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On this basis, an innovative two-stage separation process was designed and experimentally tested. The process combines densimetric separation with tribo-electrostatic separation to selectively recover valuable material fractions from heterogeneous beach litter. The results demonstrate the technical feasibility of the approach, showing improved material recovery, a marked reduction in landfill disposal, and associated environmental benefits.

The proposed methodology represents an original applied engineering contribution to sustainable coastal waste management, supporting ecosystem protection and offering scalable implementation through a mobile treatment plant suitable for different coastal settings.

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Brixhilda Lleshi

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PhD in Risk and Environmental, Territorial and Building Development

POLITECNICO DI BARI

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XXXVIII CYCLE

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Francesco Todaro

LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

La sottoscritta BRIXHILDA LLESHI nata a SHKODER il 04/11/1995

residente a BARI in via MICHELE GARRUBA, N. 171 e-mail B.LLESHI@PHD.POLIBA.IT

iscritto al 3° anno di Corso di Dottorato di Ricerca in RISCHIO E SVILUPPO AMBIENTALE, TERRITORIALE ED EDILIZIO ciclo 38°.

ed essendo stato ammesso a sostenere l'esame finale con la prevista discussione della tesi dal titolo:

GESTIONE SOSTENIBILE DEI RIFIUTI SPIAGGIATI: TECNOLOGIE DI SEPARAZIONE DENSIMETRICA ED ELETTROSTATICA PER IL RECUPERO DI MATERIA.

DICHIARA

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EXTENDED ABSTRACT *(eng)*

Coastal zones around the world face a persistent problem of beach litter, the accumulation of heterogeneous debris such as plastics, seaweed, wood, and sand along the shoreline. This PhD research focuses on an innovative environmental engineering solution for the management and valorization of beach litte, in line with sustainability and circular economy principles. The study developed a methodology for the characterization of beachcast materials and tested a tretament precess designed to separate their componenents, thereby reducing landfill disposal and enabling the recovery of valuable resources.

Firstly, three representative sites along the Apulian coast in Southern Italy were selected as case studies. These sites were chosen to encompass a range of environmental settings and litter profiles. A detailed field campaign was conducted, involving mapping of debris “hotspots,” stratified sampling of the stranded material, and characterization of the collected samples. The beach litter at these sites was found to be highly heterogeneous: natural fractions (such as Posidonia oceanica) were intimately mixed with anthropogenic waste (e.g., plastic fragments, foam, glass, etc.) and mineral matter (sand and silt). The composition and distribution of the debris varied by site, influenced by factors such as human activity levels and exposure to winds and currents. This initial characterization underscored the management challenge: conventional practice would treat all this material as undifferentiated waste, incurring high removal costs and loss of sand and biomass that arguably do not belong in landfills.

In response, the core of the research focused on designing a two-stage separation process that can be deployed directly in situ to trat mixed beach cast waste. The proposed system combined: (1) a densimetric separation to isolate light organic matter and floatable debris from heavier materials such as sand, and (2) a tribo- electrostatic separation to further segregate residual plastics from mineral fractions by exploiting differences in electrostatic behavior. Laboratory-scale experiments were carried out to evaluate and optimize each stage of the process.

The research conclusively shows that adopting an integrated, resource- recovery approach to beach litter is both technically viable and environmentally ad- vantageous. By treating beach cast material not purely as "waste" but as a mix of recoverable resources and residues, the developed process aligns with circular economy objectives: it returns natural materials to the environment and channels man-made materials to appropriate recycling/waste streams. The outcome is a significant reduction in landfill dependency and a lower ecological footprint for beach maintenance activities. Moreover, this approach helps protect coastal ecosystems for example, by returning cleaned sand, it supports beach stability and habitat integrity, and by removing plastics, it reduces wildlife ingestion and entanglement hazards.

This work lays a foundation for scaling up to pilot-scale testing through a mobile treatment plant that can be operated directly in coastal environments. Future research and pilot projects should focus on integrating these separation technologies into a robust unit that can be transported to different beaches. Considerations such as powering the unit with renewable energy could further enhance sustainability. Additionally, exploring potential end-uses for the recovered Posidonia biomass and separated plastics would help close the resource loop. By demonstrating a practical way to implement the "waste-to-resource" philosophy on our shorelines, this study contributes to global efforts in marine litter mitigation, sustainable coastal management, and the advancement of circular economy practices in environmental engineering.

keywords

beach litter, densimetric separatio, tribo-electrostatic separation, waste management, laboratory experiments, material recovery, circular economy

EXTENDED ABSTRACT (ita)

Le zone costiere di tutto il mondo affrontano il problema dei rifiuti spiaggiati, ovvero l'accumulo lungo la riva di detriti eterogenei (costiutiti, ad esempio, da plastiche, alghe, legno e sabbia). Questa ricerca di dottorato si concentra su una soluzione innovativa, in linea con i principi di sostenibilità ed economia circolare, per la gestione e la valorizzazione dei rifiuti spiaggiati. Generalmente, i cumuli di detriti rimossi dalle spiagge vengono gestiti come rifiuto indifferenziato da avviare a smaltimento, comportando elevati costi di gestione, la perdita di risorse naturali (e.g., sabbia e posidonia oceanica) che di per sé non apparterebbero alla categoria dei rifiuti da discarica. In particolare, il presente studio ha permesso di sviluppare una metodologia per la caratterizzazione dei materiali spiaggiati e sono stati testati processi di trattamento per separarne i diversi materiali che compongono i rifiuti al fine di ridurre lo smaltimento in discarica e permettere il recupero di risorse di valore. componenti, riducendo così la necessità di smaltimento in discarica e permettendo il recupero di risorse di valore.

In primo luogo, sono stati selezionati come casi di studio tre siti rappresentativi della costa pugliese dell'Italia meridionale, scelti in modo da coprire una varietà di contesti ambientali. È stata condotta una campagna sperimentale in campo che ha previsto la mappatura delle aree di accumulo ("hotspot"), il campionamento stratificato del materiale spiaggiato e la caratterizzazione dei campioni raccolti. I rifiuti spiaggiati in questi siti sono risultati altamente eterogenei: le frazioni naturali (come la Posidonia oceanica) erano strettamente mescolate con scarti di origine antropica (e.g., frammenti di plastica, polistirolo, vetro, ecc.) e materiale minerale (e.g., sabbia e limo). La composizione e la distribuzione dei detriti variavano da sito a sito, influenzate da fattori quali il grado di antropizzazione e l'esposizione ai venti e alle correnti.

La ricerca ha riguardato la progettazione di un processo di separazione a due stadi utilizzabile direttamente in situ per trattare il rifiuto spiaggiato misto. Il sistema proposto combina: (1) una separazione densimetrica che isola la materia organica leggera dai materiali più densi (come la sabbia), e (2) una separazione tribo- elettrostatica che separa le plastiche dalla sabbia sfruttando le differenze di comportamento elettrostatico. Sono stati condotti test di laboratorio per valutare e ottimizzare ciascuna fase del processo.

I risultati dimostrano che adottare un approccio integrato di recupero di risorse per i rifiuti spiaggiati è tecnicamente possibile e vantaggioso dal punto di vista ambientale. Trattando il materiale spiaggiato non come "rifiuto" indistinto ma come un insieme di risorse recuperabili, il processo sviluppato si allinea agli obiettivi dell'economia circolare: restituisce i materiali naturali all'ambiente e convoglia quelli di origine antropica verso appropriati flussi di riciclo. Il risultato è una decisa riduzione dei flussi avviati a smaltimento in discarica e una minore impronta ecologica nelle attività di pulizia delle spiagge. Inoltre, questo approccio aiuta a proteggere gli ecosistemi costieri: ad esempio, reimmettendo in loco la sabbia trattata si supportano la stabilità della spiaggia e l'integrità degli habitat, mentre rimuovendo le plastiche si riducono i rischi di ingestione e intrappolamento per la fauna selvatica.

Questo lavoro getta le basi per passare a test in scala pilota, attraverso un impianto mobile utilizzabile in situ negli ambienti costieri. Le ricerche future e i progetti pilota dovrebbero focalizzarsi sull'integrazione delle tecnologie di separazione sviluppate in un'unità robusta e trasportabile su diverse spiagge. Aspetti come l'alimentazione dell'unità tramite fonti rinnovabili potrebbero migliorare ulteriormente la sostenibilità del sistema. Dimostrando un modo concreto per applicare la filosofia del "da rifiuto a risorsa", lo studio contribuisce agli sforzi globali di mitigazione dei rifiuti marini, alla gestione sostenibile delle coste e all'avanzamento delle pratiche di economia circolare nell'ingegneria ambientale.

keywords

rifiuti spiaggiati, separazione densimetrica, separazione tribo-elettrostatica, gestione dei rifiuti, esperimenti di laboratorio, recupero di materia, economia circolare

INDEX

INTRODUCTION

Coastal and marine pollution caused by beach litter constitutes a major environmental, sanitary, and socio-economic challenge in the Mediterranean basin. These heterogeneous shoreline deposits are composed of natural materials, such as marine biomass (Posidonia oceanica) and sediments (sand), mixed with an anthropogenic fraction (e.g., plastic).

At the international level, beach litter is addressed by Descriptor 10 of the European Marine Strategy Framework Directive (2008/56/EC), which requires that "properties and quantities of marine litter do not cause harm to the coastal and marine environment" as a condition for Good Environmental Status (ISPRA, 2025). The target is set at fewer than 20 litter items per 100 m of beach, a value adopted by EU Member States as an indicative threshold for macro-litter density that is deemed compatible with (Loon, et al., 2020). Achieving this target is challenging and is intended to drive ambitious reduction measures.

In Italy, beach litter is legally classified as municipal solid waste under Article 183 of the Environmental Code (Italia, 2006, art. 183). These accumulations drive a spectrum of impacts that concern engineers, ecologists, public health officials, and coastal communities:

- Environmental Impacts: beach litter disrupts coastal ecosystems by smothering habitats, destabilizing beaches through the removal of natural wrack, and accelerating erosion . Predominantly plastic, it fragments into micro and nanoplastics that infiltrate food webs, cause toxicity, and harm wildlife through ingestion, ultimately leading to biodiversity loss and degraded ecosystem health (Buoninsegni, 2025).
- Sanitary and Public Health Issues: decaying organic material in beach litter can release unpleasant odors, attract insects, and create unsanitary conditions, while sharp debris such as glass or metal poses direct physical hazards to beachgoers. Although health risks from natural wrack are generally low, mixed litter may con-

tain pathogens or sewage-derived contaminants, requiring local authorities to balance public health concerns with environmental protection when managing beach clean-ups.

- Socio-Economic Effects: Beach litter pollution undermines coastal economies and social wellbeing by reducing recreational and aesthetic value, discouraging tourism, and generating substantial public costs for cleaning, transport, and waste disposal. In Italy and elsewhere, this creates a management dilemma, balancing the ecological benefits of leaving natural wrack in place against public pressure for visually clean beaches, resulting in economic losses, social complaints, and environmental trade-offs for coastal communities (Friedrich, 2005).

Current beach litter levels remain far above the Good Environmental Sta-tus target in Italy and across the Mediterranean. National monitoring by ISPRA and regional ARPA agencies shows a declining trend in beach litter in Italy, with the 2023 median density at about 250 items per 100 m of shoreline, the lowest observed since 2015, likely reflecting public awareness and policy measures such as the 2021 EU Single-Use Plastics directive.

Effective management of beach litter requires an integrated approach combining robust characterization of mixed debris, efficient separation technologies, and sustainable valorisation of recovered materials. Analytical data on composition, moisture, and contaminants guide the design of processes that separate sand, organic biomass, and anthropogenic debris for reuse, recycling, or safe disposal. Engineering solutions must be portable, energy-efficient, and minimally disruptive, while Life Cycle Assessment and cost analysis ensure environmental and economic sustainability. By turning beach litter into recoverable resources, this approach supports circular economy principles and informs practical, scalable strategies for coastal management.

The present doctoral research aims to contribute an innovative solution to the beach litter problem by focusing on the characterization of sites and experimental testing of two separation technologies for sustainable material recovery. Field investigations are conducted at several representative sites to collect samples of beach accumulation and assess their composition and properties, establishing a knowledge base on the feedstock variability. Building on this, two complementary separation processes are explored at laboratory scale: Densimetric Separation and Tribo-electrostatic Separation. These two separation technologies address the core challenge of fractionating beach litter into useful streams.

This research sets out the following objectives:

- Sampling and Characterization: define and validate representative sampling protocols for beach litter deposits and establish laboratory workflows for comprehensive characterization of samples (Goncalves, 2022). This objective ensures that later experi- ments use realistic input materials and that results can be scaled to real-world condi- tions. The methodology aligns with national guidelines (UNI/ISPRA) for marine litter assessment to ensure data quality and comparability.
- Density Separation Optimization: conduct laboratory-scale tests of the densimetric separation unit with beach litter samples and perform parametric optimization. The aim is to maximize sand rejection while concentrating the anthropogenic fraction in the light output (Zielinski, 2022). This objective will result in an optimized set of operating conditions and design recommendations for a density separator handling beach wrack.
- Tribo-electrostatic Separation Evaluation: evaluate the efficacy of turboelectric charging and electrostatic separation for recovering lightweight polymers from the mixed debris. The objective is to increase the recovery of clean plastic fragments and reduce organic contamination in the plastic output, enabling potential recycling (Velander, 1999).
- Sustainability Assessment: perform a comparative Life Cycle Assessment (LCA) analysis for different management scenarios.

Through these research activities, the PhD work will deliver an in-depth understanding of beach litter characteristics and a proof-of-concept for an innovative engineering process to separate and valorize beach litter components. The ultimate vision is to transform how beach clean-ups are conducted: moving away from simply hauling “waste” to landfill, and towards a resource recovery paradigm where sand, organic matter and recyclable materials are efficiently extracted and reused.

This work will contribute to closing the gap towards Good Environmental Status for coastlines, offering a practical tool for coastal municipalities to manage beach litter in a technically sound, ecologically sustainable, and economically sensible manner.

1. BEACH LITTER

1.1. Regulatory Framework

1.1.1 International Legislation and Global Agreements

Marine litter has been recognized as a trans- boundary pollution problem re- quiring international action since the late 20th century. Early global agreements ad- dressed marine pollution broadly, implicitly covering litter. The 1972 London Conven- tion on the Prevention of Marine Pollution by Dumping of Wastes and its 1996 Proto- col prohibit the ocean dumping of plastics and other persistent materials (Manyara et al., 2022). The 1973 / 1978, MARPOL International Convention explicitly bans the dis-posal of plastics at sea from ships. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) obligates States to prevent and reduce marine pollution from all sources (Art. 194) (Costa et al., 2020), laying a general legal duty that co- vers ma-rine debris even though UNCLOS does not mention “plastic” specifically. UN- CLOS Part XII calls on nations to adopt laws to prevent pollution (including land-based sources and dumping, Art. 207–212), providing an overarching framework for marine environmental protection (Costa et al., 2020).

Several global conventions on hazardous substances have indirect relevance to ma-rine litter. The 1989 Basel Convention on hazardous waste was amended in 2019 to include certain plastic wastes, tightening control over international shipments of plas-tic scrap to reduce leakage. Likewise, the 2001 Stockholm Convention restricts per-sistent organic pollutants, some of which (e.g. additives in plastics) are associated with marine debris (Manyara et al., 2022). These treaties, while not aimed solely at lit-ter, contribute to global governance of plastic waste.

Over time, the international community also developed voluntary agreements and ac-tion plans. The 1995 Global Programme of Action for land-based pollution and vari-ous (UN Environment Assembly UNEA) resolutions have highlighted marine litter. UN-EA adopted multiple resolutions (2014, 2016, 2017, 2019) urging action on ma- rine plastic litter and microplastics (Costa et al., 2020). Notably, in 2022, UNEA agreed on a landmark resolution to negotiate a new legally binding global treaty on plastic pollution, covering the full lifecycle of plastics. As of 2025, negotiations are underway with the aim to finalize a treaty that addresses plastics from production to disposal, including marine litter, by the end of the year (European Environment Agency , 2025). In parallel, G20 nations launched the Osaka Blue Ocean Vision 2019 to reduce additional marine plastic leakage to zero by 2050, and G7 nations issued an Ocean Plastics Charter 2018, reflecting high-level political commitments.

The Mediterranean's Barcelona Convention and its 2013 Regional Action Plan on Marine Litter impose obligations on countries like Italy to monitor and reduce beach litter. Similar action plans exist in the Northeast Atlantic (OSPAR, 2023) and elsewhere (Manyara et al., 2022). While these initiatives are largely non-binding, they foster coordinated monitoring and share best practices. In summary, the international regulatory landscape for marine litter is a patchwork of binding agreements and vol- untary strategies addressing land-based sources. Nevertheless, the combined effect of existing measures has elevated marine litter onto the global agenda: SDG 14.1 un- der the UN Sustainable Development Goals calls for preventing and significantly re- ducing marine pollution (including litter) by 2025, reflecting the urgency of the issue (European Environment Agency , 2025).

1.1.2 European Union Legislation

The European Union has developed an extensive legislative framework to tackle marine and beach litter, aligning with international obligations. A cornerstone is the Marine Strategy Framework Directive. Under the MSFD, EU countries must moni- tor beach litter and implement measures to reduce it. The EU's Technical Group on Marine Litter set a target threshold of 20 litter items per 100 m of coastline as a benchmark for Good Environmental Status (European Environment Agency , 2025).

To tackle sources of plastic litter, the EU introduced the Plastic Bags Directive (2015/720/EC). The EU Plastics Strategy (2018) set out a policy roadmap to transi-

tion to a circular plastics economy, directly linking to marine litter prevention (Addamo et al.,, 2018). A milestone outcome was the Single-Use Plastics Directive (EU 2019/904), which targets the top 10 plastic items found on EU beaches.These ten single-use plastic products together account for an estimated 43% of marine litter items found on European beaches, while abandoned fishing gear contributes another 27% (European Environment Agency , 2025).
Furthermore, the EU has integrated marine litter considerations into waste and water policies. The Waste Framework Directive and Packaging Directive set recycling targets for plastics (50% by 2025) and encourage product redesign to reduce leakage (Litter, 2025). The Urban Wastewater Treatment Directive has been updated to include filters for microplastics. Additionally, the European Commission’s Zero Pollution Action Plan (2021) set an interim target of 50% reduction in plastic litter at sea by 2030 (relative to 2015) (European Environment Agency , 2025). Research and innovation funding has also been directed at marine litter monitoring technology and removal innovations.
EU legislation creates a multi-tiered approach: Preventing litter at source, im- proving waste management to stop leakage and monitoring/cleaning existing litter.
The combination of these policies has begun to show measurable improve- ments; for instance, a recent analysis reported a 29% decrease in the count of plastic items on European beaches from 2015–16 to 2020–21. However, despite this pro- gress, beach litter levels in many areas remain well above targets, indicating the need for continued and additional actions (European Environment Agency , 2025).

1.1.3 National Legislation

Within Italy, the national legal framework on beach litter and marine waste has evolved in response to both EU requirements and local environmental challenges. Italy transposed the MSFD into national law via Legislative Decree 190/2010, committing to monitor and achieve Good Environmental Status including for marine litter (Simeone, Ruju, & al.), 2020). Under this framework, Italy established targets to reduce beach litter and implemented a National Marine Litter Monitoring Programme (coordinated by ISPRA) to systematically survey debris on reference beaches (Litter, 2025). Current beach litter levels remain far above the Good Environmental Status target in Italy and across the Mediterranean. National monitoring by ISPRA and regional ARPA agencies shows a declining trend in beach litter in Italy, with the 2023 median density at about 250 items per 100 m of shoreline, the lowest observed since 2015, likely reflecting public awareness and policy measures such as the 2021 EU Single-Use Plastics directive (Fig.1).

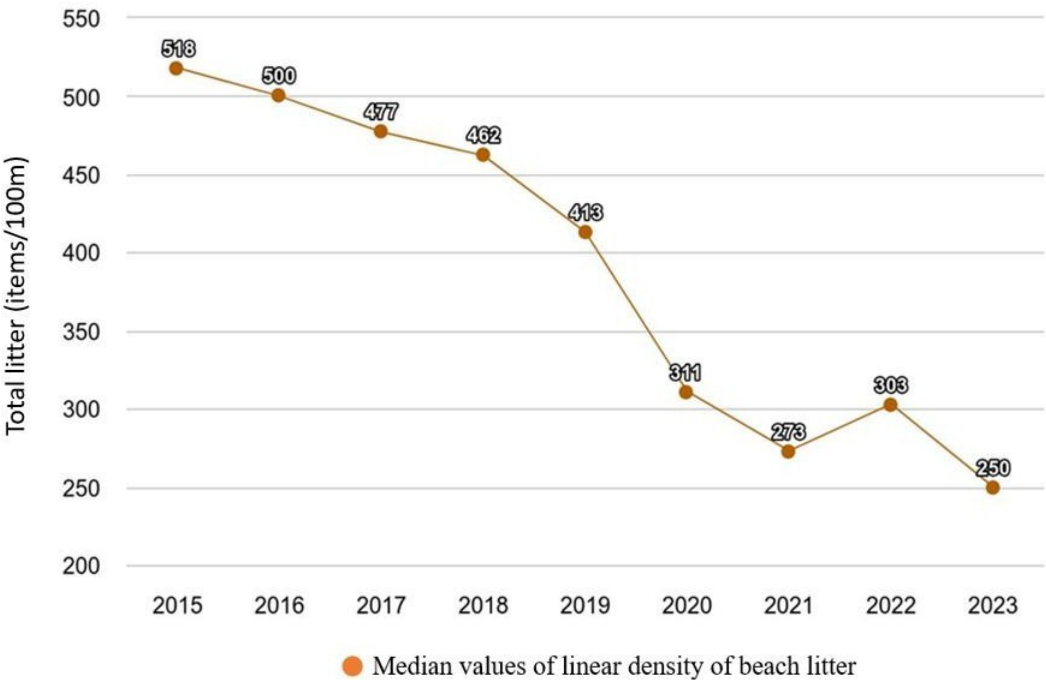

Figure 1- Median values of linear density (items per 100 m) of total litter along Italy's coasts, based on monitoring conducted as part of the Marine Strategy (source: ISPRA analy-sis of ARPA data)

Historically, anything collected from beaches, including accumulations of natural seaweed mixed with garbage was deemed “refuse” that municipalities must dispose of in landfills. In May 2022, the “Salvamare” law (Law 60/2022, Protection of the Sea) was enacted, enabling fishermen and boaters to legally retrieve and land marine litter collected at sea. Previously, if fishermen hauled in plastic debris incidentally, they were technically required to throw it back overboard to avoid being classified as unauthorized waste transporters. The Salvamare law removes this perverse incentive by allowing any marine litter brought up in fishing nets or found floating to be delivered to port reception facilities, where it is treated as municipal waste and can be sorted for recycling or disposal. This law effectively expands “fishing for litter” activities nationwide, making fishers key allies in removing debris from the sea. Salvamare also promotes public awareness and educational programs on marine litter and allows use of recovered ocean plastic for art and recycling initiatives.

Italy has also been proactive in banning specific pollutants that contribute to beach litter. Microplastics in cosmetics were banned as of January 2020 (Law 205/2017) and the sale of plastic cotton bud sticks was prohibited starting 2019. These national bans preceded similar EU-wide measures and have helped reduce two common litter items on Italian beaches.

Another area of national attention is the management of Posidonia oceanica, which lines many Mediterranean shores. For years, the removal of Posidonia oceanica was done without clear guidelines, treating it as waste mixed with sand and litter. In the absence of specific legislation, practices varied by region, and large amounts of sand-rich plant material were landfilled annually (Simeone, Ruju, & al.), 2020). To clarify this, the Ministry for Environment issued Circular n.8123/2006 and an updated Circular n. 8838/2019 on Posidonia beach casts management. This 2019 circular marked a significant shift: it stated that accumulations of pure seagrass detritus on beaches should be not automatically considered waste instead, if left in place or repositioned to protect the coast, they are a natural "resource," only becoming “waste” if destined for disposal. The guideline strongly recommends in situ preservation of Posidonia berms, especially on eroding beaches, citing their role in shoreline stability and habitat integrity. The circular instructs local authorities that if removal is necessary, they must first separate anthropogenic litter from the organic material, manually or with light sieving machinery and avoid heavy machinery that would haul away sand. Seagrass material, once cleaned of plastic and sand, can be diverted from landfill to composting or other reuse: it may be treated as biodegradable waste for compost, provided it constitutes no more than 20% of the compost mix by weight. This nuanced regulatory approach in Italy attempts to balance environmental protection with practical beach management. Some Italian regions (Sardinia, Lazio) have since issued their own guidelines aligning with the national circular, promoting the concept of an “ecological beach” where natural wrack is maintained and only actual litter is removed.

In summary, Italy’s national framework on beach litter now combines adherence to EU directives with innovative domestic measures like Salvamare and Posidonia management guidelines. These efforts are relatively recent, so their full effect on reducing beach litter and preserving sand is being monitored. Italy’s experience shows that policy tools can empower stakeholders to participate in solutions to the beach litter problem, complementing broader EU and international initiatives.

1.2. Definitions and Characteristics

Beach litter is commonly defined as any persistent, manufactured or processed solid material that has been discarded, disposed of, or abandoned in the coastal environment (Fig.2). A formal definition by UNEP (2009) describes marine litter as “any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment". This definition highlights key attributes of beach litter: it is solid, persistent, and anthropogenic in origin.

Global assessments estimate that at least 80–85% of all marine litter items are composed of plastic (Addamo et al.,, 2018) (United Nations Environment Programme, 2025). On beaches, the plastic proportion is typically extremely high: for example, surveys on Mediterranean shores find 75–90% of litter items are plastics (Greenpeace, 2021). In European beach litter data, the single most common recorded item is typically "plastic/polystyrene pieces" between 2.5–50 cm (OSPAR, 2023).

Figure 2- Beach litter composition in the study sites showing organic, mineral, and anthropogenic fractions

Besides plastics, other typical constituents of beach litter include: foamed polymers, rubber, processed wood, metals, glass and ceramics, cloth/textiles, paper and cardboard, even hazardous materials like medical waste or ammunition in certain cases. The relative composition varies by location and influence of human activities.

For instance, on urban beaches or those near river outlets, one might find more everyday consumer waste (food packaging, bottles), whereas on remote or open-ocean facing beaches, a larger share may be fishing gear, buoys, and plastic fragments transported by currents (Haseler et al., 2025).

