Beaches	X	X	X	X	X	X	X	X	X	X	X	X	X												**14**
Campsites																			X						**2**
Businesses																			X						**3**
Conference Centres																			X						**2**
Marinas			X										X						X						**7**
Tour operators																			X	X				X	**4**
Restaurants																			X						**2**
Amusement Parks																			X						**2**
Golf Courses																			X						**2**
Attractions																			X						**2**
Destinations													X	X	X	X	X	X				X		X	**9**
Activities																			X						**2**
Transport																			X						**2**
Tourism Boats			X										X						X						**5**
	1	**1**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**5**	**1**	**1**	**1**	**1**	**1**	**13**	**2**	**1**	**2**	**1**	**3**	

Fig. 4 Shortlisted ecolabels addressing the management of waste or litter at coasts or sea, including ecolabels for beaches, destinations and accommodations. On the left are the tourism sectors covered by each ecolabel. In grey are the relevant sectors for addressing the problem of beach litter

3.1.2 Evaluation of measures to reduce beach litter based on effort and efficiency

A total of 43 measures for beach litter reduction were compiled (Table 1). Since it is not necessary for ecolabels to cover a large number of measures, but rather more effective ones, stakeholders rated measures based on their perceived efficiency and required effort to reduce beach litter. The responses were highly variable (Supplementary data S4). Table 1 shows the mode of responses per Likert scale level for each measure. The most efficient measures were elimination of single-use plastics (ID 18) and non-recyclable items (ID 21), development of seasonal waste management plans (ID 30), and prohibition of waste dumping and littering in public places, including beaches (ID 31). However, some of these measures were also rated moderately to highly effortful. Measures perceived as least effortful were: handing out pocket ashtrays to reduce cigarette butt littering (ID 6), providing waste bins in public areas (ID 7), reducing unnecessary packaging (ID 20), involving decision-makers and society in environmental management (ID 36), and providing tourists with guidance on minimizing waste (ID 42). The highest-rated measures in terms of effectiveness (efficiency-to-effort ratio) were providing waste bins in public areas (ID 7), increasing the use of reusable items (ID 16), eliminating single-use plastics (ID 18), and prohibiting the dumping of waste in public places (ID 31) (Table 1).

Table 1 Efficiency and effort evaluation by experts, and effectiveness score and weight given to each measure

Category	ID	Measure	Efficiency mode	Effort mode	Effectiveness score	Weight given
Clean ups	1	regular cleaning of beaches, e.g., manual and mechanical	3	2	1.5	2
	2	regular cleaning of floating litter in the water, e.g., seabins, nets, etc.	2	3	0.66	1
	3	regular cleaning of litter on the seabed, e.g., divers	1	4	0.25	0
	4	regular cleaning of surrounding areas (e.g., parking at beaches, promenades, hotel access)	3	2	1.5	2
	5	regular litter collection from rivers, river banks and wetlands flowing into the sea, e.g. river nets and barriers	2	3	0.66	1
Avoidance of littering	6	handing out pocket-ashtrays to reduce cigarette butts littering on beaches	1	1	1	1
	7	making waste bins available at public places (e.g., at beaches)	3	1	3	3
	8	making waste bins available at public places (e.g., at beaches), **<u>separated by material</u>**	2	2	1	1
	9	making waste bins available at public places (e.g., at beaches), **<u>separate for different items</u>** (e.g., bottles)	3	2	1.5	2
	10	installation of waste bins secured against birds, wind, storm, etc.	3	2	1.5	2
	11	making toilets available (e.g., at beaches)	2	3	0.66	1
Waste reduction	12	waste sorting at source, e.g., at hotels, restaurants, etc.	3	2	1.5	2
	13	recycling of different waste streams, e.g., of glass, cans, plastic, paper	3	2	1.5	2
	14	implementing a deposit-refund scheme on plastic containers	3	2	1.5	2
	15	recovery and recycling of fishing gear (e.g., fishing for litter activities)	3	2	1.5	2
	16	increase the use of reusable items, such as (reusable) cups and bags	3	1	3	3
	17	making water refill stations available	2	3	0.66	1
	18	**<u>eliminate</u>** single-use plastic items, such as (single-use) plastic cups, straws, stirrers, unnecessary packaging, etc.	4	1	4	4
	19	**<u>reduce</u>** the use of single-use plastic items, such as (single-use) plastic cups, straws, stirrers, unnecessary packaging, etc.	2	2	1	1
	20	**<u>reduce</u>** unnecessary packaging (e.g., by buying in bulks for less packaging, providing reusable options, products in dispenser, etc.)	2	1	2	2
	21	**<u>eliminate</u>** non-recyclable items, such as PU-foam and multilayer-plastics	4	2	2	2
	22	**<u>reduce</u>** the use of non-recyclable items	2	3	0.66	1
Alternatives	23	increase the use of recycled plastic products	1	2	0.5	1
	24	increasing the use of environmentally friendly products - **<u>not certified</u>**	1	1	1	1
	25	increasing the use of environmentally friendly products - **<u>certified</u>**	2	3	0.66	1
	26	promoting the use of bio-plastics, biodegradable and compostable plastics	2	3	0.66	1

Table 1 (continued) Efficiency and effort evaluation by experts, and effectiveness score and weight given to each measure

Category	ID	Measure	Efficiency mode	Effort mode	Effectiveness score	Weight given
Management, Policy and Infrastructure	27	ensure waste disposal occurs only in facilities, that are approved by the authorities, and have no negative impact on the environment	3	1	3	3
	28	wastewater disposal at municipal treatment system, or if no such system is available, in a system on site treating wastewater to ensure no negative impacts on the environment	3	4	0.75	1
	29	develop an emergency plan for pollution risks such as discharge of storm water, waste spills, etc.	2	3	0.66	1
	30	develop seasonal waste management plans to tackle increased waste production in touristic high seasons	4	3	1.33	1
	31	prohibit dumping of waste and littering at public places, including beaches	4	1	4	4
	32	complying with local, national and international legislation regarding environmental aspects	2	2	1	1
Monitoring	33	waste monitoring and implementation of reduction measures **with clear** targets	2	3	0.66	1
	34	waste monitoring and implementation of reduction measures **without clear** targets	1	2	0.5	1
	35	implementing a long-term monitoring for beach and marine litter	2	2	1	1
Involvement of stakeholders	36	involve decision makers and society in the environmental management of the area, e.g., through round tables	2	1	2	2
	37	collaboration between private & public sector on waste handling and pollution reduction	3	2	1.5	2
	38	engage stakeholders that contribute to marine litter (e.g., fisheries, industry, tourism, etc.) in the environmental management of the area	3	2	1.5	2
	39	involve local environmental NGOs in the environmental management of the area	2	2	1	1
Awareness and capacity building	40	public awareness and education campaigns regarding **waste** (disposal, waste reduction, recycling) **or litter** (marine or beach), e.g., information stands, activities, panels, clean ups, festivals	2	2	1	1
	41	public awareness and education campaigns regarding **environmental protection**, e.g., information stands, activities, panels, prizes, apps, collective platforms of volunteers	1	2	0.5	1
	42	provide guidance to customers (tourists) on minimizing waste	3	1	3	3
	43	provide training on waste reduction, waste sorting, management, etc.	3	2	1.5	2

3.1.3 Ecolabels addressing measures for beach litter reduction

Shortlisted ecolabels addressing beach litter were compared against the list of measures (Table 1) in a scoring chart to assess level of compliance, i.e., how many of the litter reduction measures are included in their criteria. Results with and without stakeholder weights were similar (Supplementary data S5).

Overall, only two ecolabels exceeded 50% of measure compliance. For beaches, Blue Flag and NMX-AA-120-SCFI-2006 had highest level of compliance. For destinations, EarthCheck Destination and NTS-TS-001-1 scored highest. For accommodations, Certified Sea Turtle Friendly Tourism, NMX-AA-171-SCFI-2014 and Pacific Sustainable Tourism Standard. Of these, only Blue Flag, EarthCheck Destination and Certified Sea Turtle Friendly Tourism apply in North Africa (Table 2). However, no ecolabel was observed to be best suited for reducing beach litter long-term, since they fail to target low-effort and highly efficient measures that the HORECA sector could readily implement (Supplementary data S5). Commonly included measures were: promotion of recycling, awareness raising, proper waste and wastewater management, legal environmental compliance, regular beach cleaning, and stakeholder involvement. Least included measures were: littering prevention, use of alternatives (e.g., biodegradable or recycled plastics), recovery/recycling of fishing gear, reduction/elimination of single-use plastics, and cleaning of seawater/seabed/rivers (Supplementary data S5). Eight additional measures addressed by ecolabels but not in our list were excluded to avoid bias in favour of those ecolabels. These measures included prohibiting smoking near bodies of water and beaches, implementing waste hierarchy and circular economy, complying with ICZM and Marine Protected Areas, developing sustainable management plans, long-term bathing water quality monitoring, incentivizing stakeholders, and creating sustainability codes of conduct (Supplementary data S6).

