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MONITORING, POLLUTION PATTERN AND SOURCES OF LITTER IN COASTAL ZONES IN TUNISIA AND GERMANY

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ANGED: National Waste Management Agency

ANPE: Agency of Environmental Protection

APAL: Coastal Protection and Development Agency

APII: Agency for the Promotion of Industry and Innovation

CITET: International Centre of Environmental Technologies

CPAL: Crystallized Polylactic Acid

DO: Dissolved Oxygen

DR: Degradation Rate

ECO-Lef: Public system of packaging recovery

EPR: Extended Producer Responsibility

FTH: Federation of Hotels

GDP: Gross Domestic Product

INSTM: National Institute of Marine Sciences and Technologies

IUCN: International Union for Conservation of Nature

JORT: Journal of the Tunisian Republic

LISP: “Plastic Free Coastal” Strategy

MIME: Ministry of Industry, Energy and Mines

OSPAR: Convention for the Protection of the marine Environment

OTEDD: Tunisian Observatory for the Environment and Sustainable Development

PackTec: Packaging Technical Center

PEHD: Polyethylene High Density

PET: Polyethylene Terephthalate

PLA: Polylactic Acid

PS: Polystyrene

PTT: Polytrimethylene Terephthalate

SNTE: National Ecological Transition Strategy

TouMaLi: Tourism and Marine Litter

UN: United Nations

UNDP: United Nations Development Programme

UNEP: United Nations Environment Programme

UTICA: Tunisian Union of Industry, Trade and Handicrafts

SUMMARY

Marine litter is undeniably a global issue causing a threat to the planet's marine environment and resources. In particular, plastics pose the greatest threat to ocean habitats, since they degrade in the marine environment over time and harm living organisms (Barnes et al., 2009). However, the lack of information and data with regard to the quantities, sources and pathways of marine litter poses a major challenge to the assessment of marine litter pollution, an assessment which is considered necessary to support decision making for effective marine management and coastal litter avoidance.

This work deals with the issue of coastal litter in both Tunisia and Germany. **In the first part,** the main indicators related to solid waste management with regard to marine and coastal litter in Tunisia were identified, based on land and coastal areas as sources for diagnosing the current situation. Three main indicators and twelve sub-indicators were developed and classified into driving factors and resulting situations based on (1) an extensive review of the literature and interviews, and (2) field beach litter monitoring campaigns carried out on five beaches from the north to the south in different seasons over a three-year period and using the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). The findings showed that plastics represent the main litter items in coastal areas and beaches (ranging between 54% and 70%), while packaging was identified as the most littered product, ranging between 54% and 74% of the total waste identified. It's worth noting that the majority of litter found on beaches originates from tourism and recreational activities (between 89% and 95% respectively). Furthermore, the amount of litter identified was relatively important during a low tourism period in comparison to the period from the preseason preparation to the end of the high season. Finally, the findings indicate that the average quantities of plastic per kilometer identified in Gammarth, Hammamet, and Sousse tourism areas were much lower than those identified in Sfax and Gabès areas, which experience less tourism activity.

In the second phase, a benchmark of the beach litter monitoring results was carried out based on the results of beach litter monitoring campaigns conducted in Germany. The benchmark covers three main indicators - beach litter and related activities, identified plastic fractions on beaches and coastal areas, and the TOP 10 / 15 items identified on beaches in both countries. By analyzing and comparing key indicators such

as the types, sources, and quantities of litter found on beaches, this benchmark process aims to identify the strengths and weaknesses of the Tunisian approach to managing and avoiding beach litter in comparison with the German approach. It also seeks to highlight existing practices that could influence littering behaviors and pollution levels in coastal areas based on both experiences and different contexts.

In the third part of the research, the aim was to conduct a monitoring of the biodegradability of selected tableware items: polylactic acid (PLA), crystallized polylactic acid (CPLA), wood, palm leaf, paper/cellulose and sugar cane bagasse, as well as a common fossil-based plastic polystyrene (PS) as a comparative material in a water column, to determine their possible use as a substitute for single-use plastic flatware in coastal events at three areas at the Warnow estuary at Rostock-Germany in order to reduce marine litter during the coastal events. In situ experiments were performed over a one-year period to consider changes in water temperature, salinity gradients, pH values and dissolved oxygen (DO). The main findings show that tableware items composed of palm leaf, sugar cane bagasse and paper are less resistant to degradation to estuary conditions. However, wood, PLA, CPLA and PS items showed a certain degree of resistance during the experimentation period. Furthermore, items placed in the upper incubators degraded relatively faster than those of the same material but placed in the lower incubators. The results indicate that temperature and exposure to natural light could be important factors in terms of accelerating the degradation of the materials under consideration.