A notable component of beach litter, especially in the Mediterranean, is the mixture of natural detritus and man-made waste. For example, piles of dried Posidonia oceanica seagrass (known as banquette when mounded) often entangle plastic debris and other litter. This intermingling complicates clean-up and quantification, as separating the waste from natural material is laborious (Simeone et al., 2020).

Recent studies using fine mesh sieves or sediment cores have found microplastic concentrations of hundreds to thousands of pieces per kilogram of beach sand on some industrialized or enclosed sea coastlines (Haseler et al., 2025).

In terms of sources and pathways, beach litter can be categorized as land-based or sea-based in origin. Common pathways are direct littering by beach visitors, garbage blown or washed from coastal dumps and urban areas, and riverine input. Indeed, it is estimated that the majority (often cited as 70–80%) of marine litter comes from land-based sources (European Environment Agency , 2025). Typical sea-based items are fishing nets and ropes, fish traps, strapping bands, cargo packaging, and waste from vessels. Another defining property of beach litter is its persistence. Many plastics essentially do not biodegrade in the marine environment instead, they may persist for decades, only breaking into smaller pieces.

Finally, spatial distribution of litter on a beach is usually heterogeneous. Litter tends to concentrate at the high-tide line or wrack line, mingled with seaweed and driftwood deposited by waves (Haseler et al., 2025). In summary, beach litter is defined by its human origin, persistence and predominance of plastics. Its characteristics, item types, size distribution and source pathways collectively inform how we monitor and manage the issue. Understanding these attributes is crucial for designing targeted interventions, such as product bans for common items, improved waste infrastructure or customized beach cleaning technologies for microplastics.

1.3. Distribution and Environmental Impacts

Beach litter is a global problem affecting even the most remote shorelines. Distribution is highly uneven, influenced by proximity to sources, ocean currents, wind, and coastal geography. Enclosed and semi-enclosed seas with high coastal populations, such as the Mediterranean Sea, tend to have particularly high litter densities on their beaches. The Mediterranean's combination of many coastal inhabitants, tourism, inadequate waste management in some areas, and limited outflow leads to significant litter accumulation. The Black Sea exhibits the highest levels in Europe, with hundreds of items per 100 m of shoreline (Litter, 2025).

Oceanographic factors cause litter to concentrate in certain "hotspots." Within regional seas, local hotspots occur near river mouths (e.g. the Nile Delta in the Mediterranean), near large cities, or downwind of major shipping lanes. Seasonal weather plays a role too monsoon or storm seasons can flush out rivers and bring pulses of debris to coastlines, whereas calmer seasons may allow accumulation of lighter debris on the dry upper beach. For example, a study in the Bay of Bengal found that plastic litter densities on beaches were higher during the wet season when river runoff peaked.

Within a given beach, litter distribution is typically patchy. Debris tends to accumulate along the strandline where wave action deposits it among natural drift. After storms, beaches often have fresh wrack lines full of litter. Lighter items can be blown into vegetated dunes or trapped in crevices of rocky shores. Heavier debris might stay near the water's edge. This intra-beach heterogeneity means surveys must cover broad areas to get representative data. Some litter, especially microplastics and dense items, gets buried in beach sediment. Without cleanup, beaches can develop a buried reservoir of older litter beneath the surface (Poeta, 2016).

Many regions have observed an overall increase in beach litter since mid-20th century corresponding to rising plastic production. However, recent interventions are starting to bend the curve. For instance, on some European beaches, standardized monitoring shows a slight decreasing trend in litter counts in the last 5–10 years, which is attributed to policy measures like plastic bag fees and improved waste awareness (European Environment Agency , 2025). Despite such hopeful signs, the absolute levels remain high, and new types of litter (notably COVID-19 related waste) have emerged. During 2020–2021, items like disposable masks and gloves began appearing on shorelines globally, adding to the litter burden. Thus, distribution is dynamic, reflecting human behavior changes as well as policy impacts .

Beach litter has far-reaching impacts on marine and coastal ecosystems, wildlife, human health, and local economies. On the ecological side, one of the most visible impacts is wildlife entanglement and ingestion. Large plastic debris such as discarded fishing nets, ropes, and strapping bands entangle marine animals ghost fishing by lost nets can ensnare fish, turtles, marine mammals, and seabirds, causing injury or drowning.

Beyond individual animals, litter can alter habitats and ecosystems. On sandy beaches, an accumulation of debris can smother small organisms and alter the exchange of gases in the sediment. If not managed, microplastics in beach sand may affect the populations of sand-dwelling fauna by altering the sediment properties or being ingested by these organisms. Litter can also serve as a vector for invasive species transport: floating plastics that land on a beach might carry barnacles, mollusks or algal spores from distant regions, which upon arrival could colonize new areas.

An often overlooked impact is chemical pollution from litter. Plastics can leach additives into the environment. They also adsorb persistent organic pollutants from seawater onto their surfaces. When animals ingest plastics, these chemicals can transfer, potentially accumulating in the food web (Buoninsegni, 2025).

The socio-economic impacts of beach litter are significant. Aesthetic degradation of coastlines is one of the most immediate issues. Beaches fouled with trash deter tourists, reducing the recreational and amenity value of coastal areas. Coastal communities that rely on tourism can suffer economically when their beaches are perceived as dirty. Studies in Europe estimated that marine litter causes hundreds of millions of euros in lost tourism revenue annually. One analysis put the cost at a minimum €630 million per year for the EU tourism sector due to beach litter (European Environment Agency , 2025).

In summary, the impacts of beach litter are multi-faceted and predominantly negative.

2. OVERVIEW OF BEACHED WASTE MANAGEMENT

2.1 Stranded Plastics

Managing stranded plastics, the plastic debris deposited on beaches involves a continuum of strategies from prevention to collection to final disposal or recycling. Once plastics have reached the shore, the immediate response is often removal through beach clean-ups (Bellasi, 2022). Around the world, clean-up activities form the backbone of managing beach litter. These range from large-scale mechanical cleaning by munici- palities to volunteer-based manual clean-ups:

- Municipal beach cleaning
- Volunteer and community clean-ups
- Targeted fishing-for-litter programs

Post-collection handling of stranded plastics is a critical aspect. Traditionally, the mixture collected from beaches often wet, sandy, and heterogeneous has been sent to landfill or incineration. This is because beach-collected plastics are usually degraded by UV exposure and fouled by salt, sand, and organic matter, making them less suitable for conventional recycling (European Environment Agency , 2025). The disposal route chosen can significantly affect the sustainability of beach litter management:

- Landfilling.

It has been the simplest option historically, but it is increasingly discouraged. Landfilling plastic waste is a lost opportunity for material recovery and carries risk of re-release (wind can blow litter away if not properly covered). Moreover, landfill capacity is limited and costs are rising in many regions.

- Incineration (with energy recovery).

It is commonly used in Europe for contaminated or hard-to-recycle plastics. Incinerating beach litter in waste-to-energy plants can at least recover some energy and reduces volume by $\sim$90%. The downside is the cost and the generation of CO_2 and potentially toxic ash. Still, for health and safety reasons, certain beach litter (medical waste, dead animals entangled in debris, oil-contaminated debris) must be incinerated.

- Recycling of beach plastics.

It is challenging but not impossible. A limited number of projects and companies have started to recycle ocean or beach plastics into new products, usually as a marketing effort to raise awareness.

However, such efforts face logistical and economic hurdles: collecting enough homogeneous plastic, cleaning and processing it, and competing with virgin resin prices. Research indicates that only a small fraction of recovered marine plastics can be economically recycled with current technology (journal, 2025). Marine debris often consists of polyolefins (PE, PP) and some PET, which in principle can be recycled. Success stories include recycling programs for end-of-life nets in some Mediterranean ports, turning them into textiles or construction materials. For general beach litter, one approach is mechanical recycling: wash, shred, melt and reprocess. This requires removing sand and biofouling first (Forleo, 2021). Pilot projects have shown pyrolysis can convert mixed ocean plastics into low-grade oil or diesel, but the processes are still being refined for efficiency and pollution control.

Innovative separation and valorization: Simple trommel or barrel devices can be used on-site to shake out sand and remove organic debris, leaving a more purified plastic stream. One notable example is the use of a rotating sand separator barrel by cleanup groups, which by hand-cranking tumbles beach litter to sieve out sand (4Ocean, 2025). In a 2024 trial in Indonesia, this method allowed a cleanup team to reduce 2,200 kg of collected material to ~2,000 kg of plastics by removing sand on-site, making transport and processing more efficient (4Ocean, 2025). After sand removal, the remaining plastics can be baled and sent to specialized recycling or energy recovery facilities. Advanced methods like density separation tables are being researched to segregate heavier materials from lighter plastics and biomass. This can greatly improve the handling: the clean sand can be returned to the beach, and plastics concentrated for proper disposal or recycling.

Another management consideration is interim storage and sorting. Ports or municipalities often need designated storage for the collected beach litter before it is treated. Some Italian ports, for instance, have installed sorting stations where litter from Salvamare operations is manually separated into recyclables (PET bottles, aluminum cans) versus unrecyclable waste. Coastal cities are also exploring the use of compactors on beaches to allow visitors to dispose of trash without it blowing away, thus intercepting litter before it spreads.

Prevention and reduction strategies complement clean-up in managing stranded plastics. Reducing the amount of plastic reaching beaches in the first place is the most sustainable solution (Munari, 2016). This includes public education, providing adequate bins, and policies like bans on beach smoking or single-use plastics at beach con- cessions. Some Mediterranean beaches have implemented "smoke-free beach" pro- grams partly to reduce cigarette butt litter, since filters are a top item found.

Another approach is "Leave No Trace" regulations: requiring beach users (campers, picnickers) to remove everything they bring. Several marine protected areas enforce rules that nothing not even organic waste is to be left behind, with fines for non-compliance. These regulations attempt to instill a culture of stewardship.

Detection and monitoring technologies are also emerging as management tools. Drones and AI image recognition have been trialed to detect litter accumulations on remote or extensive beach areas (Frontiers in Marine Science, 2025) (Frontiers in Marine Science, 2023). Effectively, stranded plastic management is moving from a purely reactive cleanup model to a more holistic one that integrates prevention, involves diverse stakeholders and applies engineering solutions to maximize material recovery.

2.2 Posidonia oceanica

Posidonia oceanica is an endemic seagrass of the Mediterranean Sea, forming large underwater meadows that are crucial for ecosystem health (providing habitat, oxygen, and carbon sequestration). When the leaves die (especially in autumn and winter), wave action carries them to shore, where they form dense banquettes – brown, mat-like mounds that can stretch along the high tide line.

Many coastal municipalities in Italy, France, Spain, and other Mediterranean countries have removed Posidonia banquettes before the summer tourist season to "clean" the beach for recreational use. This practice, however, has come under scrutiny for its environmental drawbacks: it can exacerbate coastal erosion and disturb beach ecology (Simeone et al., 2020).

In recent years, there has been a paradigm shift towards "beneficial management" or "ecological beach" approaches for Posidonia wrack. The goal is to balance environmental protection with touristic use. Key strategies include:

- On-site preservation:

The preferred option, recommended by scientists and now by authorities, is to leave Posidonia accumulations in place, especially outside of the peak bathing areas or on beaches where erosion is a concern (Simeone et al., 2020). Educational signage is often used to inform the public that the seagrass is a natural feature and not "dirt," explaining its role in protecting the beach.

- Partial and temporal relocation:

If removal is necessary for recreational purposes, one practice is to relocate the banquette temporarily. For instance, at the start of summer, a municipality might push the Posidonia piles to one end of the beach or to the backshore, clearing the central bathing area. Then, at the end of summer or before winter, they return this material to the shoreline to allow it to continue protecting against storm erosion. This approach has been tried in parts of Italy and France. It requires coordination and some extra cost, but retains the environmental benefits of the seagrass.

- Separation and cleaning:

A recommended best practice is that any removal of banquettes should involve separating out the litter. The Italian circular (2019) mandates that beach managers must remove anthropogenic waste from the wrack either manually or with light sieving equipment.

- Utilization of removed biomass:

When banquettes are removed, rather than dumping them, there is growing interest in valorizing Posidonia biomass. Some possible uses:

Composting and soil amendment:

Dried Posidonia leaves can be composted into a soil conditioner or mulch. However, because of high salt content, they often need leaching (e.g. left in the rain) or mixing with other organic waste. Italy’s guidelines allow composting with the caveat that Posidonia should be no more than 20% of the compost mix. Co-firing or biofuel: The dry fibrous material has a calorific value and can be burned alongside other biomass in power plants. There’s research into converting seagrass wrack to biogas via anaerobic digestion, but high salt and sand content pose challenges.

Construction materials:

An innovative use in France and Tunisia has been drying Posidonia fibers and using them as an insulating material in green building, or pressing them into particle boards. Posidonia has good thermal properties and, being salt-laden, is naturally pest-resistant.

Coastal protection engineering:

In some cases, collected Posidonia banquettes have been placed at the foot of dunes or eroding banks as a natural buffer, essentially using them as an eco-friendly form of erosion control.

Clarifying the legal classification of Posidonia wrack has been key. In France, since 1988 Posidonia (even dead) is a protected species, technically forbidding removal of banquettes without special permission. Italy's policy shift recognizes it as a resource if used for beach protection. Some Italian regions (e.g. Tuscany, Lazio) have issued regional guidelines aligned with the national circular, detailing procedures for handling Posidonia (ISPRA, 2024).

In summary, the management of Posidonia oceanica on beaches has moved from viewing it purely as waste to be removed towards a more nuanced approach of conservation and smart management.

2.3 Sediment

One of the thorniest issues in beach litter management is dealing with the sand that becomes intermixed with litter. Many local guidelines now instruct that mechanical cleaning should skim only the surface and ideally use sieving mechanisms to shake out sand. The Italian Ministry's Posidonia circular explicitly prohibits tracked vehicles on banquettes and advises using light vehicles with sieves to separate sand (Simeone et al., 2020).

To tackle the sand-litter mix, several approaches are employed:

- On-site sieving and screening:

Many mechanical beach cleaning machines are designed as sand sifters, they use a conveyor belt or a vibrating screen that allows sand to fall back to the beach while retaining larger debris. For instance, a common beach cleaner will rake up the top 5–10 cm of sand and run it over a mesh; clean sand falls through, and litter is carried into a hopper.

- Manual shaking of seaweed and wrack:

When removing organic wrack (Posidonia) mixed with sand, a common practice is to shake or partially dry the material on-site so that sand and associated fauna can escape. In Sicily and Corsica, for example, guidelines for Posidonia remov- al say to stockpile the material near the beach on a geotextile surface, let the sand drain out, and then return that sand to the beach.

- Intermediate sand recovery in waste facilities:

If littered sand is collected, some waste facilities have installed sand-waste separation units. These can be rotating drums or table separators that later separate sand from the mixed waste.

This research and others are advancing portable technologies that can be deployed directly on beaches to separate sand from collected litter. One such device tested by cleanup organizations is the 4ocean Sand Separator, basically a large perforated barrel rotated by hand-crank. This simple technology dramatically reduced the weight of waste transported (4Ocean, 2025). For large-scale operations, more mechanized versions exist: air-driven density tables. Tribo-electrostatic separation for fines: For very fine microplastic-sand mixtures, one cutting-edge idea is using triboelectric separation. The benefits of recovering sand are clear: it reduces the volume and weight of waste sent to disposal (saving landfill space and transport costs) and preserves the natural capital of the beach. It also mitigates erosion because the sand is not perma- nently removed from the coastal system. A study by De Falco et al. in Sardinia (2008) highlighted that the banquette material trucked away was often 30–60% sand by weight, meaning significant sediment loss from the beach ecosystem (ResearchGate, 2023). By separating that sand and returning it, beaches maintained their profiles better and had to rely less on artificial nourishment.

The management of sand associated with beach litter focuses on retaining sand on the beach and recovering sand from collected waste: Operationally, this means favoring sieving-type beach cleaning equipment and gentle techniques. Technologically, it means developing and using separation processes (mechanical, aeration, electrostatic) to split sand from debris. Managerially, it requires guidelines and policies that encourage sand return and treat sand not as waste but as part of the beach system.

However, managing the sand in beach litter is a critical aspect that links environmental care with engineering ingenuity, and it exemplifies the need for cross- disciplinary approaches (coastal engineering and waste management) in tackling marine litter problems.

3. RESEARCH PURPOSES AND PLAN

3.1 Research Purposes

This doctoral research addresses the shortfalls in the sustainable management of beach waste. Three core problems motivate the work:

1. Inadequate characterization of waste, which prevents reliable mass-balance and process design;
2. Absence of robust, field-adapted separation technologies capable of pro- cessing abrasive and highly variable beach matrices to recover both natural and an- thropogenic components;

3. Lack of an operational, sustainable management chain that minimizes envi- ronmental and sanitary impacts while maximizing recovery of secondary raw materi- als and minimizing landfill disposal.

In this context, the research activities aimed to develop and experimentally validate a modular treatment chain, suitable for mobile deployment, in order to enable the selective separation, recovery, and valorization of beach waste. The study focused on the experimental optimisation of two innovative separation technologies, densimetric and tribo-electrostatic separation. Through comprehensive feedstock characterization and comparative sustainability assessment (LCA), the research sought to define engineering parameters and operational guidelines that can support the transition from disposal-oriented practices to a circular, resource-oriented management model aligned with the Good Environmental Status (GES) objectives of the Marine Strategy Framework Directive.

3.2 Research Plan

The experimentation plan was articulated in:

1. Representative characterisation & sampling protocol.

Define and validate a sampling plan and laboratory workflow (mass fractioning, granulometry, bulk density, moisture, organic content and basic ecotoxicological screening) to provide the input distributions required for process sizing and performance forecasting.

2. Densimetric separation optimisation. The treatability tests conducted within this doctoral research aimed to verify the technical feasibility of separating Posidonia oceanica, plastic debris, and sand through a densimetric process. Experimental trials were carried out using a laboratory-scale density table with a processing capacity of 10 kg/h. The obtained results were analysed to evaluate the efficiency of the separa- tion method and its potential scalability for larger-scale applications, with the objec- tive of optimising key operational parameters.

3. Tribo- electrostatic separation evaluation. The experimental activities in- volved treatability tests using a prototype electrostatic separation unit with a capacity of 10 kg/h, aimed at the separation of sand and plastic polymers. The results of these experiments contribute to the development of a sustainable system for beach-litter management, demonstrating the potential of electrostatic technologies to enhance material recovery and reduce the environmental impact of coastal waste.

4. Sustainability appraisal. Conduct LCA to identify break-even conditions and net environmental benefit thresholds.

The experimental activities carried out at the Environmental Technologies Laboratory of the Department of Civil, Environmental, Land, Building Engineering and Chemistry of the Polytechnic University of Bari focused on a structured set of operations designed to evaluate the technical feasibility and sustainability of innovative treatment processes for beach litter. Specifically, the treatability tests included the following activities: (i) Sampling of beach litter at three representative coastal sites Mola di Bari, Fasano, and Porto Cesareo (Southern Italy) following a well-defined and standardized sampling plan compliant with the UNI 10802:2013 protocol; (ii) Characterization of beach litter, including ecotoxicological analyses, granulometric distribution, and plastic waste classification using MIROSPAR, 2023k technology, to identify the material composition and potential environmental risks; (iii) Laboratory-scale treatability tests on two innovative separation technologies densimetric and electrostatic using different input flow conditions to assess process performance, separation efficiency, and scalability; (iv) Life Cycle Assessment (LCA) analyses to evaluate the environmental sustainability of the proposed technologies.

These integrated activities provide the experimental and analytical foundation for developing a sustainable, circular approach to beach-litter management, promoting the recovery of secondary raw materials while minimizing environmental impacts.

4. MATERIALS AND METHODS

4.1 Study Area

4.1.1 Site identification

Beached waste is defined as heterogeneous debris deposited along the shore-line, composed of an anthropogenic fraction mixed with natural organic and mineral fractions. Multiple factors influence debris accumulation in coastal zones, including beach morphology, geographic exposure, and the nature of the debris itself. In this study, reference beaches and specific sampling units were selected by prioritizing heavily littered "hotspots", areas known for significant debris accumulation.

The selected beaches met the following criteria:

Known accumulation sites (historical litter hotspots);

Preferably exposed to the open sea (promoting natural deposition of drift mat- ter);

Minimum beach dimensions of approximately 100 m length and 10 m width;

Low to moderate beach slope;

Unobstructed access to the sea (no barriers like groynes or jetties impeding drift);

Able to be sampled before seasonal municipal clean-up operations com- menced.

Numerous international and national frameworks provide standardized approaches to beach litter and microplastic monitoring (OSPAR, 2023) (Loon et al., 2020). Drawing on these sources, the common practice of classifying beaches into three typologies: natural, semi-natural, and anthropogenic was adopted. This scheme was refined based on a targeted literature review of existing classification systems (Semeoshenkova et al., 2016) to better suit our regional context. The typological framework ensures that sampling and subsequent intervention strategies are tailored to the intrinsic characteristics of each coast, thereby maximizing technical, economic, and social benefits while minimizing environmental impacts (Er-Ramy et al., 2023). The literature review highlighted that beaches with high tourist pressure require frequent cleaning by local authorities but also experience increased waste inputs due to

visitation; conversely, remote natural beaches tend to accumulate debris primarily transported by marine currents and wind (Taofiqurohman et al., 2024). It was also observed that natural wrack deposits can entangle and trap significant amounts of an- thropogenic litter within them (Asensio et al., 2021).

Based on these insights, three coastal habitat categories were defined for the project:

1. **Anthropic (urban) habitat.**

These are areas characterized by dense residential or tourist development with established public services (schools, businesses, transportation infrastructure). Beaches in urban habitats are readily accessible and subject to intensive anthropogenic pressure, including frequent municipal cleaning operations and high visitation.

2. **Semi-natural habitat.**

These areas have limited permanent settlement but substantial seasonal recreational use. Basic public services and transport access exist at a smaller scale than in urban areas. Beaches in semi-natural settings experience mixed litter inputs from local users as well as from marine currents and drift.

3. **Natural habitat.**

These are remote or semi-remote stretches of coastline with very low human presence, little to no built infrastructure, and restricted access (reachable only on foot, by boat, or via limited roads). Such beaches are dominated by natural features and primarily accumulate debris delivered by oceanographic and aeolian (wind- driven) processes rather than local human activity.

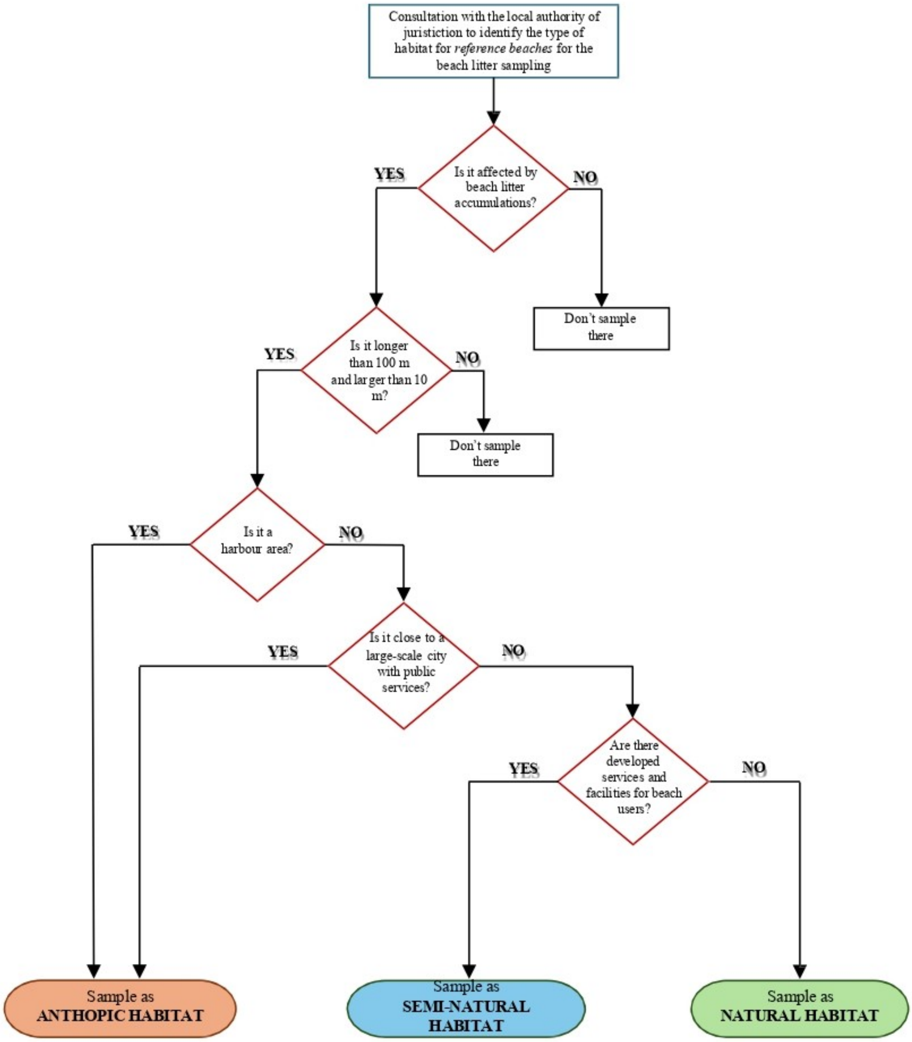

Figure 3- A decision-making flowchart used to guide the selection of representative reference beaches based on these habitat typologies

4.1.2 Sampling Plan

A systematic shoreline survey was conducted at each selected site to document baseline conditions. The GPS coordinates of the four corner points of every sampling unit were recorded, and each unit was assigned a unique Sample ID used throughout the study for traceability. Field sampling was carried out with a standardized toolkit to ensure consistency across sites. The equipment used at each sampling unit included a measuring wheel (or 100 m tape) for laying out transects and measuring distances, a metal shovel for collecting bulk material, polyethylene sheets for sorting and temporary sample placement, and marker flags or stakes to delineate the unit boundaries. Collected materials were placed into appropriate containers: large rigid items were set aside or placed in mesh bags, whereas bulk mixed samples were sealed in heavy-duty polyethylene bags.

For each treatability trial, a target bulk sample mass of approximately 6 kg was collected. This quantity ensured there was enough material to perform the full suite of laboratory analyses and experimental separations. Immediately after collection, each sample batch was labeled with its Sample ID, site name, and date of collection; identical labels were affixed to the sample container and to a corresponding chain-of-custody form (Fig.4). The samples were then transported to the laboratory under controlled conditions and stored appropriately until processing to preserve their characteristics.