Table 2 Level of compliance of ecolabels to measures for beach litter reduction. The extent of compliance with weights takes into consideration the most effective measures to reduce beach litter, based on the stakeholders´ evaluation. Ecolabels with highest compliance for each sector are indicated in bold

Sector	Ecolabel	Number of criteria	Level of compliance	Level of compliance with weights
Beaches	Bandera Azul Ecológica	18	37%	35%
	Bandera Ecoplayas	12	15%	15%
	Blue Flag for beaches	**33**	**54%**	**53%**
	ISO 13009	56	10%	7%
	IRAM 42100	42	24%	21%
	NMX-AA-120-SCFI-2006	**7[a]**	**44%**	**44%**
	NTE INEN 2631	14[c]	34%	28%
	NTS-TS-001-2	62	32%	29%
	Seaside Award – England	25	22%	24%
	Seaside Award – Northern Ireland	24	22%	25%
	Seaside Award – Wales	24	24%	25%
	Green Destinations – Quality Coast Award	84[d]	29%	26%
	White Flag	5	17%	10%
Destinations	Green Destinations – Green Destination Award	84[d]	29%	37%
	Green Destinations – Green Destination Certified	84[d]	29%	37%
	EarthCheck Destination	**114**	**49%**	**51%**
	Istanbul Environment Friendly City Award	55	24%	24%
	NTS-TS-001-1	**116**	**39%**	**47%**
Accommodations	**Certified Sea Turtle Friendly Tourism**	**291**	**41%**	**44%**
	EarthCheck Certified for companies	80	31%	29%
	NMX-AA-171-SCFI-2014	**9[b]**	**41%**	**47%**
	Pacific Sustainable Tourism Standard	**61**	**38%**	**42%**
	Seychelles Sustainable Tourism Label	109	15%	12%
	Stoke Surf	38	31%	30%

[a, b] with many subsections
[c] for gold level
[d] The same type of criteria applies to all ecolabel or award types. Which ecolabel is awarded depends on the number of criteria fulfilled, or the sector where the ecolabel should be implemented.

3.2 State of macrolitter pollution in North Africa

Beach macrolitter monitoring was conducted in North Africa in 2021–2023 and complemented with literature from 2015–2023 (Supplementary data S7). Macrolitter abundance was 0.001–3 items m^{-2} (mean: 2.77 ± 1.38 items m^{-2}, median: 2.44 ± 1.13 items m^{-2}, total samples: 70) in Morocco, 0.04–13.69 items m^{-2} (mean: 1.75 ± 2.28 items m^{-2}, median: 0.96 ± 0.60 items m^{-2}, total samples: 58) in Tunisia, and 1.18–4.95 items m^{-2} (mean: 2.77 ± 1.38 items m^{-2}, median: 2.44 ± 1.13 items m^{-2}, total samples: 7) in Egypt (only seven beaches sampled once).

Assessing the difference of macrolitter abundance across years, Moroccan beaches showed higher abundance in 2023 than in 2015–2017, while at Tunisian beaches it was slightly lower in 2022–2023 than in 2020–2021 (Supplementary data S8). Tunisia was the only country for which data was available for all seasons. Here, slightly higher abundance was observed in winter and autumn than in spring and summer (Supplementary data S8). In Morocco, the Ministry of Energy Transition and

Sustainable Development carries out monitoring twice per year. Comparing spring and autumn values, the median macrolitter abundance was very similar in both seasons. However, winter monitoring data showed much higher macrolitter abundance (Supplementary data S8, Table 3). In Egypt, only spring data was available, which showed similar pollution level as for Tunisian beaches in winter. In terms of spatial patterns, higher macrolitter abundance was observed at touristic and urban beaches in Tunisia and Egypt, whereas in Morocco, abundance was similar across beach types (Supplementary data S8, Table 3).

Table 3 Median macrolitter abundance and median absolute deviation per beach type and season, across all years available based on monitoring and literature data. No sampling data was found for remote beaches. For details on each value, refer to Supplementary data S7

Country	Beach type	Median macrolitter pollution [items m^{-2}] (no. samples)			
		Spring	Summer	Autumn	Winter
Morocco[a]	Touristic	0.05 ± 0.03 (4)	NA	0.08 ± 0.08 (4)	0.88 ± 0.01 (2)
	Urban	0.05 ± 0.02 (12)	NA	0.06 ± 0.03 (12)	1.27 ± 1.05 (5)
	Semi-urban	0.02 ± 0.01 (6)	NA	0.02 ± 0.02 (6)	0.87 ± 0.70 (3)
	Semi-rural	0.08 ± 0.05 (6)	NA	0.05 ± 0.02 (6)	0.42 ± 0.04 (4)
Tunisia[b]	Touristic	3.20 ± 3.02 (3)	2.94 ± 3.57 (2)	2.00 ± 1.19 (3)	2.37 ± 1.75 (3)
	Urban	1.31 ± 0.98 (7)	0.75 ± 0.31 (5)	1.71 ± 0.62 (6)	1.89 ± 1.47 (11)
	Semi-urban	0.58 ± 0.46 (3)	0.45 ± NA (1)	0.42 ± NA (1)	1.50 ± 0.71 (5)
	Semi-rural	0.48 ± 0.06 (3)	0.11 ± NA (1)	0.43 ± NA (1)	0.08 ± 0.06 (3)
Egypt[c]	Touristic	1.25 ± 0.10 (2)	NA	NA	NA
	Urban	3.09 ± 1.13 (5)	NA	NA	NA
	Semi-urban	NA	NA	NA	NA
	Semi-rural	NA	NA	NA	NA

[a] Nachite et al. (2019, 2020, 2021, 2022), Ministère de la Transition Energétique et du Développement Durable (2019, 2024), Haseler et al. (2025)

[b] Abdelkader et al. (2023), Dhiab Rym et al. (2022), Haseler et al. (2025), Ben Slimane et al. (2025)

[c] Haseler et al. (2025)

The Clean Coast Index (CCI) was calculated for each beach using median values for high (spring and summer) and low (autumn and winter) seasons. Morocco had, in general, the cleanest beaches during both high and low season. For several beaches, high season data was missing (when ecolabels are in place), and during low season they presented dirty to extremely dirty conditions (Fig. 5, a). In Tunisia, most beaches were highly polluted. During both high and low season, pollution levels were moderate to extremely dirty; Cap Angela (Bizerte) was an exception, having clean conditions during high season and moderate during low season. Touristic beaches around Nabeul presented moderate to dirty conditions during both seasons (Fig. 5, b). In Egypt, extremely high pollution levels were observed at all beaches in spring 2022. No data was available for low season (Fig. 5, c and d).

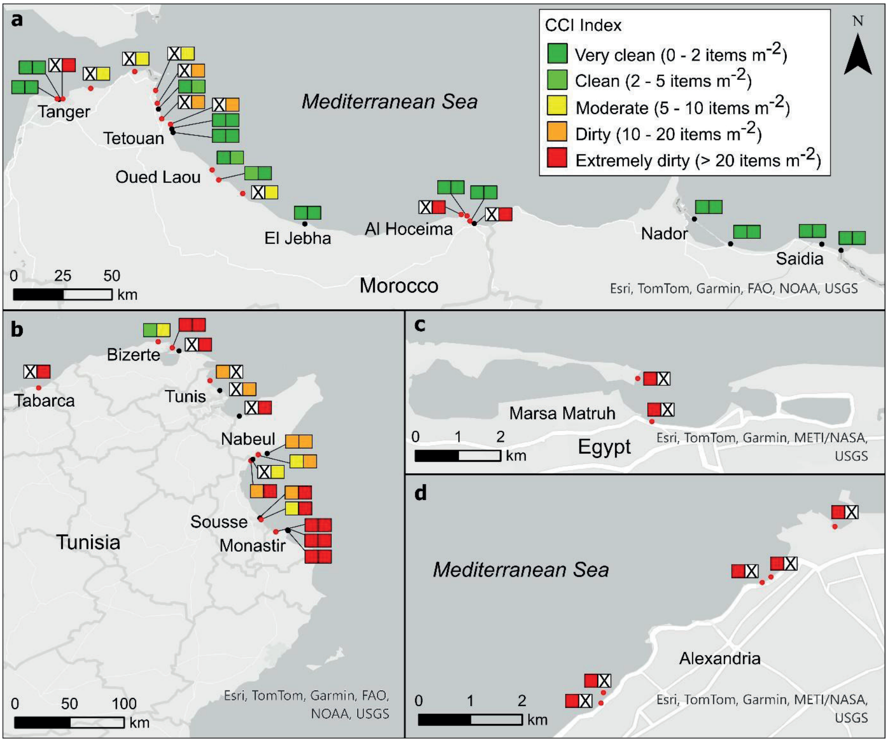

Fig. 5 Pollution map based on the Clean Coast Index (CCI) for beaches at Morocco (a), Tunisia (b) and sites in Egypt, namely Marsa Matruh (c) and Alexandria (d). Points in red correspond to our beach macrolitter monitoring and points in black are complementary sites found in the literature. The first and second square represent CCI levels based on the median litter abundance for high and low seasons, respectively. In case no data was available, it was represented with an "X". For details on each value, refer to Supplementary data S7