In summary, the results highlight that data and scientifically-grounded information are crucial for informed decision-making in combating marine litter. Identifying key indicators, developing them, and benchmarking against international results are essential for accurately diagnosing the issue, and crafting effective, tailored solutions for coastal litter management.

ZUSAMMENFASSUNG

Marine Litter ist unbestreitbar ein globales Problem, das eine Bedrohung für das marine Umfeld und die Ressourcen des Planeten darstellt. Insbesondere Kunststoffe stellen die größte Bedrohung für Meereslebensräume dar, da sie sich über die Zeit im marinen Umfeld abbauen und lebende Organismen schädigen (Barnes et al., 2009). Dennoch stellt der Mangel an Informationen und Daten bezüglich der Mengen, Quellen und Wege von Meeresmüll eine große Herausforderung bei der Bewertung der Verschmutzung durch Meeresmüll dar – eine Bewertung, die als notwendig erachtet wird, um die Entscheidungsfindung für ein effektives marines Management und die Vermeidung von Küstenschmutz zu unterstützen.

Diese Arbeit befasst sich mit dem Thema Küstenverschmutzung in Tunesien und Deutschland. **Im ersten Teil** wurden die wichtigsten Indikatoren im Bereich der Abfallwirtschaft in Bezug auf Meeres- und Küstenverschmutzung in Tunesien identifiziert, basierend auf Land- und Küstengebieten als Quellen zur Diagnose der aktuellen Situation. Drei Hauptindikatoren und zwölf Unterindikatoren wurden entwickelt und in treibende Faktoren und resultierende Situationen unterteilt, basierend auf (1) einer umfassenden Literaturübersicht und Interviews sowie (2) Feldbeobachtungen von Müll an fünf Stränden von Nord- bis Süd-Tunesien über verschiedene Jahreszeiten hinweg, während eines dreijährigen Zeitraums und unter Verwendung der Konvention zum Schutz der marinen Umwelt des Nordost-Atlantiks (OSPAR). Die Ergebnisse zeigten, dass Kunststoffe die Hauptabfallprodukte in Küstengebieten und an Stränden darstellen (zwischen 54 % und 70 %), wobei Verpackungen als das am häufigsten verunreinigtes Produkt identifiziert wurden, welches zwischen 54 % und 74 % des insgesamt identifizierten Abfalls ausmacht. Es ist bemerkenswert, dass der Großteil des Mülls an Stränden aus Tourismus- und Freizeitaktivitäten stammt (zwischen 89 % und 95 %). Darüber hinaus war die Menge an Abfall während einer tourismusarmen Zeit im Vergleich zum Zeitraum von der Vorsaison bis zum Ende der Hochsaison relativ hoch. Schließlich zeigen die Ergebnisse, dass die durchschnittlichen Mengen an Kunststoff pro Kilometer in den Tourismusgebieten Gammarth, Hammamet und Sousse deutlich niedriger waren, als in den weniger touristisch geprägten Gebieten Sfax und Gabès.

Im zweiten Teil wurde ein Benchmark der Ergebnisse der Strandschmutzmonitoring-Kampagnen in Deutschland durchgeführt. Das Benchmark

umfasst drei Hauptindikatoren – Strandverschmutzung und damit verbundene Aktivitäten, identifizierte Kunststoff-Fraktionen an Stränden und Küstengebieten sowie die TOP 10 / 15 der an Stränden in beiden Ländern identifizierten Abfallprodukte. Durch die Analyse und den Vergleich wichtiger Indikatoren wie der Arten, Quellen und Mengen des an Stränden gefundenen Mülls soll dieser Benchmark-Prozess die Stärken und Schwächen des tunesischen Ansatzes zur Verwaltung und Vermeidung von Strandschmutz im Vergleich zum deutschen Ansatz identifizieren. Darüber hinaus soll er bestehende Praktiken aufzeigen, die das Verhalten von Müllentsorgern und die Verschmutzungslevel in Küstengebieten beeinflussen könnten, basierend auf den Erfahrungen und unterschiedlichen Kontexten beider Länder.