Figure 4- Sampling bags with collected beach- litter samples

During the field surveys, two broad categories of accumulations were noted:

(i) predominantly anthropogenic litter deposits and (ii) natural organic detritus depos- its. These beach-cast assemblages often exhibited distinct spatial distribution pat- terns. Accordingly, we classified observed accumulations into three distribution types to inform our sampling strategy and subsequent subsampling for analyses. The typol- ogy (illustrated in Figure 5) is as follows: (A) Uniform continuous accumula- tions of natural organic material along the shore (e.g. extensive Posidonia oceanica wrack banks spanning the foreshore – Type A, Figure 5A); (b) Localized, patchy ac- cumula- tions dominated by litter with a minor organic component (concentrated piles of anthropogenic debris mixed with some seaweed – Type B, Figure 5B); and (c) Dif- fuse, randomly distributed litter with little or no organic fraction (scattered debris items along the strandline – Type C, Figure 5C).

Figure 5- Examples of these accumulation types: continuous seagrass “banquettes” for Type A, mixed litter patches for Type B, and dispersed litter for Type C

Based on the above typology and site characteristics, three sampling methodologies were defined (Methods 1, 2, and 3) to collect representative samples from each accumulation type. The choice of method depended on habitat type, beach length, and the nature of the debris distribution. All methods aimed to ultimately gather a ∼24 kg composite sample from each site, which would then be quartered down to a 6 kg laboratory sample per standard protocols (UNI EN 15002:2015).

Method 1 (for Type A accumulations – Figure 5A):

This method was applied to sites often in anthropic (urban) habitats such as harbor-adjacent beaches where a widespread, uniformly distributed accumulation of Posidonia or other algae was present along the coast in large quantities. The sampling strategy for these beaches involved defining a single elongated sampling unit of at least 100 m in length (along the shoreline) and ∼10 m in width (perpendicular from the waterline) (Figure 6a). If the beach stretch was shorter than 1 km, one such sampling unit was established in the most heavily littered section of the wrack bank. The designated area (∼100 m × 10 m) was further divided into three equal sub-areas of about 33–35 m length each (Figure 6). Within each sub-area, four random sampling points were selected. At each point, roughly 2 increments of ∼1 kg of material were collected using a shovel, digging through the full depth of the deposit. This yielded about 8 kg from each sub-area (2 increments × 4 points), and ∼24 kg from the entire unit (3 sub-areas × 8 kg). The ∼24 kg composite sample was then thoroughly mixed and quartered (per UNI EN 15002:2015 standard; see schematic in Figure 8) to obtain a representative laboratory sample of approximately 6 kg. If two sampling units were required, the procedure was repeated and the two 6 kg subsamples were combined and quartered again to yield one 6 kg lab sample representing the whole beach. In cases where the beach length exceeded 1 km, two separate 100 m × 10 m sampling units were sampled on that beach, spaced at least 50 m apart along the shoreline (Figure 6B). This ensured coverage of spatial variability on longer beaches while still focusing on the most accumulated sections.

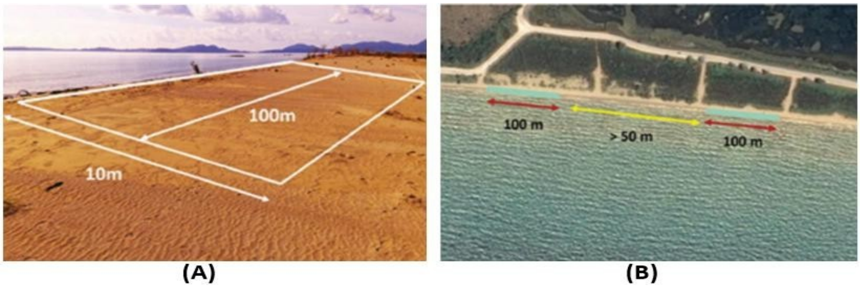

Figure 6- A) Sampling unit extension B) Sampling units for beaches longer than 1 km (Vlachogianni et al., 2017)

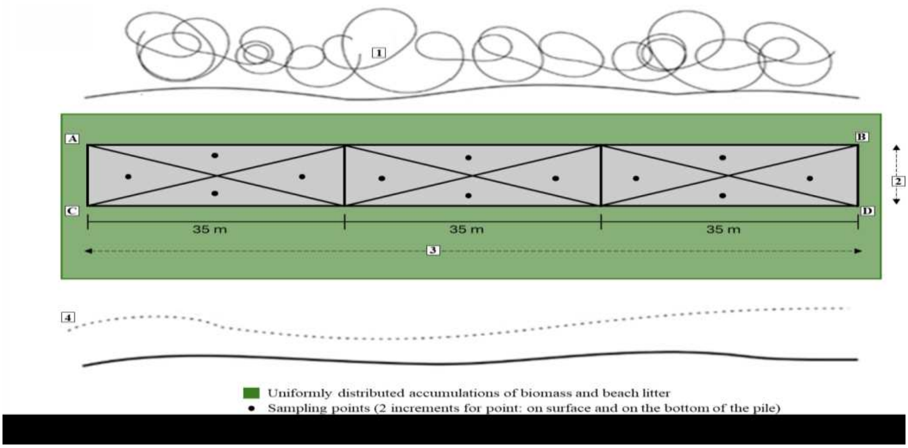

Figure 7- Sampling scheme

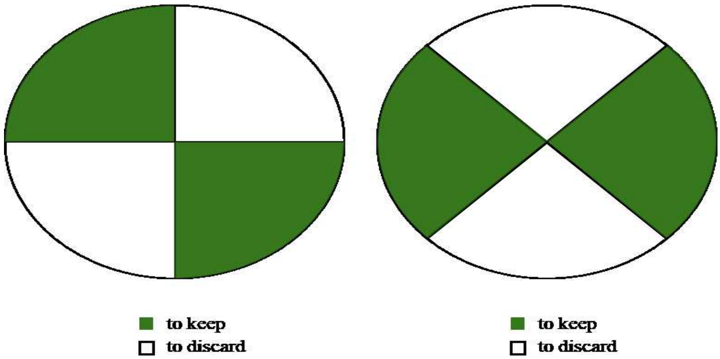

Figure 8- Quartering of the samples

Method 2 (for Type B accumulations – Figure 5B):

This method was designed for beaches where heterogeneous, patchy accu- mulations of natural and anthropogenic materials occur (Type B), multiple discrete piles of mixed seagrass and litter scattered along the shore. A stratified random sam- pling approach was used in this scenario. Along the length of the beach, three distinct sampling units (approximately 100 m × 10 m each) were identified to cover the major accumulation "hotspots" (Figure 9). Within each of these units, a procedure similar to Method 1 was followed but on a smaller scale: from each unit, 8 increments of ∼1 kg were collected (spread across that 100 m section, targeting accumulation patches). In total, around 24 increments (∼24 kg) were gathered when combining the three units (3 units × 8 kg each). These were then pooled to form one composite sample representing the entire beach's litter deposits. The composite ∼24 kg was mixed and quartered (following the protocol in UNI EN 14899:2006, analogous to the quartering in Figure 8) to produce a 6 kg laboratory sample. By mixing material from multiple points and sections of the beach, this method ensures the lab sample is representative of the beach's overall litter composition, despite the non-uniform distribution of debris.

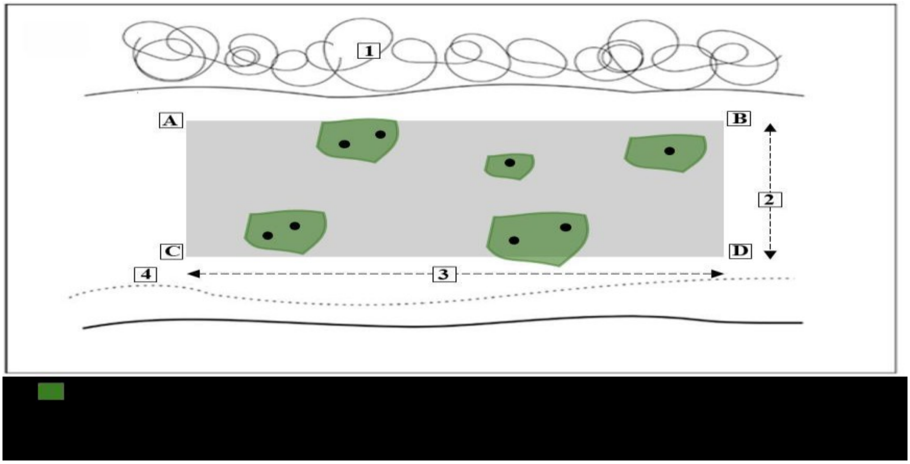

Figure 9- Sampling unit selection for Method 2

Method 3 (for Type C accumulations – Figure 5C):
This method addresses beaches where anthropogenic litter is sparsely and randomly distributed (Type C) and virtually no substantial natural wrack is present. Here, a random sampling strategy was employed focusing exclusively on anthropo- genic debris. Similar to Method 2, three 100 m × 10 m sampling units were identified along the beach, centered on the sections with the highest observed litter density (Figure 7 illustrates an example layout). Within each unit, field personnel manually collected all visible beach litter items (plastics, glass, metal, etc.) until approximately 8 kg of material was obtained per unit. Because the debris is diffuse, the "sampling points" in this method were simply the spots where litter items were found – essen- tially a random scatter dictated by the presence of waste. Combining the three units yielded roughly 24 kg of collected litter in total. This composite was then quartered (using the same

procedure as above, per UNI EN 15002:2015) to yield a ~6 kg la- boratory sample. The random placement of collection points ensures that the sample reflects the distribution of litter across the beach.

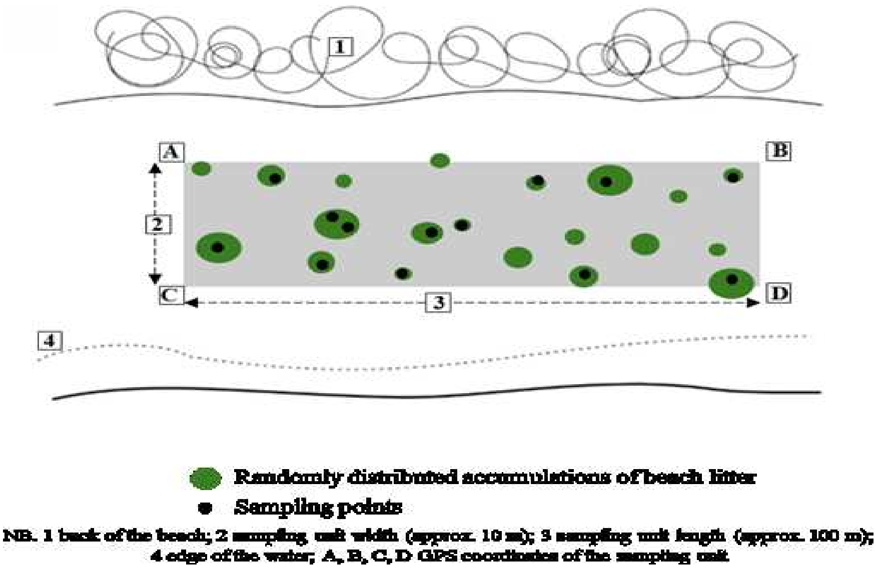

Figure 10- Sampling unit characteristics for Method 3

For all three methods, any large or heavy debris items (generally >30 cm in size or >0.5 kg) that could not be feasibly collected and included in the bulk sample were recorded in situ and photographed. The count of such oversized items in each sampling unit was noted, and their density was reported in terms of number of large items per square meter within the sampling area. This documentation of bulky debris ensures that the presence of substantial items (which might require different handling) is accounted for in the site's overall litter assessment, even though they were not part of the treatability sample.

4.1.3 Characterization Plan

This activity focuses on an integrated laboratory characterization of the collected sample (6 kg). Once at the laboratory, the total sample of 6 kg has to be sieved by a sieve with apertures of 50 mm to divide the sample into two (2) fractions, each consisting of particles within specific size limits of 50 mm: the largest particles kept at the top of the sieves (Material larger than 50 mm) and the smaller one at the bottom (Material smaller than 50 mm).

Material larger than 50 mm

By visive identification, the particles greater than 50 mm are manually divided into three main fractions:

fv1 natural organic fraction: algae and aquatic plants, beached plant materials, and e.g., egagropiles;

fm1 natural mineral fraction: shells, pebbles which could be trapped in the natural organic fraction and anthropogenic fraction;

fa1 anthropogenic fraction: beach litter trapped in the vegetal natural organic fraction.

<u>Chemical-physical characterization of the three main fractions</u>.

Each fraction is characterized by the following methods:

Moisture determination according to method A of UNI EN 15934:2012;

Ash determination and organic matter content according to UNI EN 15935:2021;

pH, conductivity, and redox potential according to UNI EN 16192:2012 and UNI EN 15934:2012. Then, the divided fractions are placed on three (3) different aluminium trays, weighed, and dried in an oven at 50 ºC for about 6 h (Simeone and De Falco, 2012), and the quantity is measured by weighing (fv1, fm1, fa1).

Material smaller than 50 mm

By visive identification, the particles greater than around 20 mm are manually removed from the sample and sorted into the three (3) main fractions (e.g., egagropiles, pebbles, anthropogenic items, bottle caps). Then, the divided fractions are placed on three (3) different aluminium trays, weighed, and dried in an oven at 50 ^oC for about 6 h (Simeone and De Falco, 2012), and the quantity is measured by weighing (fv2, fm2, fa2).

Also, for the remaining sample, the following measures are determined:
Moisture determination according to method A of UNI EN 15934:2012;
Ash determination and organic matter content according to UNI EN 15935:2021;
pH, conductivity, and redox potential according to UNI EN 16192:2012 and UNI EN 15934:2012; Afterward, the average moisture content (%) of the total sample is determined by comparing the moisture measures of the three fractions ($>$ 50 mm) and the mois- ture of the sample smaller than 50 mm.

From the remaining sample, three (3) sub-samples of approximately 200 g are prepared by further quartering. Each sample quantity is measured by weighing.

The (3) samples are placed on three (3) different aluminium trays, weighed and dried in an oven at $\leq$ 50 ^oC for about 24 h (Simeone and De Falco, 2012), and the quantity is measured by weighing.

For each sample, the three main fractions must be quantified according to the procedure described below (ASTM, 2003); (UNI, 2012); (UNI, 2017); (UNI, 2021) .

These three samples consist of natural organic, mineral, and anthropogenic components that must be quantified. Each sample has to be subjected to sieving (mesh aperture: 20 mm, 10 mm, 6.3 mm; 2 mm; 1 mm; 0.63 mm; 0.2 mm, 0.063 mm, see UNI EN ISO 17892-4:2017), achieving separation into fractions of different sizes. The remaining fraction would consist of natural organic fraction component (fv3, in case of samples of accumulation Type A and B) that could retain residuals of mineral (fm3) and anthropogenic fraction (fa3) of small size. Whereas if the samples belong to the accumulation of Type C, it is necessary to separate only the anthropogenic fraction (fa3) and the mineral fraction (fm3). This separation must be done according to the simplified procedure reported in Annex II.B, based on standard UNI EN ISO 24187:2023. The total fraction quantities are given by Equ. 1, 2 and 3:

$$fa = fa1 + fa2 + fa3 \qquad (1)$$
$$fm = fm1 + fm2 + fm3 \qquad (2)$$
$$fv = fv1 + fv2 + fv3 \qquad (3)$$

The sum of the three final fractions constitutes the total weight of the separat- ed sample:

$$ftot = fv + fa + fm \qquad (4)$$

At the end of this step, the three fraction rates are established as a percentage of the total according to equation (5):

$$f\ (\%) = fi \times 100 \qquad (5)$$

In this way, the rate of each fraction is measured. The characterization of the component fractions involves the following analysis.

Table 1- Methods summary

FRACTION	ANALYSES	REFERENCE STANDART
All fractions: Material larger than 50 mm divided into the three main fractions Material smaller than 50 mm	Moisture	UNI EN 15934:2012
	Particle size analysis	UNI EN ISO 17892-4:2017
	Moisture, ash, organic matter content	UNI EN 15934:2012; UNI EN 15935:2021
	Redox potential	UNI EN 15934:2012
	Conductivity	UNI EN 15934:2012
	pH	UNI EN 16192:2012

Anthropogenic fraction (> 50 mm)	Merceological analysis in the main classes (i.e., Paper, Glass, Wood, Plastic, Ferrous and Non-ferrous Metals)	ASTM D5231-92-2003
	Characterization of plastic fraction by IR spectro-scopic analysis	ASTM E1252-98 - 2021
Natural mineral fraction (< 50 mm)	Microplastic	Semplified procedure

At all sampling sites, polymer classification was performed using the portable mIROSPAR, 2023k system (Fig.6). In this approach each plastic item was illuminated with near-infrared (NIR) light and the diffuse reflectance spectrum was recorded. The analysis is inherently non-destructive and rapid: the mIROSPAR, 2023k's NIR module typically completes a classification, enabling high-throughput, on-site sorting of common consumer and packaging plastics.

Toxicological analysis

Toxicological analysis of beach litter was performed to evaluate toxicity through the determination of the Seed Germination Index (GI). The methodology fol- lows (Gadaleta et al., 2025).

Sediment and Posidonia samples were sieved through a 2 mm mesh to remove large debris. Each sieved sample was mixed with distilled water at a 1:10 (w/w) ratio. The mixtures were stirred for 2 hours at room temperature to extract soluble substances. After agitation, samples were centrifuged at 6000 rpm for 15 minutes to separate solids. Both the original (undiluted) extract and a 50% (v/v) dilution were prepared. The pH and conductivity of each mixture were measured and recorded. Ten

L. sativum seeds were placed on a filter paper (9 cm diameter) in each Petri dish. Distilled water was used as the negative control. All Petri dishes (samples and con- trols) were incubated in the dark at 25 °C for 72 hours. After incubation, the number of germinated seeds in each dish was counted. Seeds were considered germinated when the primary root length exceeded 1 mm. The length of each germinated seed's primary root was measured with a manual caliper. The average root length was calcu- lated for each Petri dish. The Seed Germination Index (SG) for the i-th dish was calcu- lated as: Sgi = (number of germinated seeds in dish i) / 10 The Germination Index (GI) of each sample was calculated using the formula:

GI [%] = (RLi * SGi) / (RLc * SGc) *100, where (RLi * SGi) are the average root length and seed germination index for sample i and (RLc * SGc) are the corresponding values for the control.

Figure 12- Toxicological analysis process of beach litter samples

According to UNI 10780 guidelines, if the GI of the undiluted sample exceeds 80%, no further dilutions are required unless otherwise specified by relevant standards. The results were evaluated following Cesaro et al. (2015). Phytotoxic effects were classified based on the GI of the sample:

- GI < 40%: strong inhibition (sensitive phytotoxic response).
- 40% ≤ GI < 80%: slight inhibition.
- 80% ≤ GI < 120%: no effect.
- GI > 120%: stimulation.

This toxicological analysis was performed on both sediment and Posidonia samples collected from all sampling sites included in the study.

4.2 Experimental Treatments for Densimetric Separation

A laboratory-scale densimetric table was tested to verify the feasibility of density-based segregation on beach-derived material. The experiments were conducted using two representative types of input mixtures prepared from the collected samples:

- Posidonia oceanica mixed with sand
- Plastic debris (PET) mixed with sand

4.2.1 Materials

For these densimetric separation tests, the raw collected materials were pre-processed by drying and sieving to target specific particle size ranges. The Posidonia fragments and PET plastic pieces were cut or sieved to a size of approximately 2 mm, and the sand was sieved to a median grain size of about 1 mm. Using these controlled size fractions ensured more uniform and repeatable behavior during the separation, as particle size influences settling and transport on the vibrating table.

4.2.2 Equipment

The separation trials were carried out on a vibratory air-flow table with an approximate processing capacity of 10 kg/h. The device consists of a feed hopper to introduce the material, and a rectangular porous deck that serves as the separation surface. The deck's longitudinal angle can be adjusted, and it is mounted on an eccentric drive mechanism that induces a controlled vibration along its length. A regulated airflow is blown upward through the porous deck. As the machine operates, vibration and airflow together stratify the feed material by density: lighter particles receive more lift from the air stream and migrate toward the lower end of the incline, while heavier particles remain in closer contact with the deck and move toward the upper end.

At the bottom (low) end of the deck, a collection container (Container 1) captures the separated light fraction (Posidonia); at the top (high) end, a second container (Container 2) collects the heavy fraction (sand, plastics). An operator control panel allows fine adjustment of the key operating parameters: vibration frequency of the deck, airflow velocity through the material, and the inclination angle of the table.

Figure 13- Densimetric table setup, including its compressor, th brating deck, and collection containers

Three principal operating parameters influence the table's separation performance:
Deck inclination angle (I): Controls the gravitational component along the table: a steeper angle increases the downslope force on particles, affecting how quickly material flows and segregates by weight.
Vibration intensity/frequency (V): Shaking the deck helps fluidize the material and encourages stratification, as heavier particles have more inertia and tend to stay in contact with the deck, while lighter ones bounce more and can be carried by air- flow.
Airflow rate (P): The upward air velocity through the deck provides lift to parti- cles; a higher airflow preferentially lifts lighter materials (like dry Posidonia), aiding their transport to the light fraction container, whereas dense particles resist lift and remain on the deck.
In our trials, the inclination angle was adjustable roughly between 2° and 10° relative to horizontal, the vibration frequency ranged from 45 to 60 Hz, and the airflow ranged from 45 to 60 Hz in equivalent frequency units. During preliminary tests, it was observed that using very low vibration or airflow settings led to suboptimal out- comes:

if the airflow was too weak or the vibration too low, material would either simply slide down due to gravity or, conversely, stagnate and stick to the deck due to friction. Therefore, the lower extremes of these ranges were avoided in subsequent experiments to ensure that the feed did not either bypass the separation or clog the system.

The densimetric separation experiments were structured in multiple phases to optimize performance. The objectives were to: (1) evaluate the baseline effectiveness of the density-separation process on mixed beach waste, (2) optimize the operating parameters (I, V, P) to maximize separation efficiency, and (3) assess the influence of feed composition on the separation outcomes.

4.2.3 Treatability Test

For the first series of experiments, the feed mixture consisted of 20% Posidonia oceanica (dry weight) and 80% sand (by weight), reflecting a typical composition for seagrass banquette material with entrained sand. For each trial, 500 g of this mixture was processed (equivalent to 100 g Posidonia + 400 g sand per trial). The Posidonia used in the tests was oven-dried at 50 °C prior to mixing; drying times varied (generally around 48 hours) depending on initial moisture content of each batch, ensuring a consistently dry feed.

Figure 14- Mix 1 Posidonia oceanica 2 mm $< D <$ 5 mm, Sand D $<$ 1 mm

Figure 15- Mix 2 Sand D< 1mm; PET 2 mm < D < 5 mm

Mix 1

First test series:

In the initial experimental series, the deck inclination was fixed at 10° to pro- mote material flow. A matrix of vibration frequencies (50, 55, 60 Hz) and airflow rates (45, 50, 55 Hz) was tested, yielding 3 × 3 combinations as summarized in Table 2.

Table 2- First test series

20% Posidonia - 80% Sand			
ID SET	**I [°]**	**P [Hz]**	**V [Hz]**
1	10	50	45
2	10	55	45
3	10	50	55
4	10	60	45
5	10	50	50
6	10	55	50
7	10	55	55

8	10	60	50
9	10	60	55

Each trial ran for 10 minutes, as it was observed that no further significant separation occurred beyond this duration. After each run, the contents of Container 1 (light fraction, Fig.11A) and Container 2 (heavy fraction, Fig.11B) were retrieved.

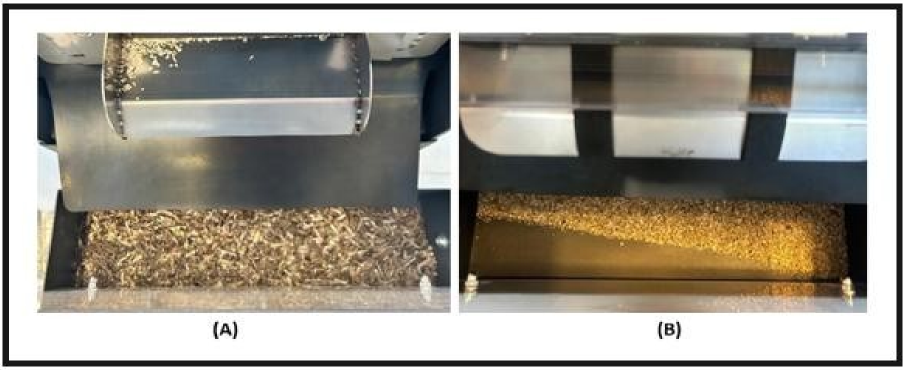

Figure 16- Container 1(A), container 2(B)

The output from each container was then sieved to separate any intermixed components: we used 2 mm and 1 mm mesh screens to retain Posidonia fragments while allowing sand grains to pass. Sieving was aided by a mechanical shaker (≈70 Hz vibration) for 90 seconds to ensure thorough separation of fine sand from fibrous Posidonia. The sieved fractions were then weighed using a precision balance (±2 g accuracy).

For each trial in this series, the purity of each recovered fraction and the sepa- ration efficiency of the process were calculated. We define purity (P) as the percent- age of the target material in a given output fraction. The overall separation efficiency (E) is defined as the percentage of the total target material in the feed that ended up in its correct fraction.

<u>Second test series</u>:

Based on the preliminary evaluation, the second series of trials fixed the deck inclination at a much lower angle of 2°. We then explored a refined set of vibration and air-flow settings around the previous ranges. Specifically, vibration frequencies of 45, 50, and 55 Hz were tested, and airflow rates of 45, 50, 55, and 60 (Hz) were ap- plied. This yielded a broader matrix of combinations, but to keep the experiment size manageable, we selected a subset of seven parameter combinations that early obser- vations indicated were promising.

Table 3- Second test series

20% Posidonia - 80% Sand			
ID SET	**I [°]**	**P [Hz]**	**V [Hz]**
1	2	50	45
2	2	50	50
3	2	50	55
4	2	55	60
5	2	50	60
6	2	45	60
7	2	45	45

Each configuration was run in triplicate to ensure statistical reliability of the results, with each trial again lasting 10 minutes. The feed composition remained the same 20%/80% Posidonia-sand mix for this series.