3.3 Ecolabel implementation in the study area – spatial mapping of beach types and ecolabeled sites

Morocco has 883 km of sandy beaches, with 218 km on the Mediterranean. Here, 9% is touristic, 13% is urban, and 78% is semi-urban, semi-rural or remote. Touristic beaches are around Tangier, Tetouan, Al Hoceima and Saidia (Fig. 6). Tunisia has 470 km of sandy beaches; 14% are touristic, 20% urban, and 66% semi-urban, semi-rural or remote. Touristic beaches are around Nabeul-Hammamet, Sousse, Monastir and Djerba (Fig. 6). In Egypt, 740 km of the Mediterranean coastline comprises sandy beaches, of which 22% are touristic, 10% urban and 68% semi-urban, semi-rural or remote. Most touristic beaches are near Alexandria and Marsa Matruh (Fig. 6).

In Morocco, beaches are awarded the Blue Flag and managed by the Mohammed VI Foundation for Environmental Protection [57]. The same foundation launched the "Plages Propres" programme in 1999, which supports beaches to qualify for Blue Flag.

The beaches shall comply with daily beach clean-ups, awareness raising campaigns, health, safety and entertainment infrastructures, and sustainable management plans [58]. In Tunisia, beaches were previously ecolabeled with Blue Flag and managed by the L'Agence de Protection et d'Aménagement du Littoral (APAL), however the program ended in 2016, with no ecolabeled beaches since then. Beach ecolabels are only available in Morocco, whereas in Tunisia and Egypt, ecolabels for Hotel, Restaurants and Catering (HORECA) establishments are more prevalent.

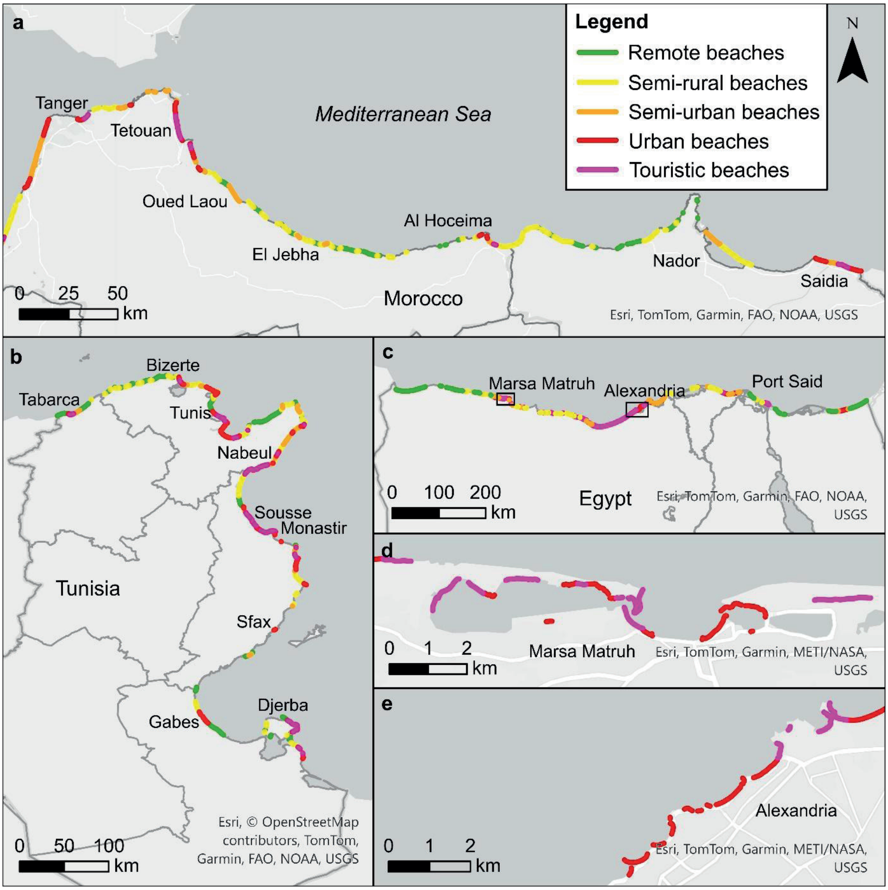

Fig. 6 Classification of sandy beaches in Morocco (a), Tunisia (b), Egypt (c), with a close-up to Marsa Matruh (d) and Alexandria (e), based on spatial mapping, and the definition from [37,42]

In Morocco, there were nine Blue Flag beaches and 29 Plages Propres beaches in 2024. A total of 125 hotels with beach access were identified; 37 on the Mediterranean coast. Only two hotels (5%) at the Mediterranean have a tourism ecolabel, namely Green Globe (Fig. 7). Ecolabeled beaches are spatially distributed, regardless of beach type. Pollution levels at these sites are moderate to very clean, with exceptions in Al Hoceima and Tetouan having higher pollution levels during low season (Fig. 5). In Tunisia, there were no ecolabeled beaches (Fig. 7). Regarding accommodation, 309 hotels with beach access were found, of which 38 (12%) were ecolabeled. Most prevalent ecolabels were Travelife and Green Key. At touristic beaches in Nabeul-Hammamet, pollution levels ranged from moderate to dirty in both low and high seasons (Fig. 5 and 7). On the Mediterranean coast of Egypt, no ecolabeled beaches were found. Of the 113 hotels with beach access, only 10 (9%) are ecolabeled, mainly with Green Star Hotel. Beaches sampled in Egypt were urban or touristic and pollution levels were extremely high (Fig. 5 and 7).

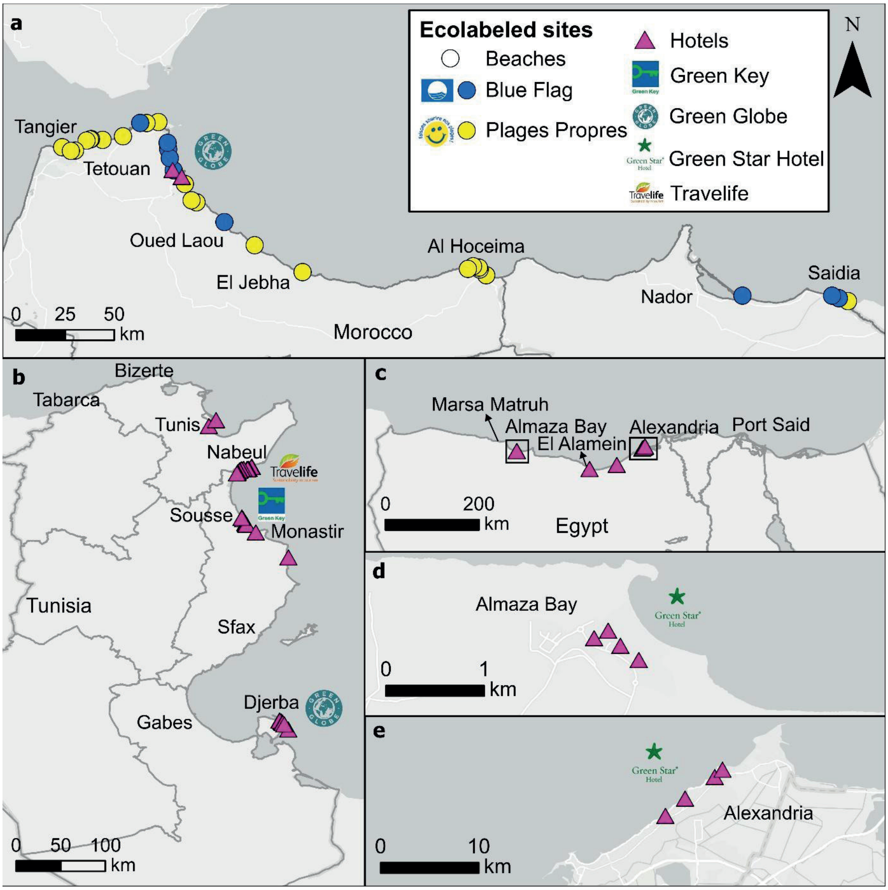

Fig. 7 Ecolabeled beaches and hotels (with beach access) in Morocco (a), Tunisia (b) and Egypt (c) – Almaza Bay (d) and Alexandria (e). The ecolabeled sites were obtained from ecolabels´ websites [50,52–55,57]