Im dritten Teil der Forschung war es das Ziel, die biologische Abbaubarkeit ausgewählter Einweggeschirr-Artikel zu überwachen: Polymilchsäure (PLA), kristallisierte Polymilchsäure (CPLA), Holz, Palmblatt, Papier/Zellulose und Zuckerrohr-Bagasse sowie ein häufiger fossiler Kunststoff, Polystyrol (PS), als Vergleichsmaterial in einer Wassersäule, um deren mögliche Verwendung als Ersatz für Einwegplastik-Geschirr bei Küstenevents in drei Gebieten des Warnow-Ästuars in Rostock (Deutschland) zu bestimmen, um den Meeresmüll während der Küstenevents zu reduzieren. Die Experimente wurden über einen Zeitraum von einem Jahr durchgeführt, um Veränderungen in der Wassertemperatur, Salzgehaltsgradienten, pH-Werten und gelöstem Sauerstoff (DO) zu berücksichtigen. Die Hauptergebnisse zeigen, dass Einweggeschirr aus Palmblatt, Zuckerrohr-Bagasse und Papier unter den Bedingungen des Ästuars weniger widerstandsfähig gegenüber dem Abbau waren. Holz, PLA, CPLA und PS zeigten jedoch einen gewissen Grad an Widerstand während des Versuchszeitraums. Darüber hinaus verrotteten die in den oberen Inkubatoren platzierten Artikel relativ schneller als diejenigen des gleichen Materials, die in den unteren Inkubatoren platziert wurden. Die Ergebnisse deuten darauf hin, dass Temperatur und natürliche Lichteinstrahlung wichtige Faktoren für die Beschleunigung des Abbaus der untersuchten Materialien darstellen könnten.

Zusammenfassend zeigen die Ergebnisse, dass Daten und wissenschaftlich fundierte Informationen entscheidend für informierte Entscheidungen im Kampf gegen Meeresmüll sind. Die Identifizierung und Entwicklung von Schlüsselindikatoren sowie die Durchführung eines Benchmarks gegen internationale Ergebnisse sind von wesentlicher Bedeutung für eine genaue Diagnose des Problems und die Entwicklung effektiver, maßgeschneiderter Lösungen für das Küstenschutzmanagement.

1. INTRODUCTION

Marine litter refers to any persistent, manufactured or processed solid material discarded, eliminated or abandoned in marine and coastal areas as a consequence of human activities, and is also often referred to as "marine debris" (Galgani et al., 2013). The problem is recognized globally, originating from both developed and developing countries (Lincoln et al., 2022). It stems from various sources and impacts oceans and coastal regions worldwide.

Marine litter, particularly plastic pollution, has become a pressing environmental issue, threatening marine ecosystems, biodiversity, and coastal communities. In Tunisia, like many Mediterranean countries, plastic waste constitutes a significant portion of marine litter due to inadequate waste management systems, inefficient recycling programs, and high plastic consumption. The accumulation of plastic debris in the sea impacts marine life through entanglement and ingestion, disrupts fisheries and tourism, and contributes to microplastic pollution, affecting both marine and human health. Despite efforts to address the issue through legislation and awareness campaigns, significant gaps remain in enforcement, infrastructure, and sustainable waste management practices. Strengthening policies, improving waste collection and recycling facilities, and promoting biodegradable alternatives are essential steps toward mitigating plastic pollution in Tunisia's coastal and marine environments.

This research seeks to examine the coastal litter situation in Tunisian coastal areas and to benchmark in terms of Germany's marine litter situation, policies, practices and measures. The research also analyzes the results of testing alternative items to tableware single-use plastics used in coastal situations in Germany, with the objective of reducing littering. The objective is to discuss current measures and identify potential recommendations for implementation in Tunisia to support the decision-making process.

Marine litter as a global problem

Marine litter, comprising an assortment of discarded materials, has emerged as a pressing environmental concern in recent years. The proliferation of marine litter poses significant threats to the delicate balance of marine ecosystems worldwide (UNEP, 2024). Today, the issue is on the global agenda as the awareness of the magnitude and impact of mismanagement of waste, particularly plastics, has increased (MacLeod et al., 2021), and world leaders, scientists, and communities recognize the need for urgent measures for the sustainability of marine ecosystems (Vince et al., 2018).

Marine litter comprises items made or used by people that are deliberately discarded into the sea, rivers, or on beaches. It also includes debris carried to the sea by rivers, sewage, stormwater, or winds, and materials accidentally lost at sea during bad weather (UNEP, 2024).

A number of studies have reported the accumulation of several forms of marine debris on coastal regions (Bergmann et al., 2017, Galgani et al., 2017, Litterbase, 2024), while ship-based observations have revealed plastic debris accumulation in offshore surface waters (Barnes et al., 2009).