Third and fourth test series:

To examine the influence of the Posidonia-to-sand ratio on separation perfor- mance, two additional sets of trials were conducted. Using the same optimized oper- ating parameters identified in the second series (incline ~2°, with vibration and air- flow at the settings that gave the best results), we prepared new feed mixtures with different compositions: a 50% Posidonia / 50% sand mix, and a 70% Posidonia / 30% sand mix.

Table 4- Third test series

50% Posidonia - 50% Sand			
ID SET	**I [°]**	**P [Hz]**	**V [Hz]**

5	2	50	60
6	2	45	60

Table 5- Fourth test series

70% Posidonia - 30% Sand			
ID SET	**I [°]**	**P [Hz]**	**V [Hz]**
5	2	50	60
6	2	45	60

These represent scenarios with higher organic content. For each of these compositions, the separation test was repeated (in triplicate for each condition). Be- cause the operating conditions were held constant (based on the previously optimized values), any changes in separation outcomes could be attributed directly to the change in feed makeup.

For each trial, the purity of each recovered fraction and the separation effi- ciency of the process were calculated. We define purity (P) as the percentage of the target material in a given output fraction (e.g. percent of Posidonia in the light fraction, or percent of sand in the heavy fraction). The overall separation efficiency (E) is de- fined as the percentage of the total target material in the feed that ended up in its cor- rect fraction (for instance, how much of the Posidonia in the feed was recovered in the light output, combined with how much of the sand was recovered in the heavy output, relative to their initial masses).

Mix 2

Sand and PET Plastic

After optimizing conditions with organic material, we applied the densimetric separation to a plastic-sand mixture to evaluate the technology's applicability to an- thropogenic debris. The chosen mix was 20% plastic (we used polyethylene tereph- thalate, PET) and 80% sand, mirroring the ratio of the initial Posidonia tests for com- parability.

Table 6- Second mix test series

20% Plastic - 80% Sand

ID SET	I [°]	P [Hz]	V [Hz]
1	2	50	60
2	2	50	55
3	2	55	60
4	2	45	60
5	2	50	50
6	2	55	45
7	2	45	45
8	2	50	45

The PET fragments were >2 mm, and sand ~1 mm. We processed this plastic-laden feed using the same operating parameters that had yielded the best performance for Posidonia (incline ~2°, vibration 45–55 Hz, airflow 45–60 range).
The goal was to see if the conditions effective for separating lightweight fi- brous organics from sand would also effectively separate lightweight plastic particles from sand. Across all densimetric tests, the raw data were recorded and later used to calculate the performance metrics (purity and efficiency as defined earlier). For clari- ty, Figure 12 presents a simplified schematic of the separation process and defines the variables used in calculations: for example, P0 and S0 are the total Posidonia (or plastic) and sand input masses, P1 and S1 are those recovered in Container 1 (light output), and P2 and S2 in Container 2 (heavy output).

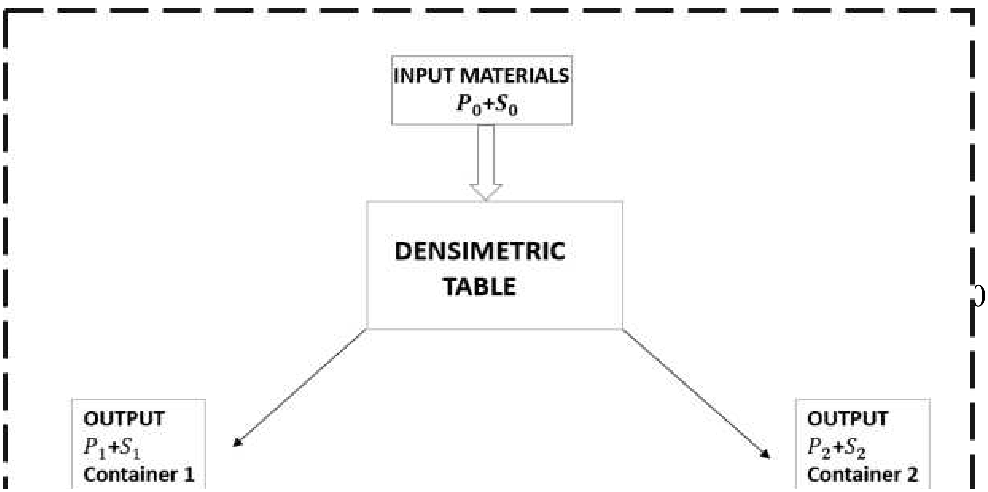

Figure 17- A simplified schematic of the densimetric separation

The purity degree is defined as:

$$P_{posidonia}(\%) = \frac{P_1}{(P_1 + S_1)} \times 100$$

$$P_{posidonia}(\%) = \frac{P_1}{(P_1 + S_1)} \times 100$$

$P_{Posidonia}$ = Purity of the Posidonia Fraction

$P_{Plastic}$ = Purity of the Plastic Fraction

P_{Sand} = Purity of the Sand Fraction

The overall performance of the separation process is expressed by a single parameter representing the total separation efficiency E(%). The following formula was used:

$$E = \sqrt{\frac{P_1}{P_1 + P_2} \cdot \frac{S_2}{S_1 + S_2}} \cdot 100$$

4.3 Experimental Treatments for Tribo-electrostatic Separation

The second technology evaluated was a tribo-electrostatic separator, intended to separate materials based on differences in their ability to hold electric charge. We used a Stokkermill laboratory-scale electrostatic separator to test dry separation of the mixed beach waste after appropriate preprocessing. This equipment can recover particles in the size range of roughly 0.04 mm up to 8 mm.

4.3.1 Materials

The laboratory test plan involved feed mixtures of sand and either polypropyl- ene (PP) or polyamide (PA) plastic granules, both with median particle sizes around (1–1.4) mm.

Figure 18- Mix 1, Sand and PP plastic

Figure 19- Mix 2, Sand and PA plastic

4.3.2 Equipment

Tribo- charger

The tribo-charger is a cylindrical device equipped with a hopper that allows the insertion of plastic particles into the chamber - Fig.15 (A). The inner wall of the device is made of PE, a material that occupies a central position in the tribo-electric series in technical-scientific literature. Inside the cylinder, there are transverse baffles to facili- tate the particle rubbing. The device is powered by an electric motor that allows the cylinder to rotate at an adjustable speed; thus, the particles inside the chamber are subjected to a rubbing or stirring action, coming into contact with each other and with the inner wall of the device. This causes electrons to transfer between the materials and a potential difference is generated between them. Some materials will acquire a positive charge, while others will acquire a negative charge, depending on their tribo- electric properties. The tribo-charging device can be controlled via a control panel that allows the following parameters to be adjusted:

Cylinder rotation speed: variable in a range of [15 - 60] Hz

Inclination: variable in a range of [0 - 20]

To evaluate the electric charge density acquired by plastic particles, a Faraday cage connected to a Keithley electrometer, model 6514 - Fig.15 (C) was used. Spe- cifically, the Faraday cage consists of a Faraday cup, which is a steel container placed on an insulating support made of a wooden base covered with multiple layers of nylon (Fig. 15 B). This setup ensures the preservation of the charge on the tribo- charged particles. Additionally, the Faraday cup is enclosed within a metallic container and surrounded by a metal mesh to minimize potential interactions between the tribo-charged sample and external electrostatic fields. The electrometer is connected to the Faraday cup and cage via cables equipped with clamps at the terminals, enabling the measurement of the charge density of the particles.

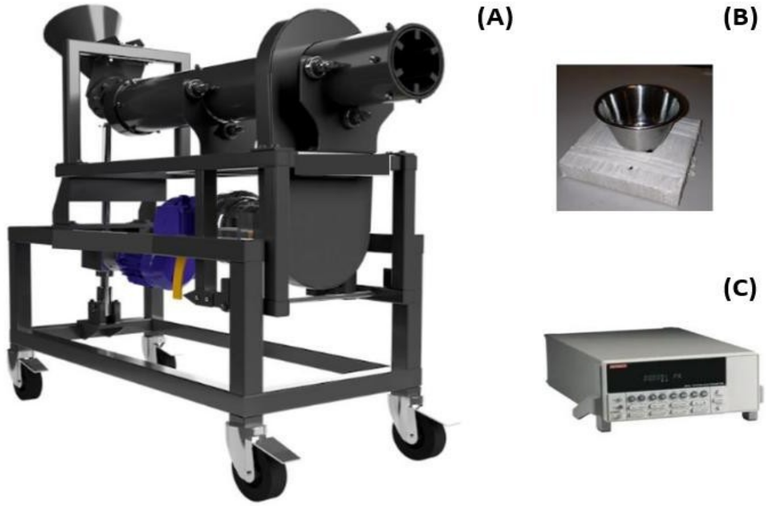

Figure 20- Tribo-charger; (B) Faraday cup; (C) Keithley electrometer – model

Electrostatic Separator

The Stokkermill separator (Fig. 16B) has a control panel (Fig. 16A) that allows adjustment of several key parameters:

Drum rotation speed: variable from 20 to 60 Hz. The rotating drum is a main component that carries charged particles; its speed influences the centrifugal force on particles and their contact time under the electric field.

Feed-bed vibration intensity: adjustable on a relative scale (1 to 10). The vi- brating feeder controls the flow of material onto the drum, ensuring a monolayer distribution of particles. Vibration must be tuned so that particles make good contact for charging but do not simply stick or bounce irregularly.

Electrode voltage: the high-voltage applied to the electrodes, adjustable from ∼2.2 kV up to 29.2 kV. This creates the electric field that deflects charged particles.

In addition to these electronic controls, there are mechanical adjustments for the physical positioning of components inside the separator:

Inclination of Electrode 1 (wire electrode): adjustable between –17° and +17° relative to vertical. This fine-tunes the geometry of the corona-discharge electrode.

Inclination of Electrode 2 (cylinder electrode): adjustable between –20° and +20°. This is the grounded (static) electrode; its angle can affect the field and collec- tion.

Inclination of Deflector 1 (right side splitter): adjustable between –40° and +40°. Deflectors guide separated streams into collection bins; their positions deter- mine cut-points between fractions.
Inclination of Deflector 2 (left side splitter): adjustable between –40° and +40°. This symmetric control allows tweaking the split between what is collected as “product” vs “reject” on either side of the drum.

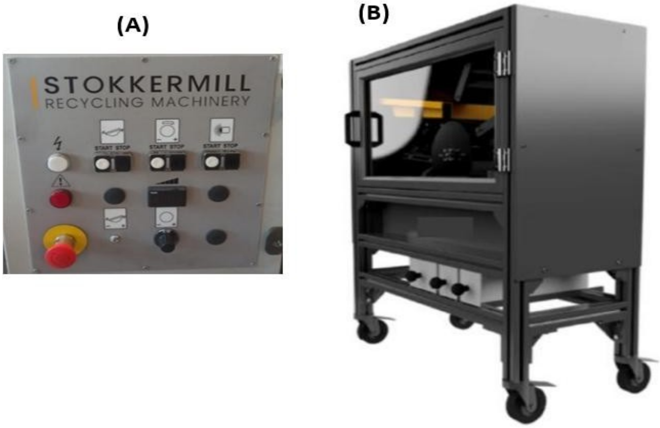

Figure 21- Control Panel (A); Stokkermill Electrostatic Separator (B)

For our tests, the electrostatic separator was configured with a vibratory feed hopper (Fig. 17A) that introduced the material onto an inclined vibrating feed plate (Fig. 17C). The feed plate ensured a steady, thin flow of particles onto the rotating drum (Fig. 17B). As particles meet the drum, they enter the corona field generated be-tween the wire and drum electrodes. Depending on their electrical properties (and any triboe-lectric charge they carried), particles would either be attracted to or repelled from the drum’s surface. Charged particles that adhere to the drum can be car-ried further until they lose charge or are mechanically dislodged by the rotating motion and deflectors. Ultimately, the particles fall into different collection bins separated by the deflectors (Fig. 17D), thereby achieving a sorting based on their charge/mass ratio and conductivity.

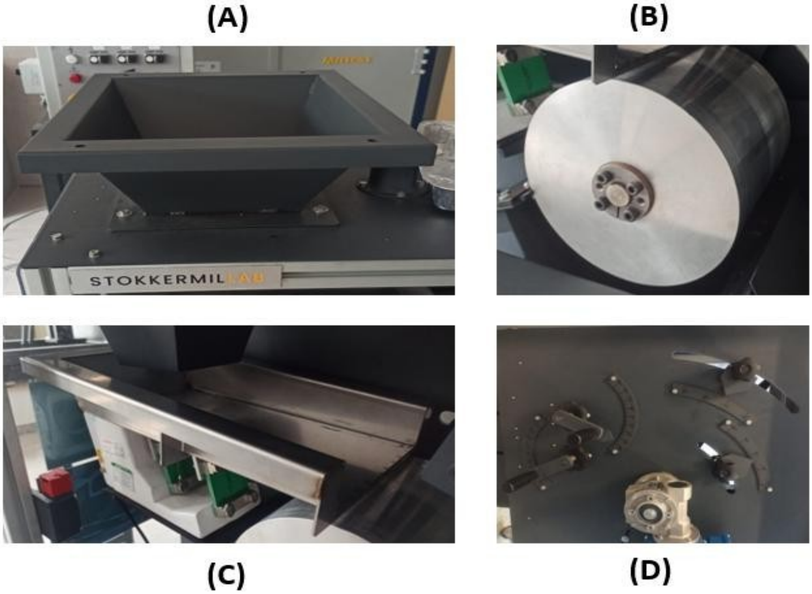

Figure 22- (A) Feed hopper; (B) Rotating drum; (C) Vibrating feed plate; (D) Deflectors

4.3.3 Treatability Test

Initially, a mix of 20% plastic and 80% sand (by weight) was used, mirroring the 20:80 ratio of the densimetric tests for consistency. In the first experimental phase, we conducted 14 preliminary tests exploring various parameter settings. The primary objective was to see if we could reach at least 80% separation effi-ciency using the PP–sand mixture, as 80% was considered a threshold for ac-ceptable performance. We systematically varied the most critical parameters: electrode positions, applied voltage, drum speed and observed qualitatively how the separation outcome changed. Each test used ~100 g of the mixture (with ~20 g PP and ~80 g sand) to ensure plenty of particles for interaction.

Table 7- First test series

TEST	DRUM SPEED [Hz]	ELECTRODE ANGEL (WIRE; DRUM) [˚]	VOLTAGE [KW]
1	40	-1 ; -9	25
2	40	-1 ; -9	20

3	40	-1 ; -9	20
4	30	-1 ; -9	20
5	40	-1 ; -9	15
6	20	-1 ; -9	10
7	20	-1 ; -9	10
8	20	-1 ; -9	10
9	20	-1 ; -9	10
10	20	-7 ; -15	22

A major challenge was the lack of inherent electrostatic charge on sand grains. Sand is initially an electrical insulator with no charge; during the separa-tion, if sand does not acquire charge, it will not respond to the electric field and tends to drop off the drum indiscriminately. In the first few tests, we found that the sand remained essentially uncharged (measured charges on the order of 10^{-6} nC nanocoulombs, which is negligible). As a result, sand grains were not being effectively separated from the plastic, many sand particles simply fell into the same bins as plastic due to gravity, undermining the separation. This caused low separation efficiencies across the initial range of parameter variations.
Realizing this, we paused to address how to impart a stronger triboelec-tric charge to sand. Sand needs to either gain or lose electrons via friction with another material so that it can be influenced by the field. Inspired by literature (Neesse, 2014, Minerals Engineering,) and the triboelectric series concept, we introduced an auxiliary material: wool. Wool tends to donate electrons (becom-ing positively charged) and leave other materials negatively charged. We devised a simple pre-treatment: mixing the sand (with plastic) thoroughly with pieces of wool fabric and subjecting them to intense vi-bration. Practically, we placed the sand–plastic mixture together with strips of recy-cled wool cloth into a Retsch AS 200 vibratory sieve shaker and vibrated at maximum intensity for 10 minutes (essentially tumbling the sand against wool). This process was akin to charging the sample in a “wool tribo-charger” (Figure 18 illus- trates this pre-treatment setup).

Figure 23- Wool Tribo- charger

The wool treatment proved effective subsequent measurements using a Fara- day cage and electrometer showed that the sand grains acquired a net neg-ative charge of about –0.33 nC per gram of sand after the wool rubbing, which is over two orders of magnitude higher than without treatment. This meant the sand would now be repelled by a negatively charged electrode or attracted to a positively charged drum, providing the basis for separation from similarly charged plastics. Importantly, we ensured the measurements were done imme-diately after charging and in an iso- lated setup to avoid rapid dissipation of the charge.

Resuming the separator tests, we observed that charged sand behaved much more predictably: sand particles, carrying a negative charge, were weakly repelled by the drum (if the drum was set to a certain polarity), whereas plastic particles (depend- ing on type) behaved differently. Initially, with polypropylene (PP), even after sand charg- ing, the overall separation efficiency remained mod-est – PP did not easily ac- quire as strong or as persistent a charge as we hoped. The first series of tests, even with wool pre-treatment for sand, yielded separa-tion efficiencies only up to around 30%. Some key findings from the first set of tests were:

A drum rotation speed around 20 Hz (relatively low) provided better separa- tion (~32% efficiency with PP) than higher speeds (e.g. 40 Hz). The slower drum al-lowed particles more residence time under the field and helped form a stable mono-layer of particles on the drum, improving separation.

Adjusting deflector angles within 20°–40° and increasing electrode volt-age within our range did not significantly boost PP recovery beyond ~33%. These pa- rameters were less critical compared to material charging and drum speed.

Using dried sand (pre-oven-dried to remove moisture) slightly improved effi- cien-cy, as moisture can dissipate charge.

To further improve results, we switched the plastic type from PP to PA (pol- yamide) for subsequent trials. PA tends to charge more readily (it's known to become more negatively charged against many materials). Indeed, replacing PP with PA and contin-uing to use wool-charged sand, while also combining all the previously opti- mized settings (low drum speed ~20 Hz, ap-propriate electrode voltage, etc.), led to a dra-matic increase in separation effi-ciency. By the end of this first phase of testing, with PA plastic and charged sand, we achieved separation efficiencies up to ~94% in a single-pass experi-ment (with certain optimal parameter combinations).

Table 8- First test series with wool pree-treatment

TEST	DRUM SPEED [Hz]	ELECTRODE ANGEL (WIRE) [°]	ELECTRODE AN-GEL (DRUM) [°]	VOLTAGE(DRUM) [KW]
11	20	-1	-9	10
12	40	10	-10	22
13	20	10	-10	24

After demonstrating that high efficiencies were possible, a second set of ex-periments was designed to statistically refine and validate the parameter choices. In this second phase, we used a structured experimental design approach to home in on the optimal ranges for drum speed, electrode voltage, vibration intensity, and elec-trode/deflector angles. Each selected combination in this phase was run in triplicate to ensure reproducibility. The idea was to restrict tests to combinations likely to yield high performance and then see if efficiencies >80% could be consistently reproduced. Each selected combination in this phase was run in triplicate to ensure reproducibility. The second phase indeed confirmed that, by operating within the optimized parameter window, separation efficiencies frequently exceeded 80% on the PA–sand mixture. One notable anomaly observed was a particular test combination where material accumulated on the edge of the feeder plate instead of entering the field (likely due to a suboptimal vibration setting causing an adhesion issue); apart from that, the results were consistent. These findings validated the reliability of the tribo- electrostatic separation approach under optimized conditions.

Table 9- Second test series with wool pre-treatment

TEST	DRUM SPEED [Hz]	ELECTRODE ANGEL (WIRE) [°]	ELECTRODE ANGEL (DRUM) [°]	VOLTAGE(DRUM) [KV]
1	20	-1	-9	10
2	20	10	-9	22
3	40	-1	-9	24
4	40	-1	-10	22
5	20	10	-9	10
6	20	-1	-9	24
7	20	-1	-10	22
8	40	10	-10	24
9	40	-1	-10	10
10	20	10	-10	22

The third test series constituted a critical experimental phase for validating and optimising the process parameters of the Stokkermill bench-scale electrostatic sepa- rator. This series was built on the configuration that yielded the highest separation efficiency in earlier trials (94%). During this block of tests all operating parameters were held constant except for a single variable, which was systematically varied to isolate its direct effect on overall separation efficiency and on the purity of the two lateral collectors. Each selected combination in this phase was run in triplicate to ensure reproducibility.

The first set of the third test experiments investigated the electrode voltage. Starting from the previously determined optimal value of 25 kV, lower voltages (20, 15 and 10 kV) were tested to evaluate system sensitivity.

Table 10- The first set of the third test experiments

TEST	DRUM SPEED [Hz]	ELECTRODE AN-GEL (WIRE) [°]	ELECTRODE AN-GEL (DRUM) [°]	VOLTAGE(DRUM) [KV]
1	20	10	-10	**10**
2	20	10	-10	**15**
3	20	10	-10	**20**
4	20	10	-10	**25**

The subsequent test series focused on drum rotational speed, starting from the previously determined optimal condition (20 Hz) while all other parameters were kept constant.

Table 11- The second set of the third test experiments

TEST	DRUM SPEED [Hz]	ELECTRODE ANGEL (WIRE) [°]	ELECTRODE ANGEL (DRUM) [°]	VOLTAGE(DRUM) [KV]
5	**20**	10	-10	24
6	**30**	10	-10	24
7	**35**	10	-10	24
8	**40**	10	-10	24

The third test series examined the influence of the two electrodes, first by var- ying their angular separation and then by translating that same separation across three different angular positions around the drum. Tests started from the best- performing configuration (wire at +10°, cylinder at −10°) and comprised four sepa- ration values progressively reduced toward the machine's minimum clearance. The same set of separations was then applied at three different absolute angular offsets to check for positional dependence.

Table 12- The third set of the third test experiments

TEST	DRUM SPEED [Hz]	ELECTRODE AN-GEL (WIRE) [°]	ELECTRODE AN-GEL (DRUM) [°]	VOLTAGE(DRUM) [KV]
9	20	**-1**	**-9**	24
10	20	**3**	**-9**	24
11	20	**7**	**-10**	24
12	20	**10**	**-10**	24

Since the previous result did not turn out as expected, in the last three trials (A, B and C), the positions of the two electrodes would be varied while nevertheless keeping their angular separation constant. To do this, the distance between the two electrodes (6.5 cm) was measured and that distance was then used to translate both electrodes into the assigned positions. In the following trials A, B and C three different positions were tested, specifically:

- A: the closest to the rotating drum;
- B: an intermediate position between A and C;
- C: the maximum distance of the electrodes from the rotating drum.

As shown in the table below, the intermediate position proved to be the worst, while the best was the one at the maximum distance from the drum, followed by the position closest to it.

Table 13-Tests with variations of the position of the two electrodes

TEST	DRUM SPEED [Hz]	ELECTRODE AN-GEL (WIRE) [°]	ELECTRODE AN-GEL (DRUM) [°]	VOLTAGE(DRUM) [KW]
A	20	**-1**	**-9**	24
B	20	**3**	**-9**	24
C	20	**7**	**-10**	24

4.4 Optimization of Tribo- Charger

4.4.1 Materials

The tests used the same feed designated as Mix 2 in the electrostatic trials: quartz sand and polyethylene (PE) plastic. Particle size distributions (granulometries) and the mass proportions of sand and plastic were kept identical to those used in the prior electrostatic experiments.

4.4.2 Equipment

The wool rubbing treatment proved highly effective: measurements with a Faraday cage and electrometer showed the sand acquired a net negative charge of approximately -0.33 nC per gram of sand after treatment, i.e., more than two orders of magnitude larger than the untreated baseline. These results demonstrate that simple triboelectric conditioning can substantially increase particle charge and thus influence electrostatic separation behaviour.

Given the positive outcome with a wool-blend material (not 100% wool), the study was extended to quantify how charge transfer varies with different rubbing materials. Two additional materials were tested: 100% wool and denim. The resulting charges on both sand and PE plastic were measured under the same protocol to evaluate material-dependent triboelectric effects.

4.4.3 Treatability Test

The third series of electrostatic separation tests was repeated using two different pre-treatment materials: 100% wool and denim to evaluate how these surface treatments affect particle charging and separation performance. All other process parameters and the apparatus configuration were kept identical to the original third series so that observed differences could be attributed solely to the pre-treatment.

Figure 24- Pree treatment materials (A) 100% wool and (B) denim

Each treatment–configuration combination was executed in triplicate to ensure reproducibility and allow basic assessment of variability. Results from these repeated runs were then compared to the baseline (no pre-treatment and the previous wool-blend case) to quantify the influence of material choice on charge transfer, efficiency and collector purity.
An additional evaluation focused on the charge dynamics of both PE plastic and sand under the two pre-treatment materials (100% wool and denim). The pre- treatment vibration time was systematically varied (1, 5, 10 and 15 minutes) while all other factors were held constant; the resulting surface charges on each fraction were measured after treatment to characterise how vibration duration affects triboelectric conditioning and charge magnitude. Each condition was repeated to ensure repeata- bility and to capture the temporal evolution of charge accumulation for both materials. This integrated analysis aims to produce a definitive picture of the factors that maximise final product quality by mapping how pre-treatment material and vibration time influence separation selectivity, collector purities and cross-contamination be- tween plastic and sand. The dataset therefore facilitates selection of the optimal pre treatment protocol (material + vibration time) that minimises mutual contamination and improves electrostatic separation performance.

4.5 LIFE CYCLE ASSESSMENT

In order to evaluate the environmental sustainability of the proposed beach litter treatment system, a Life Cycle Assessment (LCA) was conducted. The LCA aimed to compare the environmental impacts of the new approach particularly the two key separation stages, densimetric and electrostatic separation against each other and against a conventional baseline (landfill).

4.5.1 LCA Goal and Scope

The goal of the LCA was to quantify the potential environmental impacts of processing 1 kg of beach litter using the innovative mobile treatment (separating sand, organics, and plastics) versus disposing of that 1 kg as mixed waste in a landfill. Within the new process, we also examined the impact contribution of the densimetric separation stage and the tribo-electrostatic separation stage separately. This helps identify which stage is more energy- or resource-intensive. The functional unit was defined as “treatment of 1 kg of wet beach litter (as collected)”. The system boundaries for the new process included the operation of machinery (electricity use for the densimetric table and electrostatic separator) and the consumption of any auxiliary materials (e.g., the wool pads used to tribo-charge sand). For the landfill baseline, the system boundary included transport of 1 kg litter to landfill and the landfill processes (landfill equipment emissions, and potential biogas generation from the organic fraction over time, modeled in a generic way).