3.4 Knowledge and acceptance of ecolabels by managers and beachgoers

Beach and hotel managers were interviewed about beach management practices in the region. Key findings per country and beach type are summarized in Table 4. Most beaches in the study area are public, though many are leased to the HORECA sector with restricted guest access. Beach cleaning occurs daily (2–3 times per day) during the high season (April–September). In low season, public beach cleaning halts; semi-private beaches may continue at reduced frequency. Public beach cleaning is managed by municipalities and private companies, while lessees clean semi-private and hotel beaches. Hotels risk fines if cleanliness is not maintained.

Opportunistic interviews with three managers in Morocco, where Blue Flag is common, explored ecolabel benefits and challenges. Perceptions on ecolabels varied: one stakeholder noted Blue Flag “forces municipalities to maintain clean beaches”, promoted by the government and Mohammed VI Foundation (Fishermen's Association, Oued Aliane, January 2023), while another criticized it because “criteria are not scientific, and create segregation or competition between beaches” (Fisheries Department of Municipality, Tangier, January 2023). Regarding effectiveness, one said it works “due to the regular cleaning required” (Fishermen's Association, Oued Aliane, January 2023), while another argued it does not “because Blue Flag was not intended to reduce litter; the beach was cleaned for environmental reasons beforehand” (Essaouira Municipality Head of Environment, January 2023). Motivations for implementing ecolabels included a sense of “obligation” (Fishermen's Association, Oued Aliane, January 2023), “increase tourism” (Essaouira Municipality Head of Environment, January 2023) and “improve the image of the city” (Fisheries department of municipality, Tanger, January 2023). Challenges included “long-term implementation and maintenance” and “maintaining beaches clean beyond the validity period of the ecolabel” (Fishermen association, Oued Aliane, January 2023).

Surveys to beachgoers assessed knowledge and acceptance of ecolabels in the study area (215 answers). Gender distribution was balanced (42% female, 45% male, 13% preferred not to answer). Most respondents were aged 20–39 (43%) or 40–59 (31%), and were local (48%) national (27%) or international tourists (25%). By nationality, 70% were North African, 28% European, and 2% Asian or South American. While 62% of respondents preferred ecolabeled beaches, knowledge of ecolabels was low; 36% knew Blue Flag, 7–16% knew other ecolabels and 30% knew none (total responses: 264, multiple choice) (Fig. 8). Regarding acceptance and perceived effectiveness of litter reduction measures, 78% accept both awareness raising campaigns and fines for littering, while 67-68% accept plastics alternatives or deposits for reusable containers. Measures with lowest acceptance were smoking bans (49%) and single-use plastics bans (59%), which also received the highest rejection (13-29%). Fines for littering and awareness campaigns were considered the most effective measures (Fig. 8).

Table 4 Summary of interview answers on beach and litter management at each of the countries, based on type of beach (public, semi-private, private)

	Public beaches	**Semi-private beaches (public managed by private)**	**Private beaches (hotel beaches)**
Access	Morocco, Tunisia and Tunisia: Free	Morocco and Tunisia: not available Egypt: 5 – 25 EGP (0.1 – 0.5 USD)	Morocco, Tunisia and Egypt: reserved for hotel guests In Egypt: 200 – 600 EGP (4 – 12 USD) per day for externals
Beach cleaning – frequency	Morocco, Tunisia and Egypt: Daily in high season	Egypt: Daily in high season (in some beaches also during low season)	Morocco, Tunisia and Egypt: Daily in high and low season
Beach cleaning – tools	Morocco, Tunisia and Egypt: Manual, rake and machinery	Egypt: Manual, rake and machinery	Morocco, Tunisia and Egypt: Manual, rake and machinery
Beach cleaning – responsible	Morocco, Tunisia and Egypt: Municipality and waste managers (public or private)	Egypt: Municipality and waste managers (public or private)	Morocco, Tunisia and Egypt: Hotels
Cleaning of seawater	Morocco, Tunisia and Egypt: No	Morocco, Tunisia and Egypt: Some, with nets and boat	Morocco, Tunisia and Egypt: Yes, with nets and boat
Cleaning costs	Morocco: staff costs for 10 – 80 people Tunisia: staff costs for 10 people + machinery from private company, 80,000 Tunisian Dinnars (ca. 27,000 USD) in high season Egypt: staff costs for 20 – 50 people	Morocco: same as public Tunisia: Same as public Egypt: No information	Morocco: No information Tunisia: No information Egypt: 2 – 8 people, 60,000 EGP (ca. 1200 USD) per year excluding staff costs
Waste bins	Morocco, Tunisia and Egypt: Yes, during high season	Morocco, Tunisia and Egypt: Yes, during high season	Morocco, Tunisia and Egypt: Yes, during high and low season
Waste bins – Collection frequency	Daily, 2 – 3 times per day in high season	Daily, 2 – 3 times per day in high season	Daily, 2 – 3 times per day in high season
Waste bin type	Mixed	Mixed	Mixed

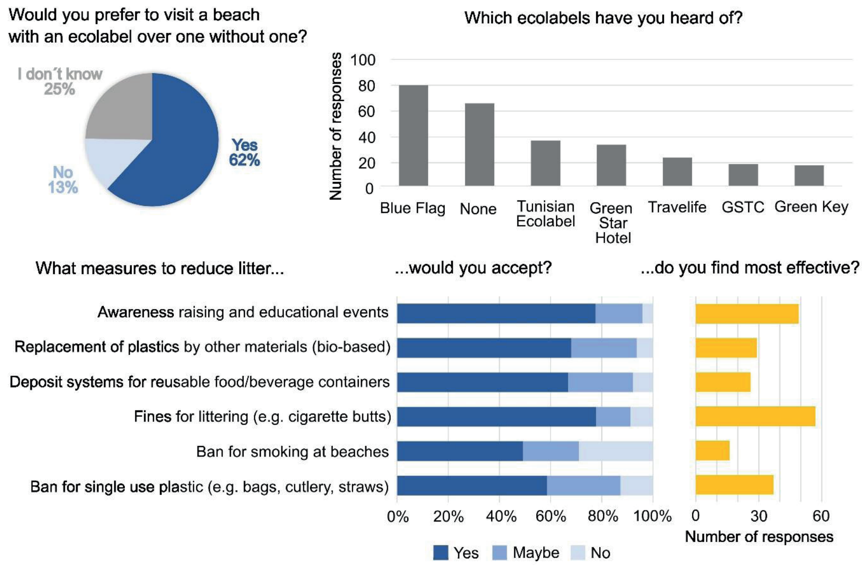

Fig. 8 Survey results for beachgoers on the knowledge of ecolabels, and the acceptance and perceived effectiveness of measures to reduce beach litter

4. Discussion

4.1 Effectiveness of ecolabels to reduce beach litter

The 24 ecolabels analyzed included only 7-53% of the total litter-reduction measures. Only Blue Flag (53%) and EarthCheck Destination (51%) exceeded 50%. Criteria are often applied flexibly, with awards granted without full compliance. This would be acceptable if ecolabels prioritized effective strategies and targeted common litter items like cigarette butts and single use plastics [37,59,60]. Yet only 3-6 ecolabels included most effective measures (Supplementary data S5), while most emphasized strategies requiring systemic policy change or public education, rather than direct, actionable practices that the HORECA sector can implement. Preventive measures with high impact, (e.g., distributing pocket ashtrays, deposit-refund systems, providing guidance to customers on minimizing waste or reducing/eliminating/replacing non-recyclable and single-use plastics) were least included, despite their reduction potential at source. Blue Flag included two from six most effective measures and several direct actions: installing bins/toilets, setting waste targets, promoting litter monitoring, and seasonal management planning. EarthCheck Destination included four, like eliminating single-use plastics and promoting reusable items, but emphasized broader strategies over immediate actions, like involving public/private sectors, training staff, and reduction targets. Both included relevant measures beyond our list (Supplementary data S6), such as smoking bans. In practice, a combination of both short- and long-term measures are needed to address litter pollution [15].