The LCA was carried out using SimaPro 9.5 software with the ReCiPe 2016 Midpoint (H) impact assessment method. Key impact categories considered were: Global Warming Potential (GWP) (climate change impact, in kg CO_2 eq); Stratospheric Ozone Depletion (ODP) (kg CFC-11 eq);

Fine Particulate Matter Formation, Photochemical Ozone Formation (smog), Terrestrial Acidification, Eutrophication (freshwater and marine);

Ecotoxicity (terrestrial, freshwater, marine);

Human Toxicity (carcinogenic and non-carcinogenic);

Land Use, Mineral Resource Scarcity, Fossil Resource Scarcity, and Water Consumption.

These categories give a broad view of environmental performance.

4.5.2 Inventory and Assumptions

We compiled an inventory for the two separation stages based on experimental data and reasonable assumptions for a scaled-up mobile unit:

Densimetric Separation Stage:

Electricity consumption was the primary input. We assumed roughly 0.5 kWh of electricity is required to process 1 kg of raw beach litter.

Electrostatic Separation Stage:

We assumed it would treat only the sand fraction (plus residual microplastics) coming from the densimetric stage. If the average sand content is, say, 50% of the raw waste, then per 1 kg raw input, ∼0.5 kg goes through electrostatic separation. The electricity use assumed for the electrostatic separator was ∼0.3 kWh per kg of material processed.

Additionally, we included the use of wool pads as a consumable to charge the sand: for each kg of sand, a small wool piece (weighing ∼0.01 kg) might be consumed over multiple uses. The production of wool carries certain impacts (ozone depletion from sheep rearing), which were included.

Baseline (landfilling):

Inventory included diesel fuel for transporting 1 kg waste (assuming a haul of ∼50 km by truck, which contributes a small amount of CO_2 and pollutants), and the long-term emissions from landfilling 1 kg of mixed organic/plastic waste. Landfill emissions (like methane from decomposing organics not captured by landfill gas systems, leachate treatment, etc.) were included using standard LCA models for municipal waste landfilling.

It is important to note that in the integrated scenario, not all 1 kg goes through both stages fully, only the mineral fraction goes to electrostatic. This “division of la- bor” is a benefit of the process. However, for comparing the stages, we also modeled each stage handling 1 kg independently to see their relative burdens.

5. RESULTS

5.1 Study Sites

Natural coastal habitat.

The Porto Cesareo area features extensive sandy beaches interspersed with low rocky stretches and is known for its rich marine and coastal ecosystems. Much of the coastline is encompassed by environmental protections. In fact, Porto Cesareo hosts the Marine Protected Area. This setting typifies a semi-natural beach environ- ment, where Posidonia oceanica meadows are present offshore and natural wrack accumulations mix with litter from both land-based and marine sources.

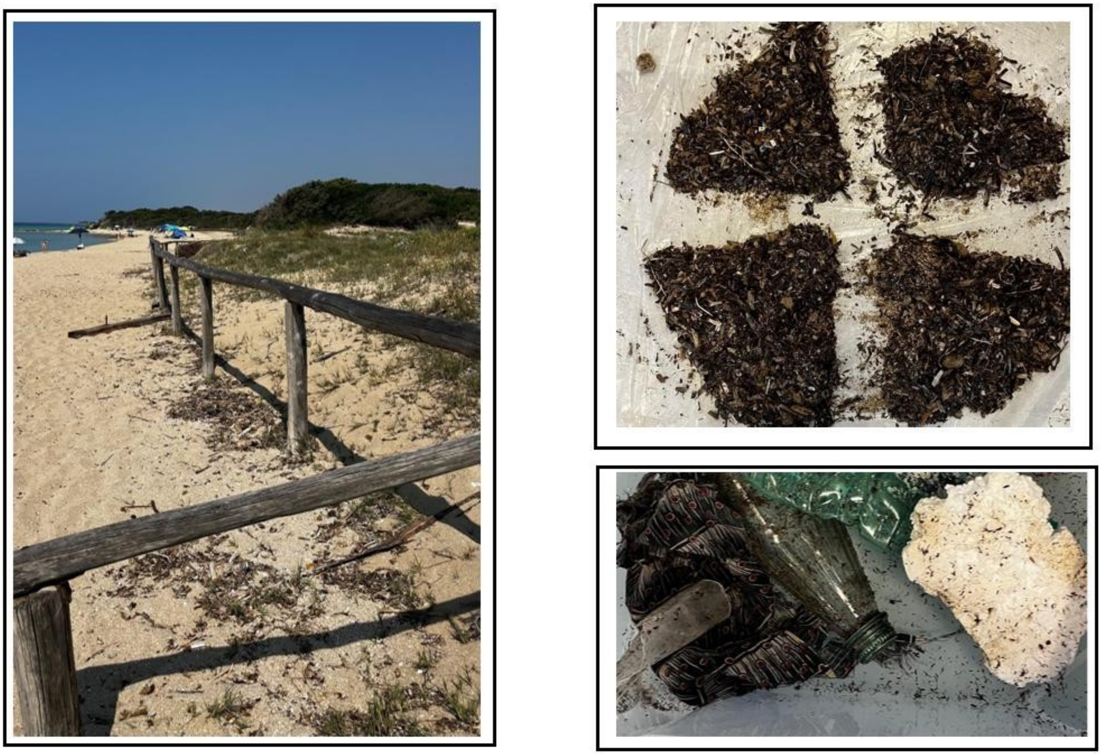

Figure 25- Natural coastal habitat, Porto Cesareo

The Porto Cesareo coast is subject to several protection measures. Key elements include:

Geomorphological features: well-preserved coastal dune systems backing the beach- es.

Hydrological and marine features: coastal wetlands (the Palude del Conte marsh) and extensive seagrass meadows in the bay, which are part of a Marine Natura 2000 site. Botanical components: Mediterranean scrubland (macchia mediterranea) and dune vegetation that harbor endemic species.

Protected areas: the overlapping Regional Nature Reserve and Marine Protected Area mentioned above, which safeguard both terrestrial and marine biodiversity.

Cultural components: historical coastal watchtowers (e.g. Torre Cesarea) and a traditional fishing harbor, reflecting the human presence that coexists with the natural landscape.

Semi-natural coastal habitat

The municipality of Fasano is about 5 km from the sea; its coastal strip, roughly 21 km long, includes the towns of Savelletri and Torre Canne. The shoreline is predominantly rocky up to Torre Canne, beyond which it becomes sandy. This area represents a near-pristine marine habitat and includes a Site of Community Im- portance (SCI), part of the European Natura 2000 network, aimed at protecting natural habitats and plant and animal species at risk of disappearance.

Figure 26- Natural coastal habitat, Fasano

Analyzing the Regional Territorial Landscape Plan (PPTR), it emerges that the study area is subject to multiple landscape and environmental safeguards. In particular, the area includes:

Geomorphological components: designated dune cordons along the coast. Hydrological components: protected coastal zones and several freshwater springs. Botanical/Vegetation components: protected woodland areas in the vicinity.

Protected Areas and Natural Sites: inclusion in the Natura 2000 network, cover- ing both land and marine portions.
Cultural components: presence of buildings and areas of notable public interest.

Anthropic coastal habitat:
The municipality of Mola di Bari features a low, rocky coast stretching about 11 km. The town's harbor is located in the southern part of the coast and is sheltered to the north by an older three-arm breakwater and to the east by a newer two-arm east breakwater (∼700 m long).The particular area selected for environmental char- acterization in Mola di Bari is representative of a marine habitat under strong anthropogenic pressure, being adjacent to an active urban port and subject to frequent hu- man disturbance.

Figure 27- Anthropic coastal habitat, Mola of Bari

According to the PPTR's protection framework, the study area includes the following elements:
Hydrological components: coastal territories with high exposure to human use. Protected Areas/Natural Sites: although heavily urbanized, the vicinity includes marine sites of conservation interest.
Cultural/Settlement components: Indicating the presence of a consolidated urban fab- ric with historical and social value.
For the purposes of field sampling in Mola di Bari, the locations with the most significant accumulations of beach litter were identified with the help of the local Envi- ronment Office and Municipal Waste Management Service. The sampling was carried out at the "Acqua di Cristo" site, which lies within the Mola harbor area and consist- ently exhibits accumulated debris and organic wrack due to its enclosed, high-use setting.

5.1.1 Characterization of Beach Litter

For each sampling site, a representative sample of the as-collected (raw) beach litter was characterized through a series of basic physico-chemical analyses:
Moisture content (water weight fraction of the wet sample);
Ash content (and by difference, organic matter content) via ignition at 550°C;
pH, electrical conductivity, and redox potential (Eh) of the aqueous extract of the wet sample. The results of this initial characterization for each site's raw waste sample are sum- marized in Table below.

Table 14- Physico-chemical characteristics of raw beach litter samples (as collected)

Sample	Moisture Content [%]	Dry Matter [%]	Ash (Mi-neral) [%, dry]	Organic Matter [%, dry]	pH	Conductivity [µS/cm]	Eh [mV]
Porto Cesareo	20,34	79,66	39,55	60,45	8,28	3509	-78,7
Fasano	28,25	71,75	47,65	52,35	8,48	2485,1	-80,4
Mola di Bari	65,08	34,92	19,54	80,46	8,15	7952,3	-60,9

The data indicate substantial differences between the sites in moisture and composi- tion. Notably, the port site at Mola di Bari had by far the highest moisture content, re- flective of a dense, water-laden Posidonia wrack pile in a sheltered area. In contrast, the natural and semi-natural sites had much drier deposits, as their materi- als were more sand-rich and exposed to sun and wind. Correspondingly, the dry mat- ter con- tent at Fasano and Porto Cesareo was around 70–80%, roughly double that of Mola's sample. The ash content was also highest for Fasano (∼48% of dry mass, in- dicat- ing nearly half the dry material was sand/mineral) and lowest for Mola (only ∼19.5%, with over 80% organic matter in the dry sample). Porto Cesareo's sample had an intermediate mineral content (∼39.5% ash, 60.5% organic). These differences align with site characteristics: the beach at Fasano had significant sand mixed into the wrack, whereas the material collected from Mola was dominated by organic seagrass detritus with relatively little sand. All samples were mildly basic (pH 8.1–8.5) due to the marine environment. The electrical conductivity of the leachate was notably high in Mola di Bari, suggesting a high salt and dissolved solids content. Fasano and Porto

Cesareo showed lower conductivity (2485 and 3510 μS/cm, respectively), consistent with more washing by rain or less salt accumulation in those more open environments. The redox potential (Eh) values were negative at all sites (approximately –60 to –80 mV), indicating reducing conditions within the accumulated wet material. This is typical for waterlogged Posidonia banks, where decomposition of organic matter consumes oxygen and can create anoxic, reduced conditions.

5.1.2 Composition of Waste

After the initial characterization, each raw sample was subjected to a manual pre-separation in the laboratory. Approximately 200 g of material from each site's sample was carefully divided into three main fractions by type: natural organic, natu- ral mineral, and anthropogenic. The natural organic fraction consists of biomass (Po- sidonia and other seaweed or woody debris), the natural mineral fraction is primarily sand, and the anthropogenic fraction includes all man-made waste components (plastics, glass, metal, etc.). The average composition of each sample in terms of these three fractions (by weight percentage of dry matter) is reported in Table 15.

Table 15- The average composition of the samples

Sample	Natural Organic [wt%]	Natural Mineral [wt%]	Anthropogenic [wt%]
Porto Cesareo	10,33	89,43	0,24
Fasano	13,24	86,36	0,39
Mola di Bari	78,13	16,77	5,10

The fractionation results highlight stark contrasts between the sites. At Fasano and Porto Cesareo, the beach litter was overwhelmingly composed of sand and other mineral matter (around 86–89% of the dry mass), with only ~10–13% organic biomass and a negligible proportion of anthropogenic debris (well below 1%). This confirms that the accumulations at the natural and semi-natural sites were largely natural wrack (seagrass, seaweed) intermixed with sand, and contained very little human-generated waste by weight. Conversely, the Mola di Bari sample was dominated by natural organic material (~78% of dry mass), and had a substantially smaller mineral fraction (~17%). Mola also had a measurable anthropogenic fraction (~5%), higher than the other two sites. This indicates that the harbor-site debris pile contained a significant amount of man-made waste as well as mainly Posidonia biomass and relatively little sand. The high organic content at Mola is consistent with the visual observation of thick seagrass wrack accumulations in the port which trap only a limited amount of sand. These differences are important for tailoring the separation process: for Fasano and Porto Cesareo, removing sand is the primary task, whereas for Mola di Bari, handling the large organic load and extracting anthropogenic debris are bigger concerns.

5.1.3 Characterization of the Natural Organic Fraction

To better understand the organic fraction, we performed further analysis on the bio- mass component (Posidonia oceanica wrack and other seaweeds). This in- cluded a granulometric analysis of the Posidonia fraction and a basic ecological char- acteriza- tion of the vegetative debris. By sieving and image analysis, we obtained par- ticle size distribution curves for dried Posidonia leaves and fragments from each site.

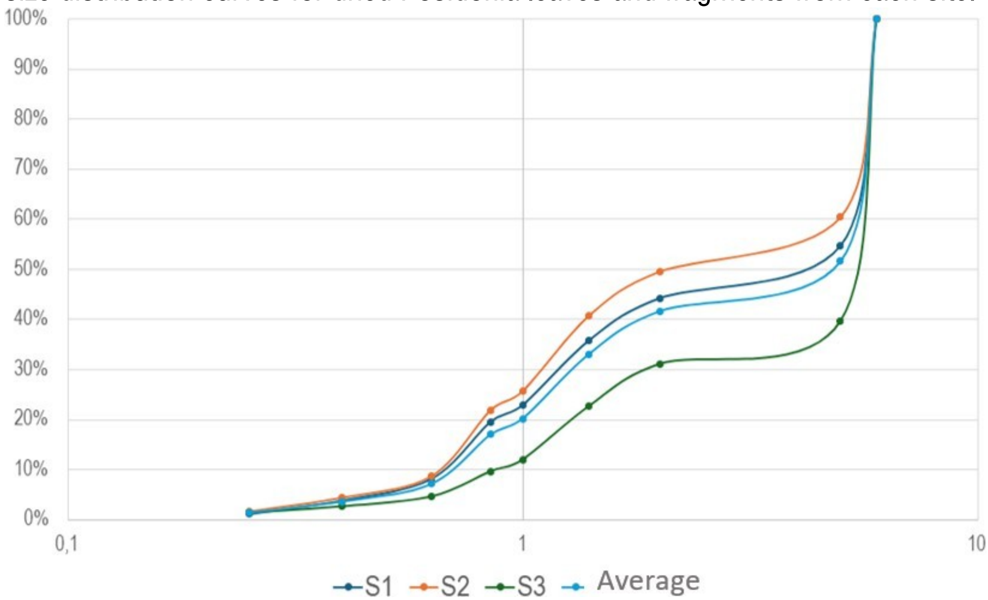

Figure 28- The grain size distribution of the Posidonia detritus from the Fasano

The majority of the seagrass fragments were on the order of a few centime- ters in length (Fig. 23), with a distribution that can be roughly approximated as sand- sized or larger particles (many pieces > 1 mm). In general, the Posidonia wrack did not contain a significant fine fraction, most of it remained as fibrous leaf pieces rather than disintegrating into powders.

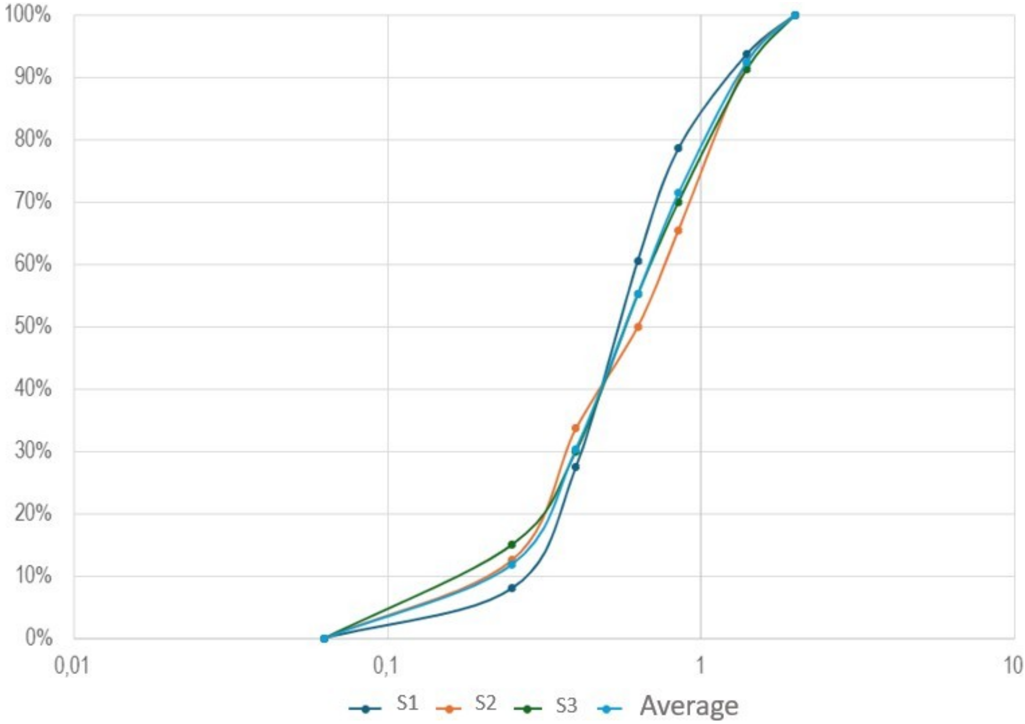

Figure 29- The grain size distribution of the Posidonia detritus from the Porto

For the Mola di Bari sample (Fig.24), the particle size curve looks somewhat different: because much of the Posidonia at Mola was in the form of egagropili, the size distribution reflects a more uniform fibrous particle size (the balls ranged roughly 4–6 cm in diameter). These egagropili are essentially tightly entangled fiber masses, which were classified separately from loose leaves in our analysis.

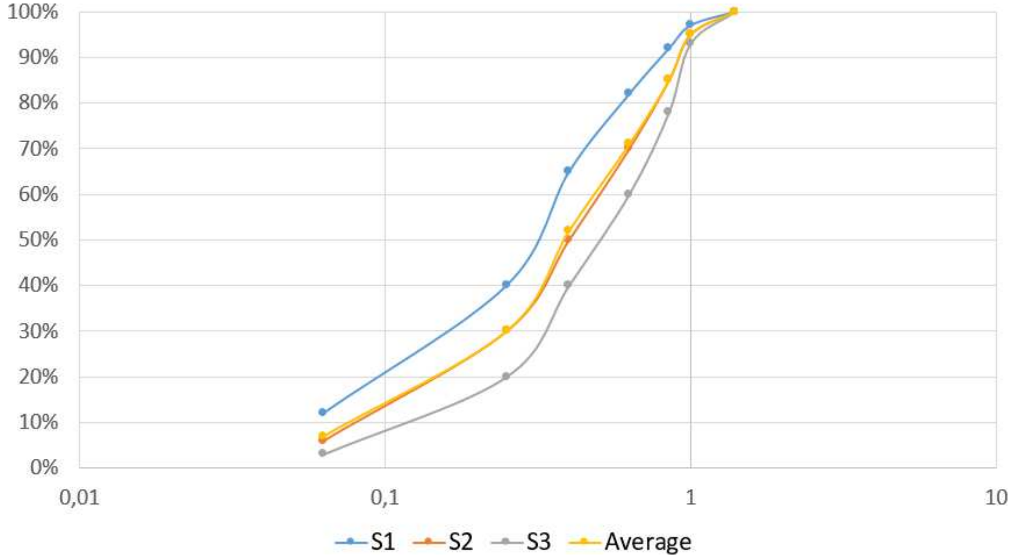

Figure 30- The grain size distribution of the Posidonia detritus from the Porto

Beyond particle size, an ecological classification of the beached biomass was carried out. The aim was to identify the types of vegetative material present as this can give insight into the origin and state of the wrack. The Posidonia detritus was sorted by color and size, distinguishing between intact leaves, broken fragments, rhi- zome pieces, and fibrous balls. In addition to Posidonia, other algae were manually separated and identified broadly as “green algae” or “brown algae” types.

Figure 31- The composition of the natural organic fraction

Table summarizes the composition of the natural organic fraction by these categories for the three sites.

Table 16- Composition of the natural organic fraction

SITE	Posido- nia leaves [%]	Posidonia rhizomes [%]	Posidonia fibrous balls (egagropi- li) [%]	Other green al- gae [%]	Other brown al- gae [%]
PORTO CESAREO	2	8	78	0	12
FASANO	41	11	0	15	32
MOLA DI BARI	51	13	0	0	36

Toxicological analysis process of Posidonia samples.

Porto Cesareo

- Posidonia 1: 110,00%
- Posidonia 2: 95,67%
- Posidonia 3: 99,30%

No acute phytotoxicity detected for Porto Cesareo samples. Posidonia 1 shows a minor stimulation tendency but remains within acceptable limits.

Fasano:

All three Posidonia samples fall within the “no effect” GI range (80–120%) per UNI 10780 (no dilution required):

- Posidonia 1: 90,43%
- Posidonia 2: 98,94%
- Posidonia 3: 110,64%

No acute phytotoxicity detected in any sample. Posidonia 3’s higher GI suggests slight stimulation potential. It is recommend a routine monitoring and repeat testing only if assessing stimulatory effects or long-term trends.

Mola di Bari:

- Posidonia 1: 108,22%
- Posidonia 2: 96,83%
- Posidonia 3: 94,93%

No acute phytotoxicity detected in the Mola di Bari samples. Posidonia 1 shows a minor stimulation tendency but remains within acceptable limits.

Figure 32- Toxicological analysis process

5.1.4 Characterization of the Natural Mineral Fraction

The mineral fraction of the samples was analyzed for grain size distribution to assess the texture of the sediment mixed with the debris. Sieve analysis and laser granulometry were used on dried sand samples from each site. The grain size curves obtained showed that the sand from these accumulations is generally well-sorted beach sand. In the Fasano sample (Fig.28), approximately 92% of the mineral particles by weight fell into the sand-size range (2 mm > d > 0.063 mm) with the remaining ∼8% in the gravel range (d > 2 mm, largely small pebbles or shell fragments). The median grain diameter (D50) for Fasano's sand was about 1.35 mm, indicating a coarse sand (almost gravelly) median size. This is consistent with the presence of shell fragments and coarse carbonate sand typical of natural dune-beach systems in that area.

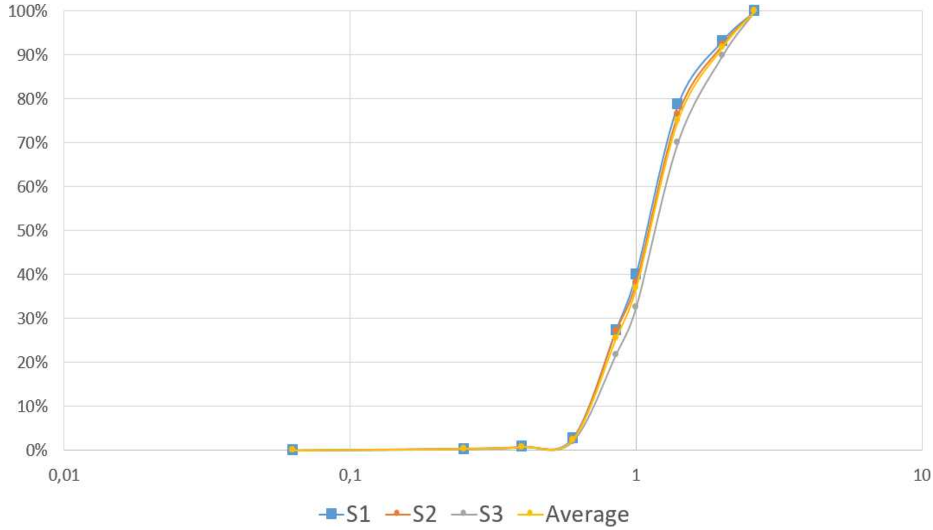

Figure 33- The grain size distribution of the sand particles from the Porto Fasano

In the case of Mola di Bari's sand fraction, the distributions were very uniform and reproducible across subsamples (Fig.29). Virtually 99.99% of the particles in the Mola sand were in the sand range (2 mm to 0.063 mm), with a D50 around 0.35 mm, which corresponds to medium-fine sand. Mola's sediment had almost no gravel or large particles; this finer sand is typical of a more sheltered or artificially modified environment (the port and adjacent beach) where finer sediments settle. Porto Cesareo's sand (not explicitly shown in figures) was qualitatively between these extremes: mostly medium sand with some fine and some coarse fractions, as expected in a dynamic bay system.

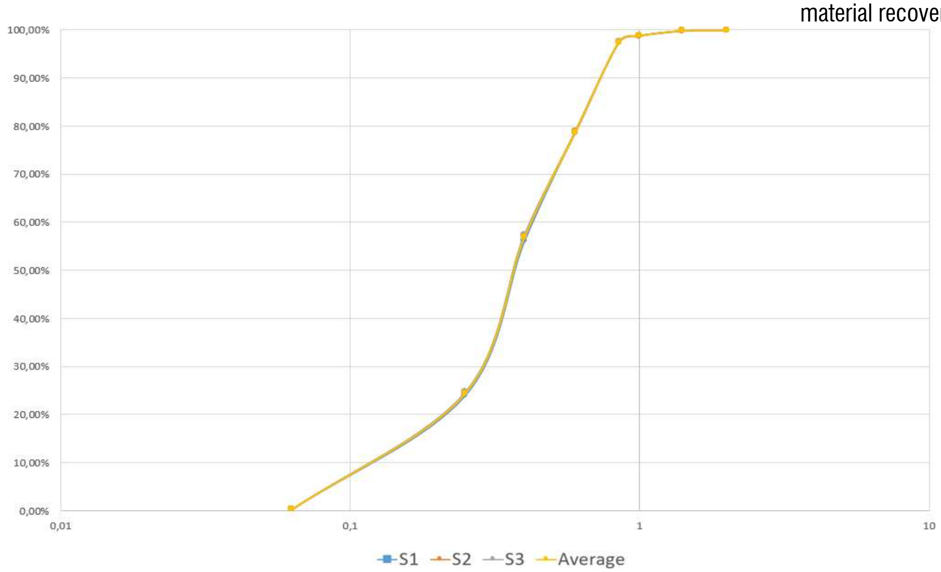

Figure 34- The grain size distribution of the sand particles from the Porto Mola

For Porto Cesareo (Fig.30), the sand is noticeably finer. The average distribution gives a D50 ≈ 0.20 mm, indicating a shift toward fine sand (and some silt) relative to Mola. About 60% of the Porto Cesareo sample is finer than 0.25 mm, and roughly 25% is finer than 0.063 mm. Subsamples are reproducible in shape, although S1 is consistently the finest and S3 the coarsest.

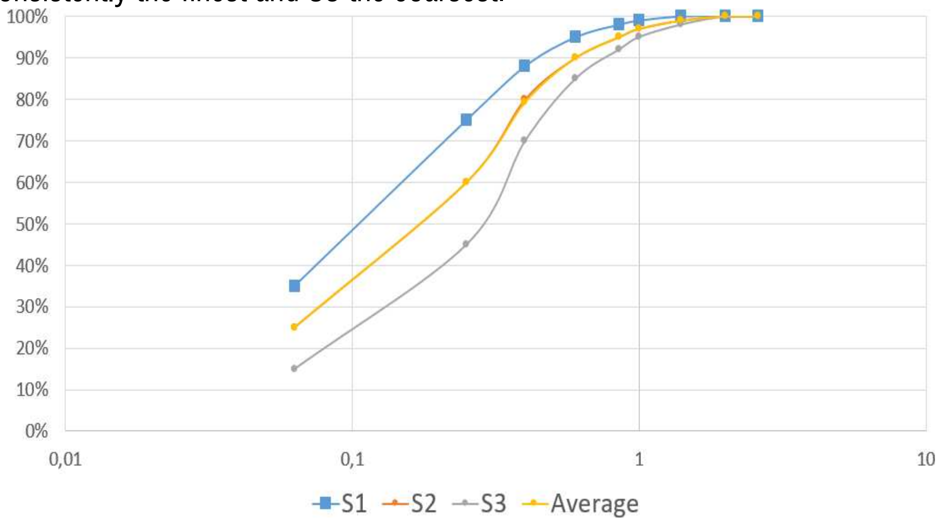

Figure 35- The grain size distribution of the sand particles from the Porto

Toxicological analysis process of Sediment samples.

Porto Cesareo sediment toxicity (GI):
- Sediment 1: 99,00%
- Sediment 2: 110,00%
- Sediment 3: 99,00%

All sediments are within the “no effect” range. No acute phytotoxicity detected. Sediment 2 shows a minor stimulatory tendency but remains <120%.

Fasano sediment toxicity (GI):
- Sediment 1: 91,13%
- Sediment 2: 99,34%
- Sediment 3: 110,59%

All three sediment samples fall within the “no effect” range (80–120%). No acute phytotoxicity detected. Sediment 3 shows a minor stimulatory tendency but remains <120%.

Mola di Bari sediment toxicity (GI):

- Sediment 1: 107,78%
- Sediment 2: 98,80%
- Sediment 3: 93,41%

All sediments are within the “no effect” range. No acute phytotoxicity detected. Sediment 1 displays a slight stimulation trend but is within acceptable limits.

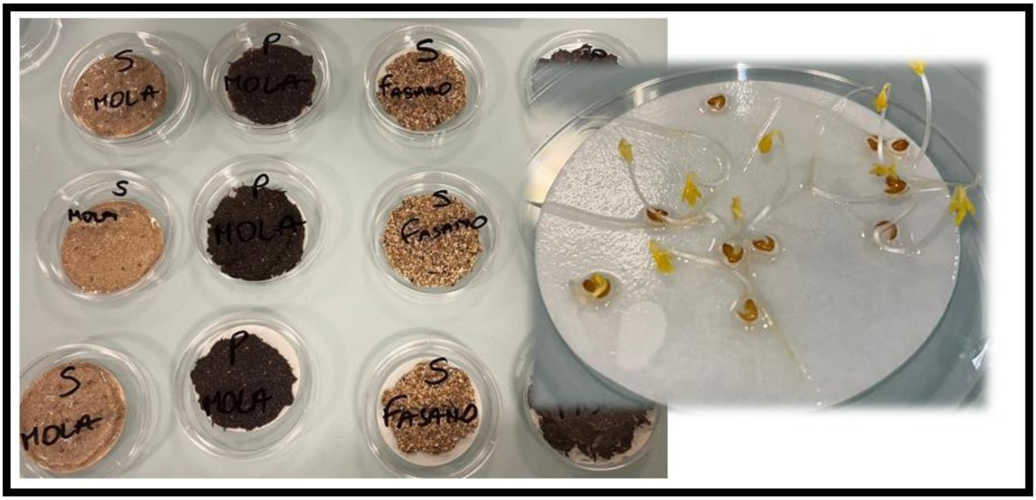

Figure 36- Toxicological analysis process

5.1.5 Characterization of the Anthropogenic Fraction

The anthropogenic fraction collected at each sampling site was consist- ently minor compared to the natural and mineral fractions. Items larger than 2 cm (macro-litter such as caps and large fragments) were hand-sorted and quantified, while the finer anthropogenic fraction (<2 cm), consisting mainly of small plastic fragments and foams, yielded only a few grams per site after removal of sand and or- ganics, a mass so low that quantification is subject to high relative uncertainty. Poly- mer iden-tification for the recovered anthropogenic pieces was performed on-site us- ing the portable mIROSPAR, 2023k NIR spectrometer, providing reliable composition- al in-formation despite the small sample masses.

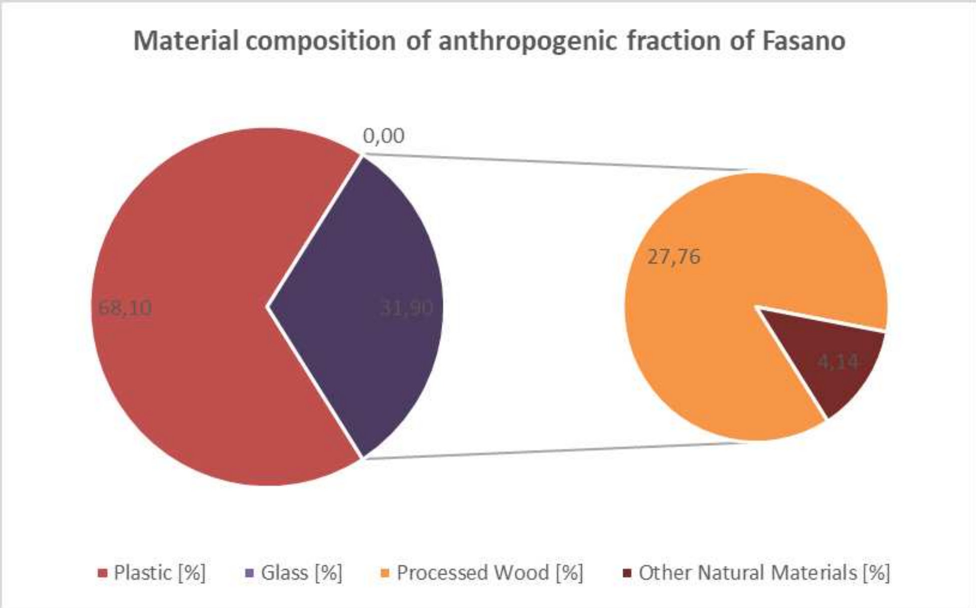

Figure 37- Material cmposition of anthropogenic fraction of Fasano

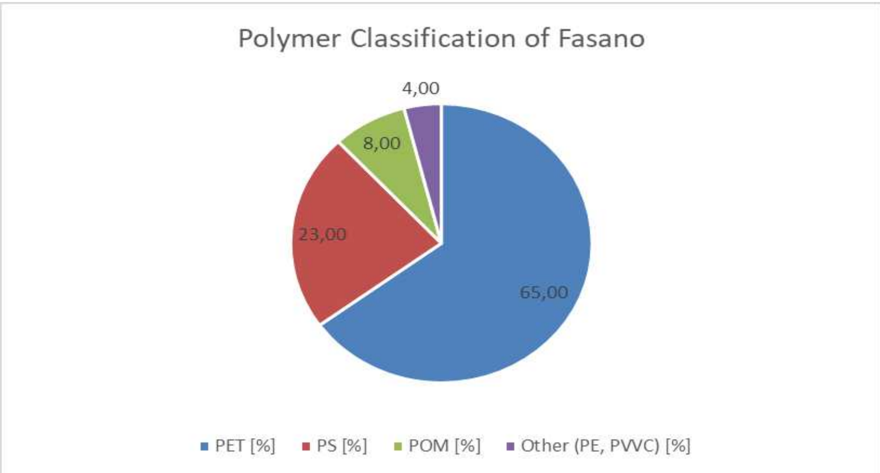

Figure 38- Polymer classification of Fasano

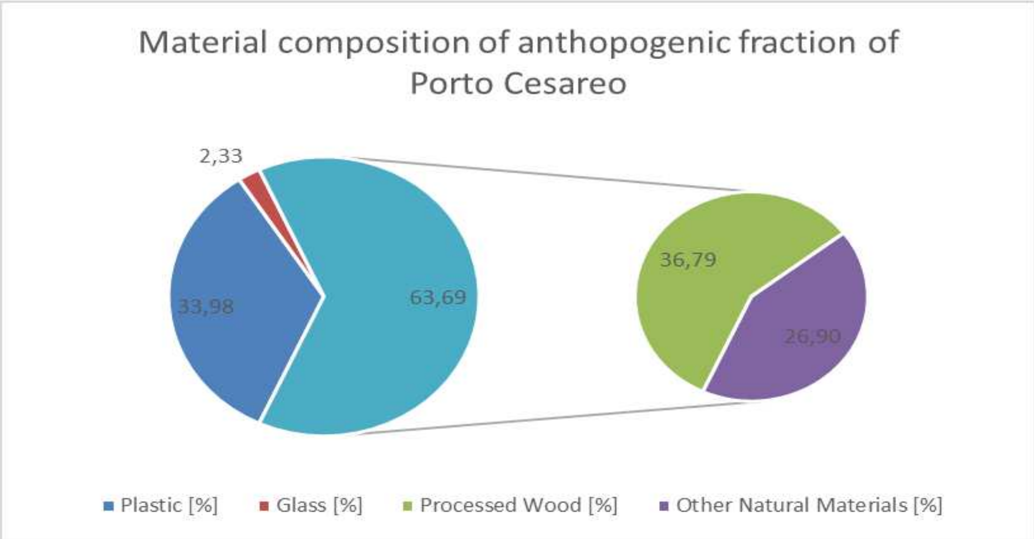

Figure 39- Material composition of anthropogenic fraction of Porto Cesareo

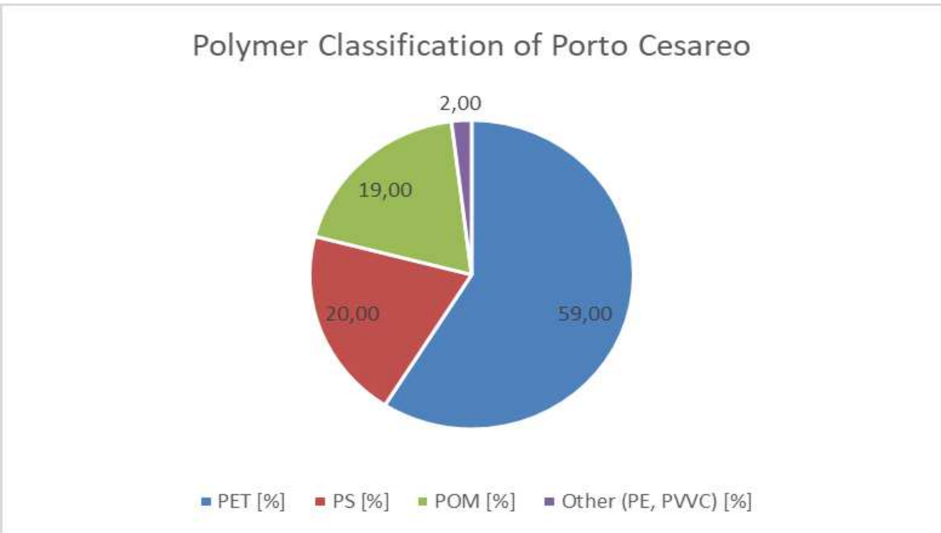

Figure 40- Polymer classification of Porto Cesareo

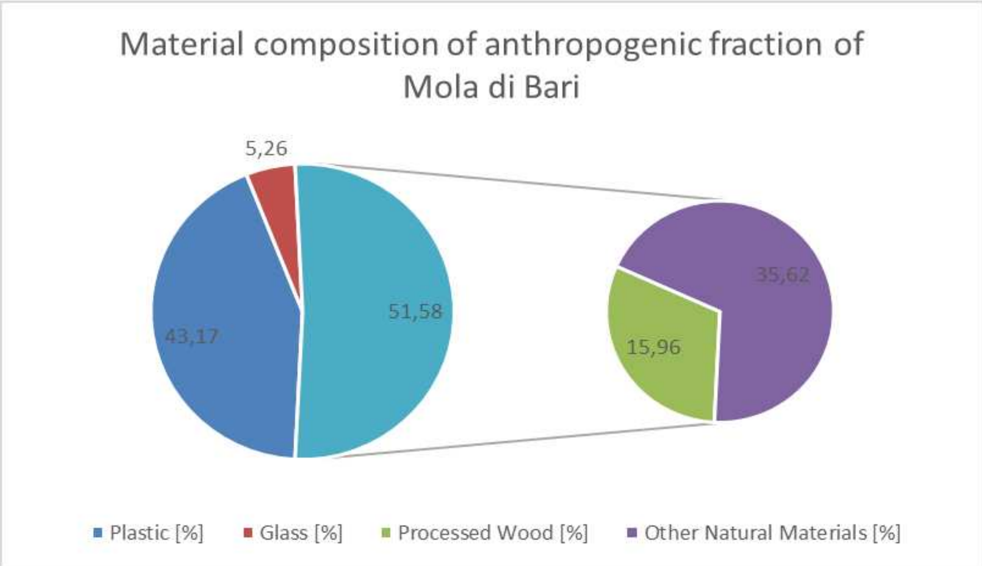

Figure 41- Material composition of anthropogenic fraction of Mola di Bari

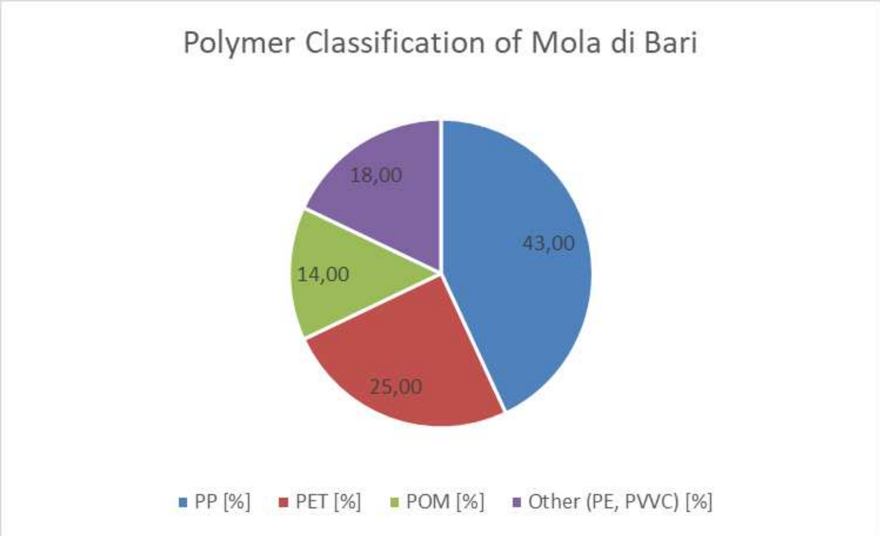

Figure 42- Polymer classification of Mola di Bari

5.2 Densimetric Separation Results

5.2.1 Trials on Posidonia/Sand Mixtures

Results of first trials:

Table 17- Results of first test series

20% Posidonia - 80% Sand			
ID SET	**Posidonia Purity in Light Fraction [%]**	**Sand Purity in Heavy Fraction [%]**	**Separation Efficiency E [%]**
1	16,75	0	15
2	16,75	0	15

3	18,44	0	15
4	16,75	0	15
5	24,16	0	15
6	20,56	0	15
7	23,28	0	15
8	18,43	0	15
9	16,96	0	15

As shown in Table 17, at 10° incline the separation was ineffective. Virtually all of the sand (heavy material) was ending up in the heavy fraction (100% sand purity there, by design the table kept all sand in heavy bins, hence sand purity is effectively 100% by definition in these trials. In the table it is listed as 0% in light fraction be- cause none went light, and 100% in heavy.

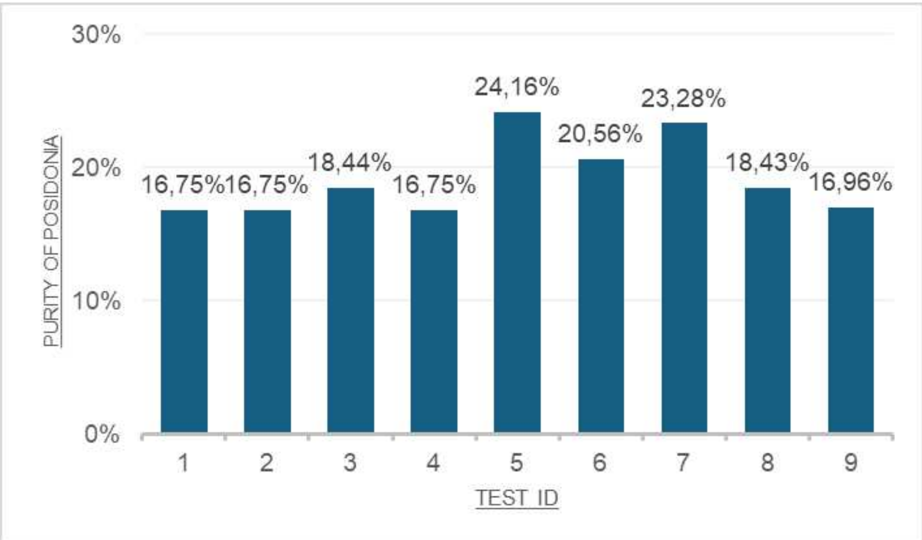

Figure 43- Purity of Posidonia for the first test series

However, the Posidonia was not being efficiently lifted into the light fraction, the purity of Posidonia in the light fraction was very low (∼17–24%), meaning that the light fraction was mostly contaminated with sand. Moreover, the overall efficiency E was consistently ∼15% for every trial, which indicates that only 15% of the Po- sidonia in the feed was actually recovered in the light fraction. Essentially, much of the Posidonia remained with the sand, indicating that the initial parameters were not optimal for separating this mix. The results were very consistent, confirming the process was reproducible but performing poorly under those conditions. After analyzing these initial results, we adjusted the table settings to improve performance. Based on the observations, the key change was reducing the deck in- clination to 2° to make the separation gentler. Additionally, airflow was fine-tuned and vibration frequency slightly modulated to encourage the light Posidonia to float and migrate without being too easily driven into the heavy stream.

Table 18- Results of the second test series with wool pre-treatment

20% Posidonia - 80% Sand			
ID SET	**Posidonia Purity in Light Fraction [%]**	**Sand Purity in Heavy Fraction [%]**	**Separation Efficiency E [%]**
1	69,71	100	48,34
2	74,64	100	51,64
3	66,18	100	86,08
4	37,26	100	46,46
5	52,42	100	93,69

6	74,65	93,39	93,31
7	62,18	100	41,60

In these optimized trials, we see a dramatic improvement (Tab. 18). The Posidonia purity in the light fraction jumped to above 50% in most tests (and even ∼70–75% in some cases), meaning the light bin material was now predominantly Posidonia with much less sand contamination. The overall separation efficiency also increased significantly, reaching as high as ∼93% in tests 5 and 6. These high efficiencies indicate that the majority of Posidonia in the feed was successfully recovered in the light fraction while the sand stayed in the heavy fraction.

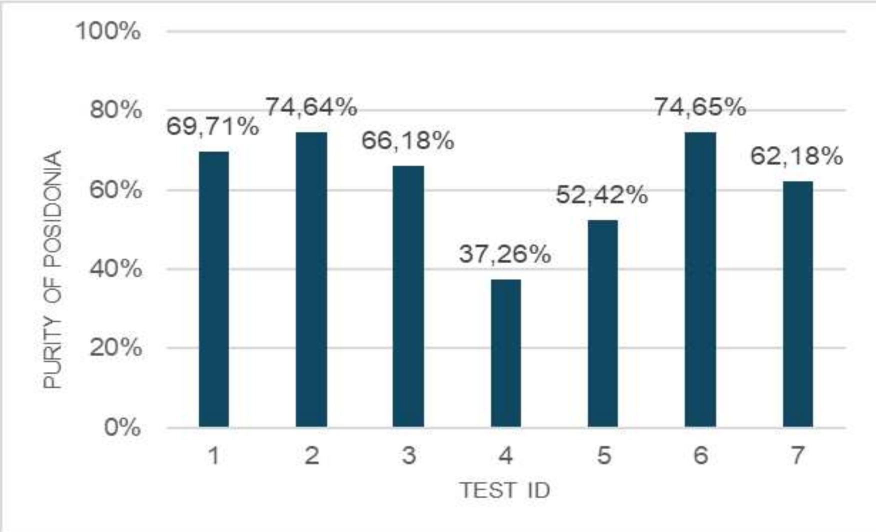

Figure 44- Purity of Posidonia for the second test series

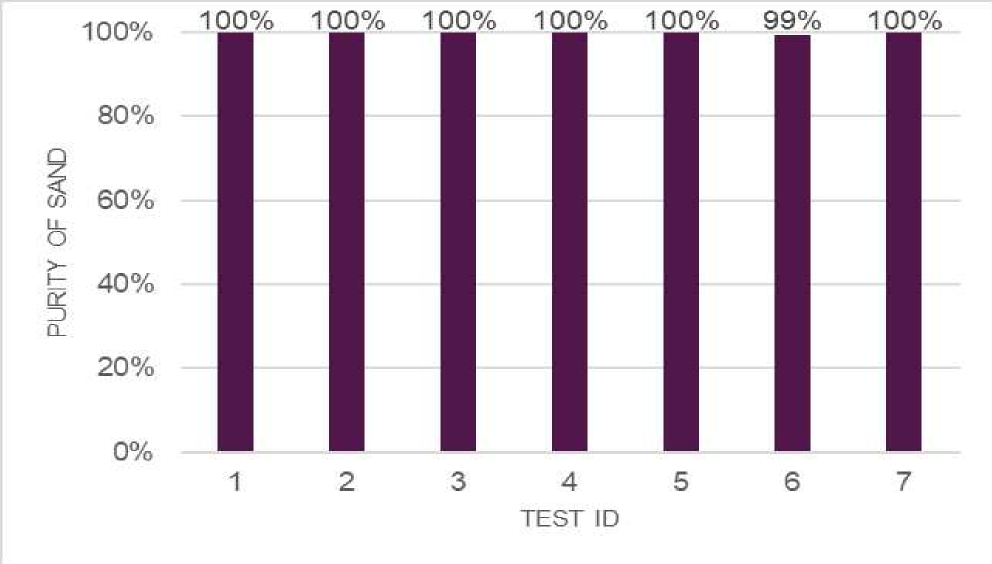

Figure 45- Purity of Sand for the second test series

In summary, by using a shallow incline and fine-tuning dynamic settings, the densimetric table was able to exploit the density and shape differences between dry Posidonia and sand much more effectively. The best cases yielded an organic (Posidonia) rich light fraction of over 80% purity and captured around 90% of all organics in that fraction in one pass. These results were also reproducible: when repeating a trial three times at the same settings, we observed consistent purity and efficiency values with only minor variations. This underscores that the method, once optimized, is stable and reliable under controlled conditions.

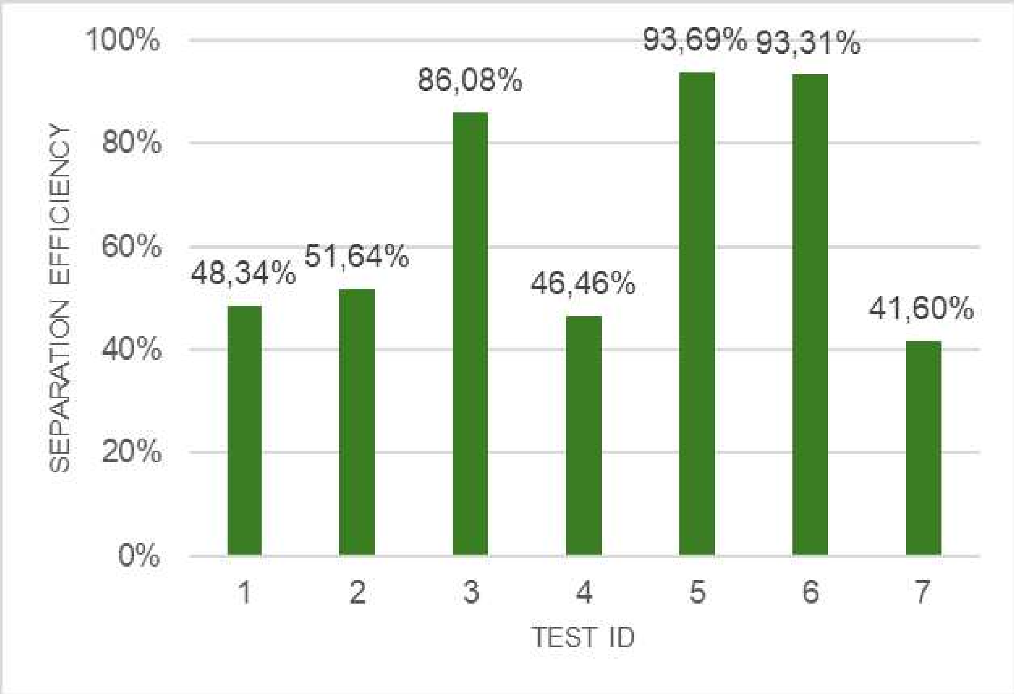

Figure 46- Separation Efficiency of the experimental test

Following the success with the 20% Posidonia mixture, we explored the system's behavior with different input mixtures to simulate various real-world scenarios. In a third set of tests, the Posidonia proportion was increased to 50% of the feed. In a fourth set, it was raised further to 70% Posidonia (simulating an extremely organic-rich wrack). We expected that with more light material, the capacity might saturate or efficiency might drop.