Among studied countries, only Blue Flag is widely implemented in Morocco. Morocco presented lowest abundances aligning with Blue Flag implementation since 2006.

Ecolabeled beaches at Oued Laou, Nador and Saidia were cleaner, while touristic beaches at Tetouan presented moderate and dirty levels during low season, when ecolabels are not in place (Fig. 5 and 7). Semi-urban/-rural beaches having the Plages Propres ecolabel showed similar pollution levels to touristic/urban beaches, suggesting high beach visitation (Fig. 5 and 6). However, pollution levels were lower than semi-urban/-rural beaches in Tunisia, suggesting a possible ecolabel effect. Still, it remains unclear whether improvements stem from ecolabels only. Plages Propres program encourage plastic reduction and litter monitoring since 2016, possibly rising public awareness. Stakeholders interviewed highlighted the “obligation” for municipalities to “keep beaches clean” mandated by the government. In Tunisia, lack of data before 2016, prevents verifying Blue Flag effects. Similarly, insufficient temporal/spatial data in Egypt limits assessment.

Blue Flag is by far the largest ecolabel, certifying 5195 sites (beaches and marinas) across 51 countries in 2025, majority located in Europe [51]. No scientific evidence confirms Blue Flag´s effectiveness to reduce beach litter over time. Research instead focused on Blue Flag’s influence on beach visitation [20,21] and ICZM management [19,22–24]. In Costa Rica, the “Programa Bandera Azul Ecológica” (PBAE) in place since 1996 [61], certified 140 beaches in 2025, majority in the Pacific coast [62]. Yet pollution at Pacific beaches is high (0 – 8.47 items m^{-2}; mean 2.01 ± 3.27 items m^{-2}) [59]. Other ecolabel examples include the NMX-AA-120-SCFI-2006 in Mexico, which certified 27 beaches in 2024, majority at the Pacific coast [63]. Litter pollution at Pacific Mexican beaches ranged 0.5 – 2 items m^{-2} (mean 1.04 ± 0.62 items m^{-2}) [59], however monitored beaches were not ecolabeled. The English Seaside Award, active since 1992, certified 144 beaches in 2025, most in the East of England, South East and South West regions [64], yet these beaches have had consistent moderate-high litter amounts between 2005 and 2014 [65]. Missing data hinder further analyses for other ecolabels.

Although more research is needed assessing pollution levels of ecolabeled beaches over time, current evidence suggests that ecolabels do not reduce litter long-term, and instead only cause a temporary (high-season) reduction. In Morocco, litter abundance was higher in low season, likely due to paused cleaning when ecolabels are inactive (Fig. 5). This seasonal focus disregards local visitors using beaches year-round, limiting ecolabels´ effect spatially and temporally. In addition, ecolabels mainly target touristic/urban beaches, while 66–78% of coastlines are semi-urban, semi-rural or remote (Fig. 6), and thus not always targeted by ecolabels. Furthermore, the few ecolabeled hotels in the study area (<12%) suggests a minimal impact in litter reduction. In Tunisia, touristic beaches with ecolabeled hotels near Nabeul, Hammamet and Sousse, presented higher pollution than urban beaches; indicating beach management fails to counteract the high tourist numbers and waste generation during high season (Fig. 5 and 7). While hotels are required to clean adjacent beaches, ecolabels in place (Travelife, Green Star Hotel, Green Key, Green Globe) do not explicitly include beach litter management. Some practices may extend beyond leased areas, however beach sections outside are excluded (personal observation). As a result, hotels likely keep ecolabel status even if their waste impacts surrounding areas.

4.2 Challenges and opportunities of ecolabel implementation: North African case study

Identified challenges for ecolabel implementation included long-term implementation, beach cleanliness maintenance off-season, and high costs. Fees vary with destination size and company revenue, with discounts for low- and middle-income countries (Supplementary data S3). In Morocco, Blue Flag is free, but compliance requires costly infrastructure and services (e.g., recycling) still lacking regionally. Ecolabels´ validity period is typically one year, except for White Flag, which is valid for five. Short durations may discourage participation due to the recurring effort and cost required for renewal. In contrast, longer validity periods (2–3 years) may weaken commitment, with improvements limited to pre-audit periods. Most ecolabels are voluntary and based on self-declaration, without third-party verification [66] making them vulnerable to corruption. These issues likely extend to other low-/middle-income countries.

North African countries experience high tourist influx and poor waste management, causing estimated losses of US$13–16 million in tourism revenue and US$1.5–4.2 million in clean-up costs [67]. Municipalities spend US$1,000–5,000 per beach annually for beach cleaning during high season (Table 4) [34]. Touristic beaches (9–22% of coastline, Fig. 6) are often managed by hotels, presenting an opportunity to shift maintenance costs to private operators through hotel ecolabels, if effective criteria are applied. Yet ecolabeled hotels remain uncommon (<12% per country). Urban beaches (10–20% of coastline) could also benefit from ecolabels if effective measures were enforced. Cleaner beaches could attract more tourists, and increase economic input. Beyond direct cleanliness, ecolabels could elevate litter as a policy issue and raise public awareness, but success depends on enforcement mechanisms in the region.

Political instability further undermines waste management [33], highlighting the need for low-effort and low-cost measures targeting problematic items. Awareness campaigns were rated most effective by beachgoers but least effective by stakeholders, who preferred bans and fines, which was in turn the least popular among beachgoers. This reflects public preference for short-term, visible measures, and resistance to stricter, long-term policies such as bans on single-use plastics or smoking, which has also been observed at other sites [68]. Managers´ view ecolabels as tools to boost tourism, however public awareness on ecolabels remains low. In Morocco, 53% were unaware of Blue Flag, despite widespread adoption. For hotel ecolabels, 71% of Tunisian beachgoers did not know the Tunisian Ecolabel, and only 15% knew the Egyptian ecolabel Green Star Hotel. Although ecolabels are intended as marketing tools, their effect is limited, lasting up to 3 seasons for domestic tourists and causing no influence in international tourist visits [17].

Thus, ecolabels implementation in North Africa is constrained by enforcement gaps, limited infrastructure, and weak monitoring. Collaborative, context-specific initiatives could help overcome these barriers. For instance, Latin America's ProPlayas Network unites researchers, businesses, governments, and NGOs to co-develop beach management and certification adapted to local realities [69]. Its integration of science, policy, and practice could serve as a model for North Africa, offering a bottom-up, inclusive approach to beach certification that aligns with regional capabilities and needs.

4.3 Improving tourism ecolabels to address beach litter reduction

Growing tourism in the region requires sustainable measures to mitigate the impacts of mass tourism. Studies argue that ecolabels, like Blue Flag, can enhance environmental management and sustainable development [70] providing a framework with procedures and goals [21] to reach agreements and collective commitments, especially at sites of complex cultural and political contexts [71], thereby promoting stakeholder collaboration, funding, and accountability [16]. However, our findings show ecolabels are not effective for litter reduction and need to be revised to serve for this purpose. Ecolabels fail to target common litter items or most effective strategies, making them insufficient as stand-alone solutions. Current ecolabels emphasize management actions (e.g., cleaning) over outcomes (e.g., reducing litter pollution/specific items), do not define thresholds for acceptable pollution levels and overlook seasonal variation, restricting their effect to short-term seasonal efforts. We recommend that ecolabels should integrate effective and site-specific litter reduction measures identified by an independent group of local stakeholders, informed by litter monitoring campaigns, and source identification to assess the impact of mitigation measures. Ecolabels should define thresholds for acceptable litter levels aligned with international legal frameworks (e.g., MSFD or Barcelona Convention), with monitoring across seasons to adapt measures based on effectiveness. Moreover, they should include short-term, low-effort actions implementable by beach or hotel managers, as well as long-term policy strategies such as banning single-use plastics or enforcing extended producer responsibility. Existing indices could strengthen ecolabels by incorporating environmental thresholds and measurable outcomes. The Integrated Beach Quality Index (IBQI) [42] integrate human health, ecosystem health, and recreational aspects. Incorporating such tools could provide thresholds and track reductions of specific litter items, enabling impact evaluation across beaches and the wider HORECA sector (restaurants, cafés, hotels). Finally, ecolabels should emphasize ecosystem preservation. For instance, Fraguell et al. [19] recommends setting tourist capacity limits to prevent overcrowding, allow recovery periods, and preserve ecosystem services.