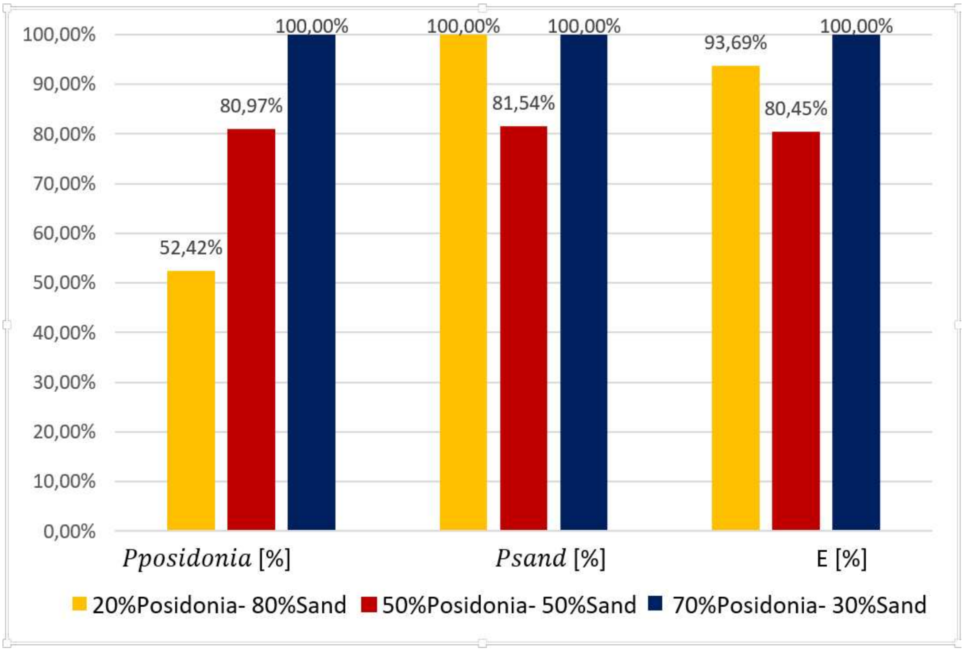

Figure 47- Purity of the mixed materials and the separation efficiency

Interestingly, the outcomes showed some expected trends but also positive signs: With more Posidonia in the feed, the absolute amount of organic matter recovered in the light bin naturally increased.

The **purity of Posidonia** in the light fraction remained high and comparable to the 20% feed case. This implies the table's effectiveness did not diminish with higher loads of light material; the Posidonia still mostly separated cleanly from the sand.

In the **50/50 mix**, there was naturally more interaction between sand and Posidonia (since amounts are equal), but even then the separation performed well, with only a modest reduction in efficiency compared to the 20% case.

As we can see in Fig. 43 in one of the 70% Posidonia trials at optimal settings, both Posidonia and sand purities in their respective fractions were measured at 100%, and the overall efficiency was ~100%.

These findings suggest that the densimetric separation method can accommodate a range of organic content scenarios commonly seen in beach wrack without losing function.

5.2.2 Trials on Sand/Plastic Mixtures

In addition to organic separation, we tested the densimetric table's ability to separate plastic fragments from sand, mimicking a scenario where anthropogenic litter (lplastic) is mixed into sand. We quantified the outcome by calculating the purity of plastic in the light frac- tion and the overall recovery efficiency of plastic. The results of a series of trials are given in Table 19.

Table 19- Results of Mix 2 test series

TEST ID	Plastic Purity in Light Fraction [%]	Sand Purity in Heavy Fraction [%]	Plastic Recovery Efficiency [%]
1	33,0%	99,0%	82,0%
2	56,2%	96,3%	52,7%
3	36,1%	96,8%	55,6%
4	33,2%	98,2%	84,0%
5	41,4%	95,8%	31,8%
6	36,2%	50,8%	4,8%
7	48,5%	97,7%	24,2%
8	35,2%	98,1%	28,9%

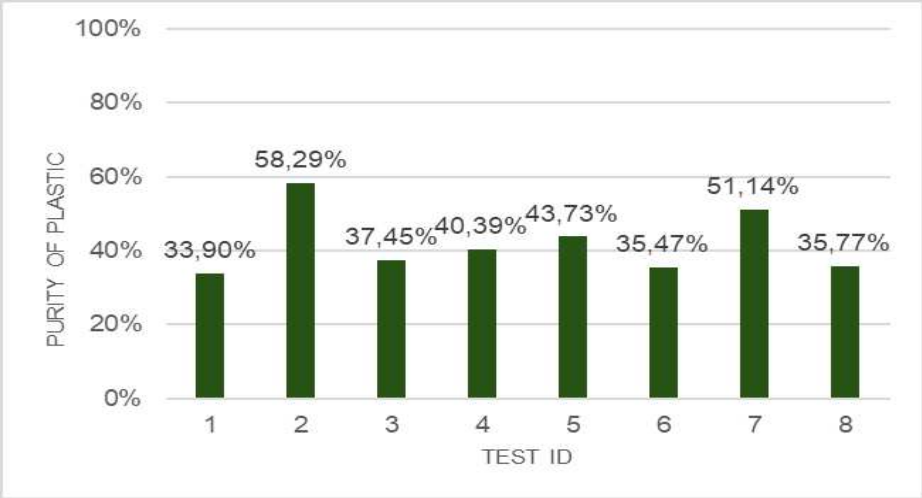

Figure 48- Purity of plastic for the second test series

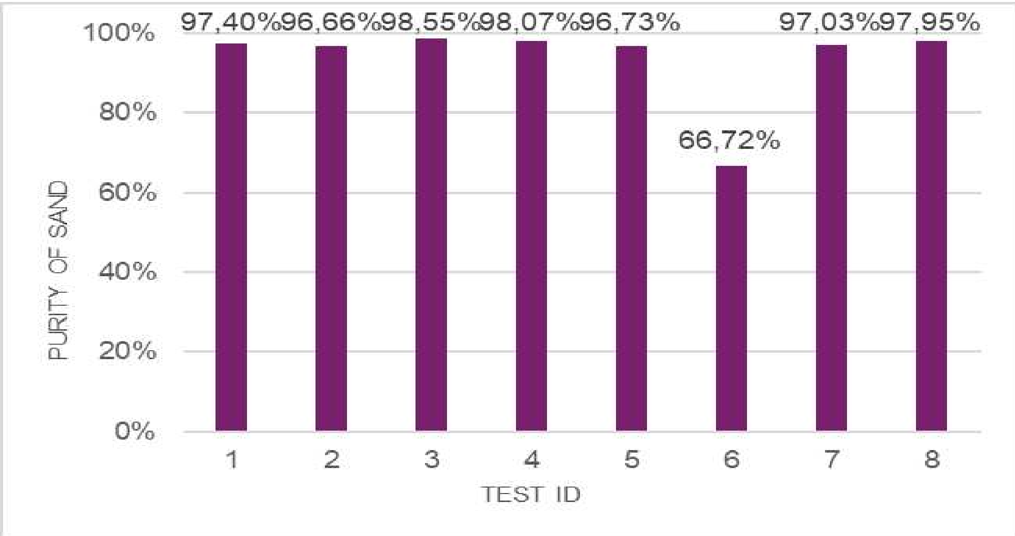

Figure 49- Purity of sand for the second test series

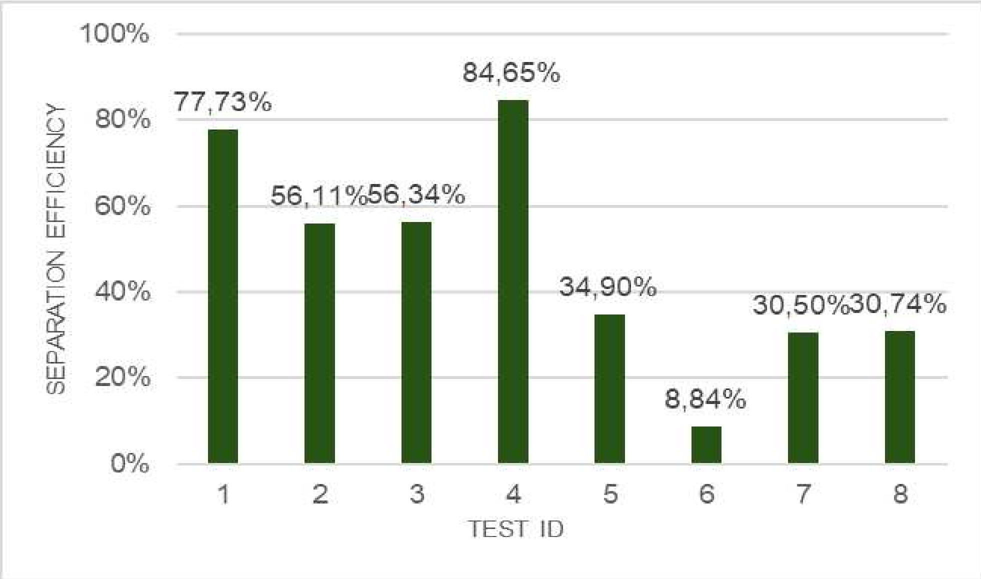

Figure 50- Seaparation efficiency for the second test series

From these trials, we observed plastic purities in the light bin ranging roughly from 33% to 56% in most runs, significantly higher than the 20% in the feed, so the plastics were indeed enriched in the light output relative to feed concentration. However, none approached anywhere near 100% purity.

In the best-case compromise we found, just over half of the PET plastic was recovered in the light bin with a plastic purity around 50%. In practical terms, this means the densimetric table in one pass was able to substantially reduce plastic con- tamination in sand (by concentrating plastic into one output), but it did not eliminate it. The heavy fraction still contained some plastic, and the light fraction still contained a good amount of sand. The densimetric separation is very effective for divergent materials like dry seagrass vs sand, but for plastic vs sand the density difference is smaller and air flow interactions are more complex. This resulted in only partial separation. To improve plastic removal via densimetric methods, one could experiment with lower airflow, different deck vibrations, or multiple sequential passes where the sand-plastic mixture is run through the table multiple times, each time hopefully peeling off more plastic. However, within the scope of this project, we simply demonstrated the concept: a densimetric table can partition some fraction of microplastics or plastic flakes from sand in a dry process.

In conclusion for the densimetric trials: for organic vs mineral separation, the method achieved very high efficiency and purity after optimization, validating it as a viable first-stage separation for beach litter. For plastic vs sand separation, the den- simetric approach showed potential but was not fully sufficient by itself, which leads to the need for a more specialized second stage namely, the electrostatic separation described next to target the fine intermixing of plastics and sand.

5.3 Electrostatic Separation Results

This section details the results of the tribo-electrostatic separation experiments aimed at removing plastics from the sand fraction. The trials were carried out in two phases: an initial exploratory test set using polypropylene (PP) plastic, and a subsequent optimized test set using polyamide (PA, nylon) plastic with improved parameters (including a pre-charging step for sand using wool). Performance is evaluated in terms of separation efficiency.

5.3.1 Purity and efficiency with first Mix

Table 20- First test set of PP plastic and sand mixture

TEST	Drum Rotation Speed [Hz]	Electrode Angles (wire; cylinder) [°]	Electrode Vol- tage [kV]	Separation Ef- ficiency [%]
1	40	-1 ; -9	25	23,12
2	40	-1 ; -9	20	23,20
3	40	-1 ; -9	20	23,10
4	30	-1 ; -9	20	24,50
5	40	-1 ; -9	15	29,81
6	20	-1 ; -9	10	32,43
7	20	-1 ; -9	10	32,43
8	20	-1 ; -9	10	21,44
9	20	-1 ; -9	10	23,59
10	20	-7 ; -15	22	21,01

The key qualitative findings from this PP trial series were:
A drum rotation speed of ∼20 Hz yielded the best result. Higher drum speeds (30–40 Hz) did not improve separation; in fact, they often performed worse. Likely, at high speed, particles (especially lighter plastic) are flung off the drum too

quickly, not giving the electric field enough time to act. Slower drum rotation allowed more residence time under the field.
Variations in the electrode angles (we tried wire and plate angles be- tween ∼–1° and –15° relative to horizontal) showed little effect within the tested range. Similarly, increasing the electrode voltage up to 25 kV did not significantly raise efficiency beyond ∼25–30%. These adjustments alone could not overcome the fundamental challenge that PP was not charging well.

5.3.2 Purity and efficiency after the wool charge pre-treatment

It became evident that with the baseline setup using PP plastic, it was nearly impossible to exceed ∼30% separation efficiency. In other words, the majority of PP did not respond to the field as desired, it wasn't being sufficiently charged and pulled away from the sand. We introduced a crucial change: pre-charging the sand by mix- ing it with wool. we replaced PP granules in the feed with an equal amount of PA granules of similar size (∼1–2 mm pieces). We also applied all the incremental opti- mizations together: wool pre-charging of sand, keeping the drum speed at 20 Hz (as found optimal), using a high electrode voltage (we tested ∼10–15 kV on the wire and ∼10–24 kV on the drum in various runs), and sticking with the more effective elec- trode angles. The impact of these changes was immediate and dramatic. With PA, the plastic particles acquired and retained charge much more effectively than PP. Visibly, more PA stuck to or moved with the drum, and less fell straight down. The charged PA could be deflected by the field, separating it cleanly from sand.

Table 21- High-efficiency results with PA plastic (after optimizations)

TEST	Drum Speed [Hz]	Electrode Angles (wire; drum) [°]	Voltage (wire) [kV]	Separation Ef- ficiency [%]
11	20,00	-1 ; -9	10,00	**60,36**

12	40,00	10 ; -10	22,00	**79,17**
13	20,00	10 ; - 10	24,00	**94,15**

We achieved substantially a higher efficiency of ~94.1% (Table 21), far surpassing the 80% goal. These tests confirmed that the combination of dried sand + wool pre-charge + PA plastic + low drum speed is a winning combination for this separator. Once the plastic (PA) could hold charge and the sand had an opposite charge, the separator effectively pulled nearly all plastic to one side. Encouraged by these results, we proceeded to a second phase of testing to further validate and fine-tune the tribo-electrostatic separation with PA. In the second phase, we focused on measuring purity of outputs in addition to efficiency, and we simulated continuous operation with multiple passes and mixing.

Table 22- Results of the second test series with wool pre-treatment

TEST	DRUM SPEED [Hz]	ELECTRODE ANGELES (WIRE, DRUM) [°]	VOLTAGE(DRUM) [KV]	SEPARATION EFFICIENCY [%]
1	20	-1; -9	10	47,01
2	20	10; -9	22	84,93
3	40	-1; -9	24	<10
4	40	-1; -10	22	81,94
5	20	10; -9	10	41,41

Key findings from the second phase included (Table 22):

• The trials confirmed that with PA plastic, we could consistently achieve high separation efficiency (80–95%) and high purities for both output streams (plastic-rich and sand-rich). For instance, in one representative run, the plastic collected was over 85% pure plastic, and the sand remaining was >80% pure sand, with only a few percent cross-contamination in each, excellent results for a single-stage dry separator.

• We noted that the presence of any moisture severely hurt performance – thus all materials had to be completely dry and ideally pre-conditioned (like the sand with wool) for optimal results. This underscores the importance of the drying step and tribo-charging preparation.

- When we attempted to process mixed plastics or plastics with lots of biofouling, results were worse. The best case was achieved with a uniform plastic type (PA). This suggests that in a real scenario, one might first isolate certain plastic types or clean them before electrostatic separation, or accept lower efficiency for mixed plastics. For our goal (microplastics removal from sand), focusing on one type gave us a proof of concept that it can be done extremely well under ideal conditions.

5.3.2 Variation in the main process parameters

Table 23- Results for the voltage variation

TEST	VOLTAGE(DRUM) [KV]	PURITY OF PLA- STIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIEN- CY [%]
1	**10**	47,65	48,96	22,32
2	**15**	67,18	52,68	30,74
3	**20**	92,40	72,40	76,39
4	**25**	99,81	85,18	91,71

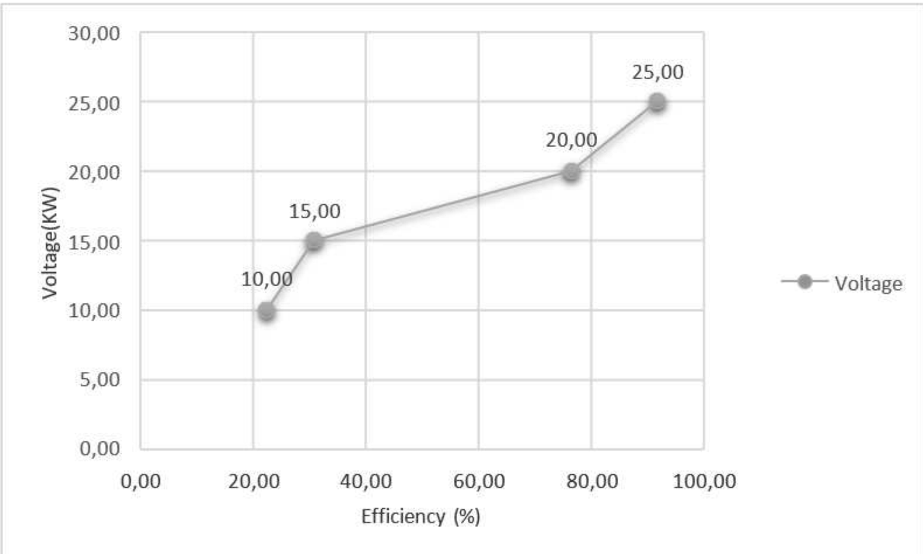

Figure 51- Variation of the separation efficiency with the voltage

Table 24- Results for the drum speed variation

TEST	DRUM SPEED [Hz]	PURITY OF PLASTIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
5	20	88,16	91,26	89,80
6	30	99,65	80,62	86,78
7	35	91,28	72,86	74,20
8	40	99,00	67,21	73,62

Figure 52- Variation of the separation efficiency with the drum speed

Table 25- Results for the electrode variation

TEST	ELECTRODE ANGEL (WIRE) [°]	ELECTRODE ANGEL (DRUM) [°]	PURITY OF PLASTIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
9	-1	-9	92,40	82,94	86,27
10	3	-9	92,19	85,50	86,98
11	7	-10	99,97	80,33	88,12
12	10	-10	99,94	79,62	87,07

Table 26- Results for the electrode angel position

TEST	ELECTRODE ANGEL (WIRE) [°]	ELECTRODE ANGEL (DRUM) [°]	PURITY OF PLASTIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
A	-1	-9	93,60	79,79	83,59
B	3	-9	82,79	68,44	68,10
C	7	-10	92,98	87,11	89,64

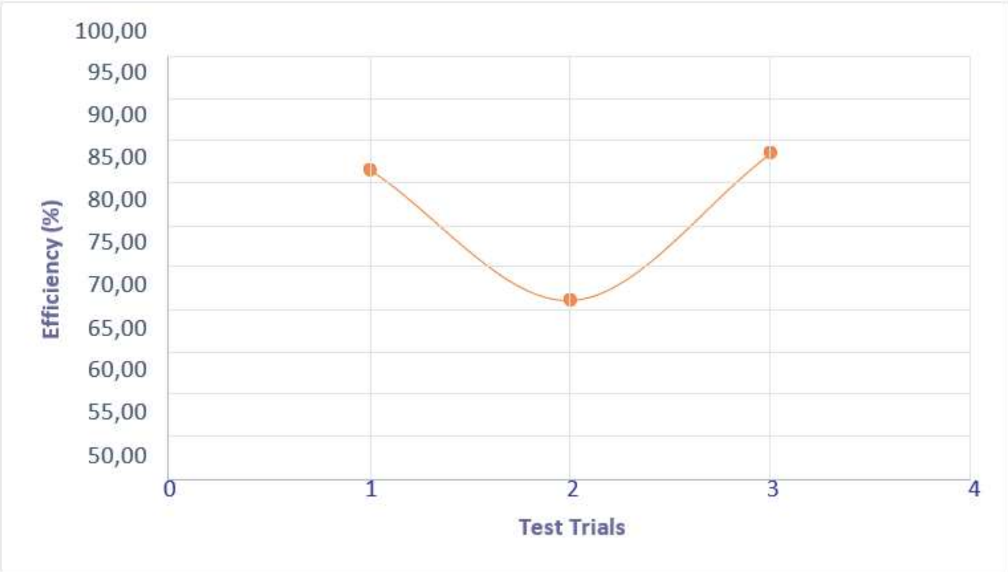

Figure 53- Variation of the separation efficiency with the electrode position

In summary, the electrostatic separation experiments demonstrated that high efficiency removal of plastics from sand is achievable, but only when the materials are amenable to charging. The change from PP to PA was a pivotal discovery: it showed that if plastics have higher triboelectric affinity (like PA) and if sand can be charged oppositely (using wool), the electrostatic method can recover nearly all plastics, leaving clean sand. For more inert plastics (like PP, PE) that do not charge easily, additional measures are needed (pretreatments, additives, or using multiple stages).
These results are important for the integrated process: they indicate that an electrostatic separator can serve as a second-stage treatment to target the residual micro-

plastics in sand after the densimetric separation has removed the bulk of organ- ics. In practice, not all beach plastics will be PA; many are PE/PP. But our experi- ments suggest that if conditions are optimized (drying, possibly adding a charge en- hancer like wool or even mixing in a bit of a more chargeable plastic), a significant fraction of even those plastics could be separated. The tribo-electrostatic technology thus offers a viable, water-free complement to the densimetric separation, focusing on the fine cleanup of sand that is otherwise difficult to achieve.

Overall, combining the two stages: the densimetric separation first concentrates organics and removes large debris, yielding a mostly sand + microplastic residual; then the electrostatic separation can be applied to that sand to extract microplastics. The experiments in this chapter provided the data to design such an integrated system, and the next section (Life Cycle Assessment) will consider the environmental implications of employing these innovative processes in lieu of traditional beach waste management.

5.4 Optimization Tribo- Charger Results

5.5.1 Effect of Charging Duration

Two different materials used to pre-load the sand–plastic mixture were considered, namely 100% wool and denim. These materials were selected based on tests performed to evaluate the charge levels; all tests were conducted at an operating frequency of 40 Hz and with a loading time of 5 min. From the tables below (Table 27 and Table 28), corresponding to 100% wool and denim respectively, it is evident that the optimal charging time for both materials is 10 min.

Table 27- Charging time variation tests with 100% wool

TEST	CHARGING TIME [min]	PLASTIC [nC]	SAND [nC]
1	1	0,91	-0,13
2	5	1,49	-0,11
3	10	3,12	-0,05
4	15	2,88	-0,08

Table 28- Charging time variation tests with denim

TEST	CHARGING TIME [min]	PLASTIC [nC]	SAND [nC]
1	1	1,41	-0,11333
2	5	1,61	-0,05067
3	10	2,07	-0,06833
4	15	0,95	-0,05267

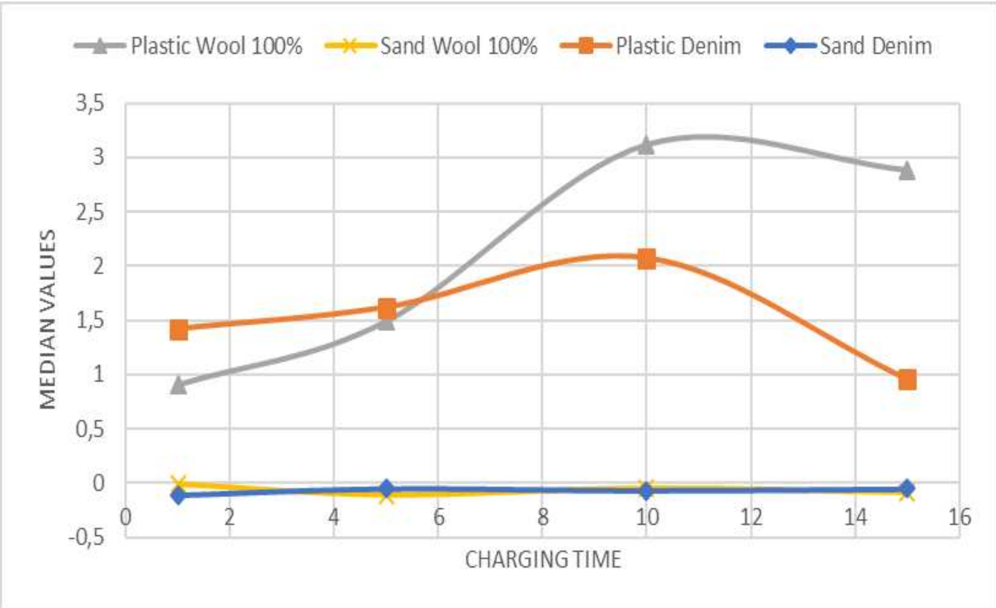

Figure 54- Electrostatic charge variation of the different materials (100% Wool and Denim) across different pre-treatment times

5.4.2 Efficiency of Pre-treatment

The applied voltage proved to be the most influential parameter affecting the separator's performance (Table 29, Table 30), in agreement with the literature

(Achouri et al., 2024): Efficiency showed a dramatic increase (from ≈20% to ≈90%) after exceed- ing the 15 kW voltage threshold. The highest efficiency was reached at the maximum tested voltage of 25 kW: 88.17% for wool and 91.29% for denim.
Purity followed a similar trend; the maximum plastic purities (90.94% for wool, 92.27% for denim) and the maximum sand purities (85.65% for wool, 90.68% for denim) were obtained at the maximum voltage of 25 kW.

Table 29- Efficiency and voltage variation with 100% wool

TEST	VOLTAGE(DRUM) [KW]	PURITY OF PLA-STIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
1	10	37,33	47,49	16,88
2	15	54,74	48,82	25,64
3	20	88,18	66,27	68,75
4	25	90,94	85,65	88,17

Table 30- Efficiency and voltage variation with denim

TEST	VOLTAGE(DRUM) [KW]	PURITY OF PLA-STIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
1	10	47,57	48,69	20,32
2	15	45,02	48,89	19,35
3	20	89,4	75,87	79,54
4	25	92,27	90,68	91,29

The drum speed exhibited a critical and often opposite behavior compared with voltage, affecting inertial forces and exposure time (Table 31, Table 32): The ef- ficiency peak occurred at the lowest rotation rate (20 Hz), reaching ≈90% for wool and ≈92% for denim. High speeds (40 Hz) produced a marked col- lapse in efficien- cy (down to ≈70% for wool and ≈85.5% for denim). Sand purity proved sensitive to increasing speed, decreasing at the maximum rotation regime. Under these conditions, excessive centrifugal force alters particle tra- jectories and promotes recontamination of the sand fraction.