4.4 Evaluation of the methods and future research

To our knowledge, this study presents the first global compilation and analysis of beach and tourism ecolabels for litter reduction. While not exhaustive, it establishes a baseline for future research, including spatially mapped sandy beaches and ecolabeled beaches/hotels, creating a novel dataset in the absence of regional monitoring. Data was primarily sourced from ecolabel websites, thus some ecolabeled sites may be missing.

The list of litter reduction measures grouped them into eight categories covering a broad range of solutions, aligned with UNEP objectives, the Mediterranean Strategy for Sustainable Development 2016-2025, the Guidelines on Marine Litter Management for the Mediterranean, and the Global Sustainable Tourism Council (GSTC). Scientific literature and stakeholder input complemented the final list. Measures provided in Table 3 may serve as a self-assessment tool for beach and hotel managers to assess their engagement and contribution, and strive for higher measures, as suggested in Schumacher et al. [72]. In the MCA, only ecolabels with explicit beach litter management criteria were analyzed. For this reason, Green Key, Green Globe, and Travelife, common in the region, were excluded. Although hotels with leased beaches are generally responsible for beach cleaning, compliance could not be verified and was not assumed.

A limitation in evaluating measure effectiveness was stakeholders´ limited knowledge. To minimize "I do not know" responses, stakeholders were asked to rate measures based on their best judgment, which may have led to uninformed evaluations. A different list of measures could yield different results; therefore, measure prioritization should be interpreted conservatively. Perceptions of efficiency and effort may vary with location and stakeholder background. Most stakeholders were European, with half working in the countries studied, primarily from environmental research or environmental engineering sectors. We could not engage tourism professionals from Tunisia, Egypt, or Morocco, who may offer different perspectives. Given these limitations, results should be seen as a first attempt to guide measure and ecolabel selection, and further context-specific evaluations are recommended. Opportunistic interviews were conducted during monitoring campaigns, reaching only three stakeholders. Time constraints and stakeholder fatigue are often limitations for research [73,74]. For this reason, findings on ecolabel implementation are not conclusive, and interviews with stakeholders are highly recommended. Nevertheless, the responses provide initial insights into perceived benefits and concerns of ecolabels.

5. Conclusion

Ecolabels are advertised as tools for sustainable coastal management but scientific evidence has shown only limited effects. This study conducted the first global compilation and evaluation of 142 beach and tourism ecolabels, of which only 24 addressed beach litter management. Ecolabels only included 7-53% of measures to reduce beach litter, with only two exceeding 50%. Most measures addressed by ecolabels either require the revision of local policies and waste management systems, or address consumers through awareness raising, but fail to address low-effort/high-impact practices, such as eliminating single-use plastics, that beach/hotel managers could implement.

Ecolabels, as currently designed, are not effective to reduce beach litter, mainly due to their focus on criteria compliance rather than environmental outcomes, failing to address litter pollution off-season or most common litter items. Ecolabels must evolve to include outcome-oriented indicators with thresholds that align with international policies. Furthermore, ecolabel implementation should be based on local pollution data and engage local stakeholders in selecting the most effective measures, targeting prevention over mitigation/remediation measures, and combining short-term, low-effort actions with long-term strategies. Finally, their effectiveness must be supported by regional collaboration networks, stronger policy enforcement, and public education, fostering integrated coastal zone management that goes beyond their symbolic and aesthetic value.

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Appendix

Appendix 1. **Efficiency and effort evaluation by experts, and effectiveness score and weight given to each measure.**

Category	ID	Measure	Efficiency mode	Effort mode	Effectiveness score	Weight given
Clean ups	1	regular cleaning of beaches, e.g., manual and mechanical	3	2	1.5	2
	2	regular cleaning of floating litter in the water, e.g., seabins, nets, etc.	2	3	0.66	1
	3	regular cleaning of litter on the seabed, e.g., divers	1	4	0.25	0
	4	regular cleaning of surrounding areas (e.g., parking at beaches, promenades, hotel access)	3	2	1.5	2
	5	regular litter collection from rivers, river banks and wetlands flowing into the sea, e.g. river nets and barriers	2	3	0.66	1
Avoidance of littering	6	handing out pocket-ashtrays to reduce cigarette butts littering on beaches	1	1	1	1
	7	making waste bins available at public places (e.g., at beaches)	3	1	3	3
	8	making waste bins available at public places (e.g., at beaches), **separated by material**	2	2	1	1
	9	making waste bins available at public places (e.g., at beaches), **separate for different items** (e.g., bottles)	3	2	1.5	2
	10	installation of waste bins secured against birds, wind, storm, etc.	3	2	1.5	2
	11	making toilets available (e.g., at beaches)	2	3	0.66	1

Appendix 1 (continued). **Efficiency and effort evaluation by experts, and effectiveness score and weight given to each measure.**

Category	ID	Measure	Efficiency mode	Effort mode	Effectiveness score	Weight given
Waste reduction	12	waste sorting at source, e.g., at hotels, restaurants, etc.	3	2	1.5	2
	13	recycling of different waste streams, e.g., of glass, cans, plastic, paper	3	2	1.5	2
	14	implementing a deposit-refund scheme on plastic containers	3	2	1.5	2
	15	recovery and recycling of fishing gear (e.g., fishing for litter activities)	3	2	1.5	2
	16	increase the use of reusable items, such as (reusable) cups and bags	3	1	3	3
	17	making water refill stations available	2	3	0.66	1
	18	**eliminate** single-use plastic items, such as (single-use) plastic cups, straws, stirrers, unnecessary packaging, etc.	4	1	4	4
	19	**reduce** the use of single-use plastic items, such as (single-use) plastic cups, straws, stirrers, unnecessary packaging, etc.	2	2	1	1
	20	**reduce** unnecessary packaging (e.g., by buying in bulks for less packaging, providing reusable options, products in dispenser, etc.)	2	1	2	2
	21	**eliminate** non-recyclable items, such as PU-foam and multilayer-plastics	4	2	2	2
	22	**reduce** the use of non-recyclable items	2	3	0.66	1
Alternatives	23	increase the use of recycled plastic products	1	2	0.5	1
	24	increasing the use of environmentally friendly products - **not certified**	1	1	1	1
	25	increasing the use of environmentally friendly products - **certified**	2	3	0.66	1
	26	promoting the use of bio-plastics, biodegradable and compostable plastics	2	3	0.66	1

Appendix 1 (continued). **Efficiency and effort evaluation by experts, and effectiveness score and weight given to each measure.**

Category	ID	Measure	Efficiency mode	Effort mode	Effectiveness score	Weight given
Management, Policy and Infrastructure	27	ensure waste disposal occurs only in facilities, that are approved by the authorities, and have no negative impact on the environment	3	1	3	3
	28	wastewater disposal at municipal treatment system, or if no such system is available, in a system on site treating wastewater to ensure no negative impacts on the environment	3	4	0.75	1
	29	develop an emergency plan for pollution risks such as discharge of storm water, waste spills, etc.	2	3	0.66	1
	30	develop seasonal waste management plans to tackle increased waste production in touristic high seasons	4	3	1.33	1
	31	prohibit dumping of waste and littering at public places, including beaches	4	1	4	4
	32	complying with local, national and international legislation regarding environmental aspects	2	2	1	1
Monitoring	33	waste monitoring and implementation of reduction measures **with clear** targets	2	3	0.66	1
	34	waste monitoring and implementation of reduction measures **without clear** targets	1	2	0.5	1
	35	implementing a long-term monitoring for beach and marine litter	2	2	1	1

Appendix 1 (continued). **Efficiency and effort evaluation by experts, and effectiveness score and weight given to each measure.**

Category	ID	Measure	Efficiency mode	Effort mode	Effectiveness score	Weight given
Involvement of stakeholders	36	involve decision makers and society in the environmental management of the area, e.g., through round tables	2	1	2	2
	37	collaboration between private & public sector on waste handling and pollution reduction	3	2	1.5	2
	38	engage stakeholders that contribute to marine litter (e.g., fisheries, industry, tourism, etc.) in the environmental management of the area	3	2	1.5	2
	39	involve local environmental NGOs in the environmental management of the area	2	2	1	1
Awareness and capacity building	40	public awareness and education campaigns regarding **waste** (disposal, waste reduction, recycling) **or litter** (marine or beach), e.g., information stands, activities, panels, clean ups, festivals	2	2	1	1
	41	public awareness and education campaigns regarding **environmental protection**, e.g., information stands, activities, panels, prizes, apps, collective platforms of volunteers	1	2	0.5	1
	42	provide guidance to customers (tourists) on minimizing waste	3	1	3	3
	43	provide training on waste reduction, waste sorting, management, etc.	3	2	1.5	2

Appendix 2. Updated cost-efficiency calculations for aerial drones vs. OSPAR method

Costs for 4 beaches, 4 surveys per year

			Macro (> 2.5 cm) 100m beach monitoring		Large items > 50 cm 1km beach monitoring	
			Drone	Spatial-OSPAR	Drone	Spatial-OSPAR
Costs	Investment and initial costs for	Costs of equipment and tools	€ 2,600.00	€ 100.00	€ 2,600.00	€ 100.00
		Implementation testing period (methodological training on the field, calibrations, training for analysis) *	€ 30,000.00	€ 15,000.00	€ 30,000.00	€ 15,000.00
		Total initial costs	€ 32,600.00	€ 15,100.00	€ 32,600.00	€ 15,100.00
	Office costs	Staff cost/hours**	€ 37.50	€ 37.50	€ 37.50	€ 37.50
		Staff effort in hours***	160	160	160	160
		Organization & Planning (orders, selection of sites, drone permissions, drone license)	€ 5,000.00	€ 5,000.00	€ 5,000.00	€ 5,000.00
		Reporting	€ 5,000.00	€ 5,000.00	€ 5,000.00	€ 5,000.00
		Total office costs	€ 10,000.00	€ 10,000.00	€ 10,000.00	€ 10,000.00
	Field & Lab costs	Staff cost/hours**	€ 37.50	€ 37.50	€ 37.50	€ 37.50
		Staff effort in hours	1040	608	1088	560
		Annual running field costs*** (travelling to site, survey on the field - set up and sampling)	€ 1,800.00	€ 2,400.00	€ 2,400.00	€ 1,800.00
		Annual running costs for analysis of data**** (counting, measuring, categorizing, pictures, input data on excel)	€ 1,200.00	€ 2,400.00	€ 2,400.00	€ 1,200.00
		Annual replacement costs* (for materials)	€ 1,400.00	€ 1,000.00	€ 1,400.00	€ 1,000.00
		Total field costs	€ 4,400.00	€ 5,800.00	€ 6,200.00	€ 4,000.00
		Total annual running costs	**€ 14,400.00**	**€ 15,800.00**	**€ 16,200.00**	**€ 14,000.00**
		Total annual costs	**€ 25,266.67**	**€ 20,833.33**	**€ 27,066.67**	**€ 19,033.33**
		Total hours	**1200**	**768**	**1248**	**720**
		Score costs	**4**	**4**	**4**	**4**
Efficiency		**Criteria**				
		Accuracy	4	4	4	5
		Reproducibility	5	3	5	5
		Flexibility	1	4	1	4
		Quality	4	5	4	5
		Score Efficiency	**3.50**	**4.00**	**3.50**	**4.75**
Cost-Efficiency score			**14.0**	**16.0**	**14.0**	**19.0**
			Moderate	**High**	**Moderate**	**High**

Salary#		
Salary/year	€	60,000.00
Salary/month	€	5,000.00
Hours/year		1600
Hours/month		133
Salary/hour	€	37.50

*one-time investment to be done every 3 years, considering a drone life-time of 3 years and renewal of training
**employee at a federal state authority in Germany
*** sampling 4 times a year at 4 beaches with 2 persons using 1-2 hours
****analysis considers one person hours
considers Brutto salary

Score Costs	Money	Scale	Meaning
	<15,000€	5	Very low
	<30,000€	4	Low
	<45,000€	3	Moderate
	<90,000€	2	High
	>90,000€	1	Very high

Score Efficiency	Scale	Meaning
	1	Very low
	2	Low
	3	Moderate
	4	High
	5	Very high

Criteria	Definition
Accuracy	Percentage of items found assuming different persons, drones and software
Reproducibility	Same method applied on another day by another person
Flexibility	How flexible is the method with respect to weather conditions, external disturances, permissions, battery life
Quality	Quality of the result: Are items well defined e.g. type of item, type of material, number of items, spatial distribution
Time	How much time does monitoring take with said method

Cost-efficiency score	Scale	Meaning
	<5	Very low
	<10	Low
	<15	Moderate
	<20	High
	>20	Very high

Appendix 2 (continued). **Updated cost-efficiency calculations for aerial drones vs. OSPAR method**

Purchase Costs Drone

One-time purchase

Material	Quantity	Costs (Brutto)	Total	Rounding
Drone DJI Phantom 4 Pro V2.0	1	1,699.00 €	1,699.00 €	
DJI P4P V2 Extra battery Obsidian	1	175.00 €	175.00 €	
Set Polar Pro cinema filters (3er set, ND8, ND16 and ND32)	1	80.00 €	80.00 €	
DJI Battery charger	3	86.00 €	258.00 €	
SD card Scandisk extreme micro SDXC 125GB 160Mb/s Video speed class 30	1	39.99 €	39.99 €	
Smartphone (+ USB cable + charger) (Apple Iphone 7)	1	248.95 €	248.95 €	
DJI Landing pad	1	14.95 €	14.95 €	
Software for image analysis ArcGIS	1	15,000.00 €	NA	
Total			2,515.89 €	2,600.00 €

Materials that need replacement/update yearly

Material	Quantity	Costs (Brutto)	Total	Rounding
Flight mapping apps	1	1,188.00 €	1,188.00 €	
DJI P4P V2 Extra battery Obsidian	1	175.00 €	175.00 €	
DJI propellers (pair)	1	11.00 €	11.00 €	
Software ArcGIS (yearly update)	1	2,000.00 €	NA	
Total			1,374.00 €	1,400.00 €

Purchase Costs Adapted OSPAR

One-time purchase

Material	Quantity	Costs (Brutto)	Total	Rounding
100m measure band	1	14.95 €	14.95 €	

Materials that need replacement/update yearly

Material	Quantity	Costs (Brutto)	Total	Rounding

Incidentals purchased from time to time, for monitoring of one year at one beach

Material	Quantity	Costs (Brutto)	Total	Rounding
Plastic bags (in different sizes) to collect the litter	1	16.81 €	16.81 €	
mm-paper for the size analysis	1	4.20 €	4.20 €	
Pair of gloves	2	3.79 €	7.58 €	
Total			28.59 €	1,000.00 €

Appendix 2 (continued). Updated cost-efficiency calculations for aerial drones vs. OSPAR method

Travelling and Working Costs

*considers time needed to survey with 2 people

Costs for OSPAR surveys, 100m, based on the suggestions of regular macro-litter sampling locations at the German Baltic coast within the MSFD

Start	Beach survey location	Working hours: Travel by car, both ways (in hours)	Survey time* at the beach (in hours)	Litter analysis steps: counting, measuring, categorizing (in hours)	Overall time needed per beach survey (approx.) (in hours)
IOW	Diedrichshagen/Stoltera	2	2	4	8
IOW	Warnemünde	2	2	4	8
IOW	Ahrenshoop/Darß	2	2	4	8
IOW	Other	2	2	4	8
Total for 4 beaches		8	8	16	32
Total for all beaches, for 4 surveys a year		**32**	**32**	**64**	**128**

Costs for UAV surveys, 100m; based on the suggestions of regular macro-litter sampling locations at the German Baltic coast within the MSFD

Start	Beach survey location	Working hours: Travel by car, both ways (in hours)	Survey time* at the beach (in hours)	Litter analysis steps: counting, measuring, categorizing (in hours)	Overall time needed per beach survey (approx.) (in hours)
IOW	Diedrichshagen/Stoltera	2	1	2	5
IOW	Warnemünde	2	1	2	5
IOW	Ahrenshoop/Darß	2	1	2	5
IOW	Other	2	1	2	5
Total for 4 beaches		8	4	8	20
Total for all beaches, for 4 surveys a year		**32**	**16**	**32**	**80**

Costs for adapted OSPAR surveys, 1km, based on the suggestions of regular macro-litter sampling locations at the German Baltic coast within the MSFD