Table 31- Efficiency and drum speed variation with 100% wool

TEST	DRUM SPEED [Hz]	PURITY OF PLASTIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
5	20	92,53	87,22	89,72
6	30	90,42	82,44	85,41
7	35	92,33	82,89	86,5
8	40	84,48	67,54	69,1

Table 32- Efficiency and drum speed variation with denim

TEST	DRUM SPEED [Hz]	PURITY OF PLASTIC [%]	PURITY OF SAND [%]	SEPARATION EFFICIENCY [%]
5	20	93,9	87,06	91,96
6	30	92,18	90,35	89,35
7	35	94,19	89,33	90,15
8	40	92,02	81,94	85,42

The electrode position proved to be a critical parameter for field stability (Table 33, Table 34): 100% wool: The minimum tested inter-electrode distance (7 mm) was found to be the optimal configuration for the separation process, since it yielded the highest overall efficiency (90.47%), the highest combined purity of the two fractions (plastic 88.21% and sand 93.33%), and an effective separation due to the high electric field intensity while remaining compatible with the plant's operational safety.
Denim: The process reached its maximum efficiency (90.82%) at an inter- electrode distance of 8 mm. This suggests that a slight reduction in field intensity relative to the maximum achievable value can improve operational stability without compromising

separation quality. Under these conditions the overall purities of the separated fractions were maximized (plastic 92.81% and sand 89.21%).

Table 33- Efficiency and Electrode Position variation with 100% wool

TEST	ELECTRODE AN- GEL (WIRE) [°]	ELECTRODE AN- GEL (DRUM) [°]	PURITY OF PLA- STIC [%]	PURITY OF SAND [%]	SEPARATION EF- FICIENCY [%]
9	-1	-9	89,74	89,31	89,42
10	3	-9	90,14	86,51	88,26
11	7	-10	87,13	86,04	85,63
12	10	-10	88,21	93,33	90,47

Table 34- Efficiency and Electrode Position variation with denim

TEST	ELECTRODE AN- GEL (WIRE) [°]	ELECTRODE AN- GEL (DRUM) [°]	PURITY OF PLA- STIC [%]	PURITY OF SAND [%]	SEPARATION EF- FICIENCY [%]
9	-1	-9	88,51	85,26	87,43
10	3	-9	88,34	91,72	89,18
11	7	-10	92,81	89,21	90,82
12	10	-10	89,6	82,87	85,41

5.5 LCA Results

A comparative analysis of the two separation stages revealed that the densimetric separation stage has a substantially lower environmental impact per kg of input treated than the electrostatic stage.

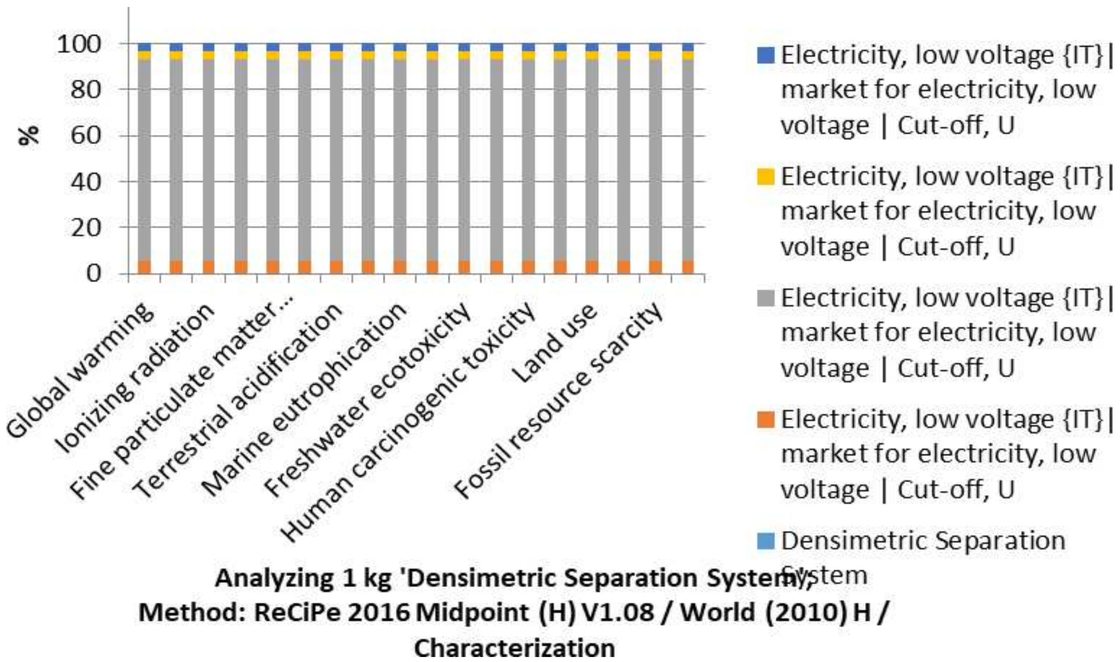

Figure 55- Analyzing 1 kg 'Densimetric Separation System'

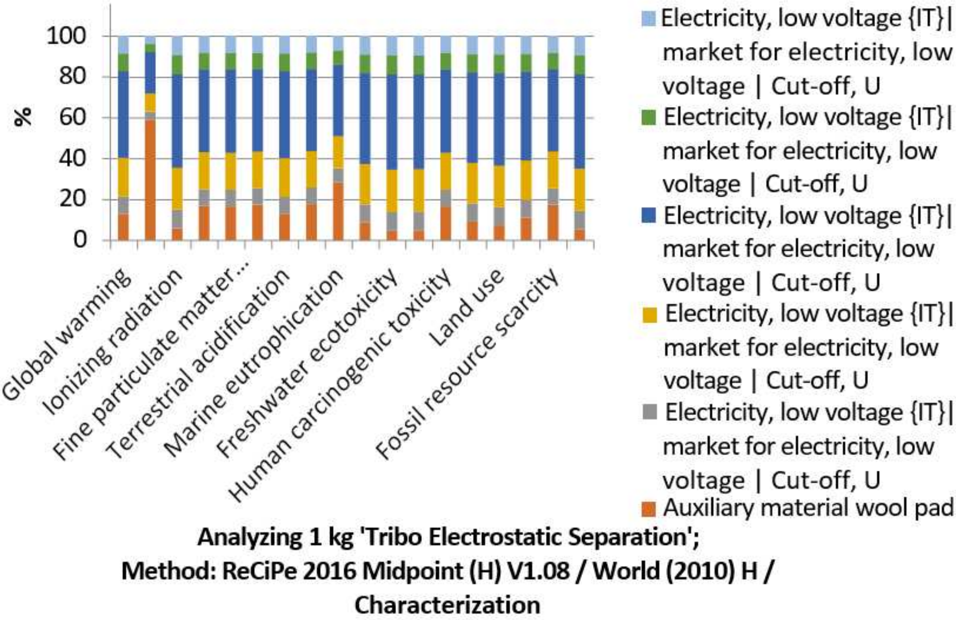

Figure 56- Analyzing 1 kg 'Tribo Electrostatic Separation'

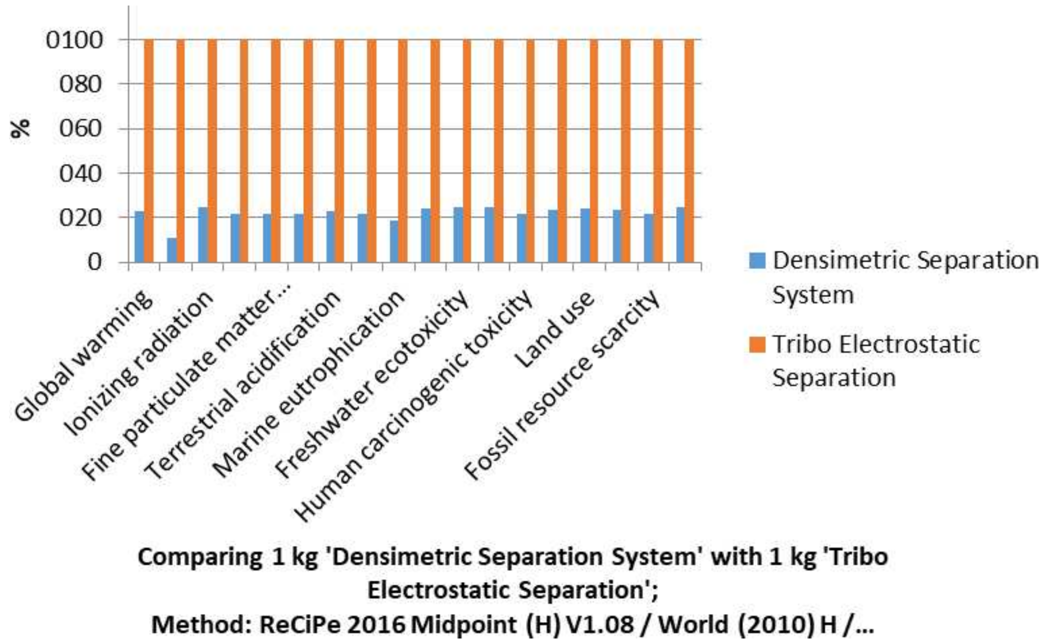

Figure 57- Comparing 1 kg 'Densimetric Separation System' with 1 kg 'Tribo Electrostatic Separation'

Across all 18 midpoint impact categories analyzed, the densimetric process scored between roughly 20% and 30% of the impacts of the electrostatic process (when each is considered as the sole treatment of 1 kg). For instance:

Global Warming Potential (GWP):

The densimetric separation's GWP was only about 23% of the electrostatic separation's GWP for the same 1 kg treated. In other words, the electrostatic stage had roughly 4–5 times the carbon footprint of the densimetric stage. This is mainly due to higher electricity consumption and the production of the wool pad for electro- static charging.

Fossil Resource Use: Similarly, the densimetric stage showed ∼22% of the fossil fuel resource depletion compared to electrostatic. This aligns with its lower en- ergy use (electricity in Italy still partly fossil-based) and lack of additional materials.

Water Consumption: The processes themselves are dry, but upstream elec- tricity generation uses water. Densimetric had ∼25% of the water consumption im- pact of electrostatic, reflecting its lower power needs.

Human and Ecotoxicity Categories: Densimetric ranged ∼22–25% of elec- trostatic impacts in categories like human toxicity and ecotoxicity. Electrostatic's higher electricity use (and the production of wool) contributes to more emissions (like heavy metals, etc., from power generation and agriculture) that influence these cate- gories.

Ozone Layer Depletion: One noticeable difference was in the stratospheric ozone depletion category, where densimetric was only ∼11% of the electrostatic pro- cess's impact. The electrostatic stage's use of wool was a significant factor here – surprisingly, the production of wool (or the processes associated with it) had non- negligible ozone-depleting emissions (likely due to agriculture and manufacturing pro- cesses). Because densimetric uses no such consumable, its ODP impact was much smaller.

Photochemical Smog and Particulate Formation: These air emission-related impacts were also consistently lower for densimetric (around 20–25% of electrostatic's values), again tracing back to electricity use differences.

The conclusion from this comparison is that the densimetric separation stage is relatively eco-efficient, incurring only about one-fifth of the environmental burden of the electrostatic stage per unit of material processed. The electrostatic stage, while effective at microplastic removal, is more energy and material intensive, which mani- fests as higher impacts in multiple categories.

5.5.1 Interpretation and Discussion

The LCA results need to be interpreted in context. The two separation stages are not meant to be alternatives to each other but rather complementary steps in a single system. Therefore, a more relevant question is: what is the impact of treating 1 kg of beach litter using the integrated densimetric + electrostatic process, versus sending that 1 kg to landfill? When combining stages, one must consider that not all of the 1 kg goes through both stages fully. In a typical scenario based on our experi-

ments, out of 1 kg of wet beach litter: Roughly 30–50% might be sand (which would proceed to electro- static separation); The rest is organic matter and a small amount of anthropogenic debris which are separated out by the densimetric stage and do not go through elec- trostatic. Thus, the electrostatic machine might only treat ~0.3–0.5 kg of material per 1 kg input. If we factor this in, the integrated process impacts are a weighted sum: all 1 kg passes the densimetric (low impact) stage, and only half (for example) passes the higher-impact electrostatic stage. The net effect is to reduce the overall footprint of treating that 1 kg compared to if one were to use electrostatic on the entire mass. In quantitative terms, suppose electrostatic processing of 1 kg has a GWP of X kg CO_2 eq. Densimetric processing of 1 kg might be ~0.23X. If only half the mass goes to electrostatic, the combined GWP $\approx$ 0.23X (for densimetric on 1 kg) + 0.5X (for electrostatic on 0.5 kg) = 0.23X + 0.5X = 0.73X. That is still 27% lower GWP than using the electrostatic step on everything. And crucially, we must compare that 0.73X to the landfill baseline.
The landfill baseline for 1 kg beach litter, which is mostly organic and wet, might include emissions of methane (if not captured, methane contributes a large GWP) and the production of CO_2 from transport and decomposition. A rough estimate using waste LCA models: 1 kg of mixed beach waste (say 30% organic, 70% inert) sent to landfill could have a GWP on the order of 0.05–0.1 kg CO_2 from transport, plus potentially 0.2–0.3 kg CO_2 eq from decay (methane release). If Posidonia de- composes anaerobically, it could generate methane, though slowly. Let's assume ~0.2 kg CO_2 eq net per kg waste in landfill (this is conservative; some studies indi- cate higher if organics are significant).

Now compare: if the integrated process uses electricity from the grid, Italian grid electricity has about 0.33 kg CO_2 per kWh. The densimetric (0.5 kWh) + electrostatic (0.3 kWh for 0.5 kg, =0.15 kWh) totals ~0.65 kWh, which is ~0.215 kg CO_2. Production of wool for 0.5 kg sand might add a small amount (negligible GWP compared to power, maybe 0.01–0.02 kg CO_2). So maybe ~0.23 kg CO_2 per kg waste treated by our system, comparable to the landfill's ~0.2+ kg, perhaps slightly higher.

However, our process avoids the need for new sand. More importantly, if we consider avoided impacts (credit for sand and biomass recovery), the picture changes to favor our process. For example, returning sand to the beach avoids quarrying new sand for beach nourishment. Quarrying and transporting 0.3–0.5 kg of sand would have its own footprint, likely small per kg, but scaled up, avoiding that is beneficial. Also, by removing plastic from the environment, we avoid its continued fragmentation and potential harm (though that's not captured in standard LCA impact categories yet).

The LCA results indicate significant environmental benefits of the on-site separation approach when considering a broader system perspective. The integrated process: - Reduces GWP and energy use compared to hauling heavy, wet waste to landfill. Even though the process consumes electricity, much of the weight (sand, water) is left on site, meaning fewer emissions from trucking and no emissions from landfilled organics (which would generate methane). The LCA model showed a net reduction in climate change impact for the integrated process relative to baseline, primarily due to these avoided landfill emissions and reduced transport. - Excels in resource-related categories. By recovering sand and biomass, the need for extracting new sand (a non-renewable resource in coastal management terms) and disposing of biomass is lowered. The impact category Mineral Resource Scarcity was much lower for the new process, reflecting that we are not consuming mineral resources but rather returning them. Fossil Resource Scarcity was also lower, due to avoided fuel use in transport and the relatively modest electricity use (especially if renewable electricity is used, this improves further). - Has trade-offs in some pollution categories. The electrostatic stage's wool pads and electricity use cause higher Ozone Depletion Potential and possibly higher eutrophication in some subcategories, compared to simply dumping the material. However, these trade-offs are minor in magnitude and can be mitigated (for example, sourcing wool second-hand or using an alternative charging method could cut that ODP impact, and using cleaner electricity reduces most pollutant emissions).

In particular, the Global Warming Potential (GWP) for the integrated system was found to be significantly lower than the landfill baseline in our model. The primary reason is that landfilling organic matter creates methane, a potent greenhouse gas, whereas our process avoids that by recovering the biomass (which can be composted or otherwise handled aerobically). Also, every kilogram of sand returned to the beach is a kilogram less that might be quarried elsewhere (avoiding those emissions). The LCA model estimated on the order of 50–70% reduction in GWP for the integrated approach compared to landfill, under reasonable assumptions.

5.5.2 Sensitivity Analysis

We tested the sensitivity of results to energy sources. If the mobile unit is powered by a diesel generator instead of grid electricity, the emissions would be higher (diesel has ~0.7 kg CO_2/kWh delivered). In that case, the integrated process might have a similar GWP to landfilling, eroding the climate benefit. However, if powered by renewable electricity (solar panels, or simply using Italy's increasingly decarbonized grid), the impacts drop sharply. Therefore, powering the system with renewable energy is a key recommendation to maximize sustainability.

The use of consumables like wool pads was also examined. The wool contributed notably to a few impact categories (ODP, some toxicity categories) despite being a small mass, due to the intensive nature of wool production data. Using a synthetic charging material or redesigning the charging method could reduce those specific impacts. However, even with the wool included, the overall environmental performance of the integrated system remained favorable.

6.6 Summary of LCA Findings. The LCA confirms that the innovative beach litter treatment can significantly reduce environmental impacts across multiple categories relative to the status quo. The densimetric separation is a low-impact, high-gain step (mostly mechanical, little energy use) that yields immediate benefits by keeping sand on site and concentrating organics. The electrostatic separation, while more energy-intensive, addresses the critical issue of microplastics and yields a cleaner sand output. Its impacts, though higher, are justified by the outcome of removing persistent pollutants. Moreover, the modular nature means it only operates on the fraction that truly needs it (mineral residuals), optimizing resource use. In terms of system sustainability, the integrated approach aligns with circular economy principles: materials are not just disposed but re-routed – sand to the beach, biomass potentially to compost or bioenergy, and plastics to recycling or proper disposal. The LCA's impact results for categories like fossil fuels, minerals, and GWP all trend lower for the new system, indicating improved environmental per- formance and resource efficiency.

One important implication of the LCA is that the choice of technology and operating conditions can shift burdens. For example, if one were to rely solely on electrostatic separation for everything (which some might consider, theoretically, to dry-separate all fractions), the impacts would be much higher. By using the densimetric stage first, we achieve a bulk separation in an eco-friendly way, and only use the high-tech, higher-impact stage on a targeted subset. This cascade approach is environmentally intelligent.

Finally, the LCA results reinforce the idea that such a mobile treatment system not only keeps beaches cleaner but does so with a net positive environmental outcome when compared to conventional removal and landfilling. It reduces waste sent to landfill (extending landfill life and reducing emissions), avoids the need for replacement sand (conserving natural sediments), and could reduce the carbon and energy footprint of beach management – especially if integrated with renewable energy. These findings support the sustainability and scalability of the proposed system as a green technology for coastal zones.

CONCLUSIONS

This doctoral research has explored an integrated approach to sustainable beach litter management, focusing on the recovery of resources from beached waste within a circular economy framework. The study addressed a pressing environmental engineering challenge: the accumulation of mixed natural and anthropogenic debris along coastlines, by developing and evaluating a prototype process for in situ treatment of stranded beach litter.

Three representative coastal sites in Apulia (Southern Italy), each exemplifying a different environmental context (natural, semi-natural, and anthropic habitat), were investigated to characterize the composition and dynamics of beach-cast waste. A tailored sampling methodology was successfully implemented, ensuring that the collected samples accurately reflected the heterogeneity of debris deposits. These samples were subjected to a series of laboratory-scale treatment trials that form the core innovation of this work: a mobile separation process designed to fractionate beach litter into useful output streams. Specifically, a vibratory densimetric separation table was used to separate lighter organic matter (Posidonia oceanica) and low-density litter from heavier sand, and a tribo-electrostatic separator was employed to further segregate plastics from mineral particles.

The experimental results demonstrated the technical feasibility of this two-stage separation strategy. The densimetric table proved effective in isolating a clean sand fraction and concentrating the organic biomass, especially after optimizing operational parameters. At its best, the densimetric process achieved ~85% overall separation efficiency for organics vs. sand in a single pass, yielding an organic-rich fraction with over 90% purity. This performance indicates that a majority of beached Posidonia and similar materials can be separated from sand on-site, allowing the sand to be largely recovered and returned to the beach, thus preserving a critical natural resource and reducing the need for external sand nourishment.

The tribo-electrostatic separation experiments further addressed the challenge of removing residual microplastics and plastics from the recovered sand. Initial trials highlighted the importance of material conditioning. Dried sand and proper triboelec-

tric charging were necessary to achieve substantial separation. Through an innovative pre-charging step (tumbling sand with wool to impart static charge) and by selecting a plastic with favorable electrostatic properties (polyamide), the separator reached over 90% separation efficiency under optimized conditions. Plastics were effectively separated into a concentrated fraction, leaving behind sand with minimal plastic con- tamination. This is a remarkable outcome given the complexity of dry separation of granular mixtures, and it underscores the potential of tribo-electrostatic technology as a clean, water-free solution for microplastic removal.

Environmental and Economic Implications: A Life Cycle Assessment (LCA) was conducted to evaluate the environmental sustainability of the proposed mobile treatment system compared to conventional management (the baseline scenario of hauling mixed beach litter to landfill as municipal solid waste). The LCA results indicate that the on-site separation and valorization of beach litter can lead to significant environmental benefits. By returning cleaned sand to the local ecosystem, the need for quarrying or importing sand for beach replenishment is reduced, avoiding the associated carbon emissions and habitat disturbance. The recovery of organic biomass opens possibilities for circular reuse pathways, such as composting to create soil amendments or anaerobic digestion to produce biogas, rather than treating this biomass as waste. Additionally, isolating plastics and other recyclable materials at the source increases the likelihood that these can enter appropriate recycling streams or be treated with higher efficiency, thus mitigating pollution and the energy use of producing virgin materials. Notably, the analysis did highlight that the electrostatic stage carries a larger share of the process's impacts per kg (due to higher electricity and material use), but when integrated into the system its footprint is moderated by the densimetric stage handling the bulk first.

Parallel to the environmental analysis, a Life Cycle Costing (LCC) assessment provided insight into the economic viability of the new approach. The LCC considered capital and operating costs of a mobile treatment unit (including equipment for densimetric and electrostatic separation, power supply, and maintenance) against current expenditures for beach cleaning, transport, and disposal. The study found that while there are upfront costs to deploying specialized machinery, there are also offsetting savings: notably, lower landfill tipping fees (due to reduced waste volume needing disposal), lower transport costs (since sand and water weight are largely left on the beach), and potential value or cost offset from the sale or reuse of recovered materi- als (e.g. using the clean sand locally, or integrating the biomass into municipal green waste streams). Under realistic operational scenarios (e.g. a municipality deploying the unit during the summer season across multiple beaches), the cost per ton of beach litter managed with the mobile system was found to be competitive with, and in some cases lower than the traditional practice. When environmental externalities (the economic cost of carbon emissions, loss of ecosystem services, etc.) are factored in, the cost-benefit balance tilts further in favor of the sustainable approach. The LCC thus supports the economic practicality of integrating the developed process into coastal zone management programs, especially as part of a preventive strategy to handle beach litter before it accumulates into more costly forms.

Contribution to Sustainability and Circular Economy: The conclusions of this research reinforce the concept that seemingly "valueless" beach waste can be transformed into useful resources through engineering innovation. By embracing principles of the circular economy, the project demonstrated that materials like sand and biomass, which would otherwise be discarded as waste or cause environmental harm can be recovered and looped back into productive use. This not only reduces the environmental footprint of beach litter management but also turns a waste problem into an opportunity for resource efficiency. The approach embodies sustainable development goals: conserving natural resources (sand), reducing pollution (less plastic leakage into oceans), and protecting coastal and marine ecosystems, all while potentially lowering management costs in the long run.

The research also contributes new knowledge on the performance of mechanical and electrostatic separation techniques for unconventional waste streams. It addresses a gap in waste management literature by focusing on in situ treatment at the point of collection, an approach that can be more sustainable than centralized processing for diffuse pollution like beach litter. The findings support the idea that future marine litter mitigation strategies can integrate engineering solutions (like the one studied) as a complement to policy measures that reduce litter at source, thereby tackling the problem from both ends.

While the outcomes are promising, this study was conducted at laboratory scale and under controlled experimental conditions. Future research should pursue several avenues to build on and scale up these findings:

Pilot-Scale Demonstration: The next step is to design and construct a pilot-scale mobile unit embodying the separation processes tested here.

Integration of Renewable Energy: As indicated, powering the system via solar panels, wind, or other renewables on-site would enhance its sustainability. • Refinement of Electrostatic Separation: Exploring alternate tribo-pair materials (besides wool) could complement the current approach.

Material End-Use Solutions: The ultimate success of the circular ap- proach depends on what is done with the recovered fractions. Thus, investigating end-use or disposal pathways is crucial. For the organic fraction (Posidonia and al- gae), studies on composting, biomethanation (anaerobic digestion), or use as soil amendment should be advanced, including any pre-treatment needed (e.g., washing out salt). For the recovered plastics, an assessment of recycling feasibility should be done. Can these weathered plastics be recycled mechanically or chemically, or is en- ergy recovery more appropriate? Demonstrating that each recovered stream can be put to productive use will solidify the environmental gains.

Economic and Social Evaluation: Beyond technical performance, fu- ture work should evaluate the economic model and the social acceptance. Public per- ception studies could gauge how beachgoers and local communities feel about on- site processing (which might involve visible machinery on the beach periodically). Education and outreach could amplify the positive impact, turning beach cleanup from a waste removal activity into a resource recovery demonstration for the public.

In conclusion, this PhD research has laid a strong foundation for an innovative system of beach litter management that aligns with circular economy and sustainability goals. The combination of characterization, densimetric separation, and electrostatic separation proved effective in the lab, and the supporting LCA/LCC analyses suggest it can be both environmentally beneficial and economically feasible. Implementing this approach in real-world settings can help transform the way coastal municipalities deal with the recurring issue of stranded litter, shifting from a paradigm of disposal to one of recovery and reuse. By doing so, it addresses not only the symptoms (unclean beaches) but also contributes to solving broader problems: conserving natural resources, preventing pollution, and promoting a more circular flow of materials even in the context of environmental debris. This integrated strategy, therefore, represents a meaningful step toward sustainable coastal management, where engineering innovation and ecosystem stewardship go hand in hand.

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