Start	Beach survey location	Travel by car, both ways (in hours)	Survey time* at the beach (in hours)	Litter analysis steps: counting, measuring, categorizing (in hours)	Overall time needed per beach survey (approx.) (in hours)
IOW	Diedrichshagen/Stoltera	2	1	2	5
IOW	Warnemünde	2	1	2	5
IOW	Ahrenshoop/Darß	2	1	2	5
IOW	Other	2	1	2	5
Total for 4 beaches		8	4	8	20
Total for all beaches, for 4 surveys a year		**32**	**16**	**32**	**80**

Costs for UAV surveys, 1km; based on the suggestions of regular macro-litter sampling locations at the German Baltic coast within the MSFD

Start	Beach survey location	Working hours: Travel by car, both ways (in hours)	Survey time* at the beach (in hours)	Litter analysis steps: counting, measuring, categorizing (in hours)	Overall time needed per beach survey (approx.) (in hours)
IOW	Diedrichshagen/Stoltera	2	2	4	8
IOW	Warnemünde	2	2	4	8
IOW	Ahrenshoop/Darß	2	2	4	8
IOW	Other	2	2	4	8
Total for 4 beaches		8	8	16	32
Total for all beaches, for 4 surveys a year		**32**	**32**	**64**	**128**

***Appendix 3*. Scoring chart of ecolabels´criteria against a list of measures to reduce litter at beaches. Each ecolabel criteria were thoroughly revised to assess compliance with the list of measures, rated by the stakeholders. For references, refer to the supplementary material of the manuscript.**

			Beaches												Destinations				Accomodations						
Category	ID	Weight	Bandera azul ecológica	Bandera Ecoplayas	Blue Flag (beaches)	ISO 13009	IRAM 42100	NMX-AA-120-SCFI-2006	NTE INEN 2631	NTS-TS-001-2	Seaside Award - England	Seaside Award - Northern Ireland	Seaside Award - Wales	White Flag	Green Destinations (Quality coast Award, GD Award, G	EarthCheck (destinations)	Istanbul Environment Friendly City Award	NTS-TS-001-1	Certified Sea Turtle Friendly	Earth Check Certified (companies)	NMX-AA-171-SCFI-2014	Pacific Sustainable Tourism Label	Seychelles Sustainable Tourism Label	Stoke Surf	
Clean - Ups	1	2	2	2	2	2	2	2	2	2	2	2	2	NA					2		2			2	28
	2	1	NA	NA	NA	NA	NA	1	NA	NA	NA	NA	NA	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2
	3	0	NA	NA	NA	NA	NA	1	NA	NA	NA	NA	NA	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2
	4	2			2		2			2	2	2	2			2					2				16
	5	1						1	1					1											3
Avoidance of littering	6	1																							0
	7	3	3	3							3														9
	8	1			1		1	1	1	1			1			1		1				1			9
	9	2			2		2																		4
	10	2			2			2		2		2	2						2		2				14
	11	1	1	1	1			1	1	1	1	1	1			1			NA	NA	NA	NA	NA	NA	10
Waste reduction	12	2	2		2			2							2	2		2			2	2			16
	13	2	2	2	2			2				2	2	2	2	2	2	2	2	2	2	2	2		32
	14	2																							0
	15	2																	NA	NA	NA	NA	NA	NA	0
	16	3						3								3		3	3	3				3	18
	17	1	1		1	1	1		1	1		1				1		1	1			1			11
	18	4													4	4		4	4		4	4			24
	19	1														1			1					1	3
	20	2																2	2					2	6
	21	2													2										2
	22	1																	1						1
Alternatives	23	1																		1				1	2
	24	1																							0
	25	1																							0
	26	1																1		1					2
Management, Policy & Infrastructure	27	3	3		3			3	3	3					3	3	3	3	3	3	3	3		3	42
	28	1	1				1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	16
	29	1			1				1		1		1			1			1	1					7
	30	1			1			1	1						1	1					1				6
	31	4			4			4			4	4	4		4			4			4	4			36
	32	1	1		1	1	1		1	1	1		1			1	1			1	1	1		1	14
Monitoring	33	1													1	1					1	1	1		5
	34	1	1		1												1	1	1	1				1	7
	35	1		1	1	1		1	1		1			1										1	8
Involvement of stakeholders	36	2	2		2			2	2	2		2	2		2	2	2			2	2	2		2	28
	37	2							2						2	2	2					2			10
	38	2	2		2												2								6
	39	1	1		1			1									1								4
Awareness raising and capacity building	40	1	1		1		1	1		1				1				1	1		1	1	1		11
	41	1	1	1	1		1	1	1	1		1			1	1	1	1	1	1	1	1	1		17
	42	3														3		3	3						9
	43	2			2		2			2						2		2		2	2	2	2	2	20
		Sum	24	10	36	5	14	31	19	20	16	17	18	7	25	35	16	32	29	19	31	28	8	20	
		Extent of conformance	35%	15%	53%	7%	21%	44%	28%	29%	24%	25%	26%	10%	37%	51%	24%	47%	44%	29%	47%	42%	12%	30%	

Appendix 4. List of ecolabels addressing waste and litter at coastal areas, number of criteria, period of validity, costs of implementation and granting body.

	Ecolabel	Region of application	Geographical scope	Global recognition	Number of criteria	Validity	Costs	Granting body
Beaches	Bandera Azul Ecológica	Costa Rica	National	-	18	1 year	Free	Government of Costa Rica
	Bandera Ecoplayas	Spain	National	ISWA, EU	12	1 year	Free, only 140 € for the flag costs	ATEGRUS
	Blue Flag	International	International	UNWTO, EEA	33[a]	1 year	Free in Morocco	Foundation for Environmental Education (FEE)
	Green Destinations – Quality coast/Award	International	International	GSTC	84	2 years	from 2,300 € annually, discount for low & middle-income countries	Green Destinations
	ISO 13009	International	International	ISO	56	3 years	Audit fees, registration fees and travel expenses for auditors	ISO
	IRAM 42100	Argentina	National	ISO	42	NI	NI	Government of Argentina
	NMX-AA-120-SCFI-2006	Mexico	National	-	7[a]	2 years	NI	SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales)
	NTE INEN 2631	Ecuador	National	-	14[c]	3 years	NI	Government of Ecuador
	NTS-TS-001-2	Colombia	National	-	62	NI	NI	Government of Colombia
	Seaside Award - England	England	National	-	25	NI	NI	Keep Britain Tidy
	Seaside Award – Northern Ireland	Northern Ireland	National	-	24	NI	NI	Keep Northern Ireland Tidy
	Seaside Award – Wales	Wales	National	-	11	1 year	£ 260 + VAT	Keep Wales Tidy
	White Flag	International	International	-	5	5 years (annual inspection)	NI	White Flag International

***Appendix 4 (continued)*. List of ecolabels addressing waste and litter at coastal areas, number of criteria, period of validity, costs of implementation and granting body.**

	Ecolabel	Region of application	Geographical scope	Global recognition	Number of criteria	Validity	Costs	Granting body
Destinations	EarthCheck Destination	International	International	GSTC	114	NI	From AU$ 7,500 annually, ca. 8,500 € for destinations with < 150,000 inhabitants, 14,000 € with < 500,000 inhabitants	EarthCheck
	Green Destinations Certified	International	International	GSTC	84	3 years	from 5,250 €	Green Destinations
	Istanbul Environment Friendly City Award	Mediterranean countries	Continental	GSTC, UN	55	NI	NI	Government of Türkiye, UNEP/ MAP
	NTS-TS-001-1	Colombia	National	-	116	NI	NI	Government of Colombia
	Certified Sea Turtle Friendly Tourism	International	International	GSTC	291	NI	NI	Wildlife Friendly Enterprise Network
	EarthCheck Certified for companies	International	International	GSTC	80	NI	From AU$ 6,600 annually	EarthCheck
	NMX-AA-171-SCFI-2014	Mexico	National	-	9[b]	NI	NI	SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales)
	Pacific Sustainable Tourism Standard	Pacific Island countries	Continental	GSTC	61	Every few years or as GSTC criteria is updated	NI	SPTO (Pacific Tourism Organization)
	Seychelles Sustainable Tourism Label	Seychelles	National	GSTC	109	2 years	Hotels 1 to 24 rooms = 400 €. 25 to 50 rooms = 800 €, > 50 rooms = 1000 €	Seychelles Tourism Board
	Stoke Surf	International	International	GSTC	38	1 year	Based on annual revenue, < 249k USD = 500 USD annually; 1M - 4.9M USD = 1,000 USD annually, 250M - 499M USD = 16,000 USD annually	Stoke Certified

[a] 33 for beaches, 38 for marinas and 97 for tourism boats
[b,c] with many subsections
[d] for gold level

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Doctoral dissertation

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