Litter found in the coastal and marine environment ranges from macro-debris such as large industrial containers, plastic bags, drink containers, cigarette butts, and plastic fragments, to small micro-debris including manufactured plastic pellets and micro-beads from consumer items (Thompson et al., 2009). This anthropogenic litter, comprised mostly of plastic, interacts not only with marine megafauna such as seabirds, turtles, marine mammals, and fish, but also with bivalves, lugworms, oysters, and corals (Vince et al., 2016).

Sources of marine litter, both land- and marine-based

Addressing the problem of marine litter requires the need for comprehensive strategies to reduce plastic pollution at its source. Actions should take place at different levels, based on pollution origins, either land- or sea-based (Seyed et al., 2023).

However, land-based sources of marine litter continue to dominate scientific output, public attention and political dialogue. According to the UNEP (2015), land-based sources account for 80% of marine litter, of which approximately 85% is plastic (EEA, 2023).

Our understanding of sea-based sources of marine litter such as debris from fishing, particularly abandoned, lost, or discarded fishing gear (ALDFG), lags behind our knowledge of other sources, both in terms of their levels and of their impact. It is acknowledged that in some contexts the impact of sea-based litter, may be more harmful than other types of marine debris, particularly with regard to ‘ghost fishing’, the entanglement of marine species and acting as a hazard to safety and navigation at sea. Sea-based litter can originate from various sources, including the tourism sector, aquaculture, the shipping industry, and more (GESAMP, 2017).

General effect of marine litter

Marine litter’s overall impact on marine ecosystems is predominantly negative. It can cause entanglement and ingestion hazards for marine animals, alter habitats, release harmful chemicals through degradation, and contribute to ecosystem degradation and biodiversity loss (Werner et al., 2016).

The detrimental effects of marine litter on organisms encompass a wide spectrum of ecological disruptions, ranging from physical entanglement and ingestion to chemical contamination and habitat degradation. Furthermore, as marine ecosystems serve as vital resources for human sustenance and economic prosperity, the repercussions of marine litter reverberate beyond ecological boundaries, underscoring the urgency for concerted action (Andrady, 2017).

Moreover, marine litter can cause economic losses for industries such as tourism, fishing, and shipping. Beaches littered with plastic debris may deter tourists, while lost or abandoned fishing gear (ghost gear) can damage fishing gear, vessels, and marine infrastructure.

The research realized by Mouat et al. 2010 highlights that while the economic impact of marine litter occurs at a local level, action to reduce it must be global. With marine litter originating from many diffuse sources, there needs to be a step change in how the problem is treated at a national and international level. As a starting point, marine litter needs to be regarded as a pollutant on the same level as heavy metals, chemicals and oil, and therefore given the same political credibility.

While it is still unclear, some studies suggest that plastic bags and Styrofoam containers can take up to thousands of years to decompose, contaminating soil and water, and posing significant ingestion, choking and entanglement hazards to wildlife on land and in the ocean (Jambeck et al., 2015). Due to their light weight and balloon-shaped design, discarded plastic bags are easily blown around, eventually ending up on land and in the ocean (UNEP, 2018).

Effect of marine litter on living organisms

The impact of marine debris on marine life is of particular concern, and effects can be wide-reaching, with the possibility of ingestion and entanglement which can be harmful (Gall. et al., 2015) and result in the death of hundreds of thousands of marine mammals and sea turtles worldwide every year. Entangled animals may drown or starve because they are restricted by fishing gear, or they may suffer physical trauma and infections from the gear cutting into their flesh. Entangled animals may also be unable to avoid vessels as they normally would, thus increasing the risk of vessel strikes. Smaller marine animals such as sea turtles, seals, porpoises, dolphins, and smaller whales, may drown quickly if the gear is large or heavy. Entanglement is considered a primary cause of human-caused mortality in many whale species, especially in the case of right whales, humpback whales, and gray whales (NOAA Fisheries).

Chemicals of concern in terms of plastics can impact health and the environment. In fact, extensive scientific data on the potential adverse impacts of about 7000 substances associated with plastics show that more than 3200 of them have one or more hazardous properties of concern. These include chemicals that are persistent and mobile in the environment, accumulate in the body, and which can mimic, block or alter the actions of hormones, reduce fertility, damage the nervous system and, consequently possibly cause cancer (UNEP, 2024).

Furthermore, physical pollution can have wider effects on biodiversity and ecosystem functioning. As a result of the degradation of plastic products and packaging into small pieces, microplastics have been found in the digestive system of many aquatic organisms, including in every marine turtle species and nearly half of all surveyed seabird, together with small fish and invertebrates which can lead to detrimental effects across the food chain (Jambeck et al., 2015).

Continued data monitoring consistently reveals that collisions with macro-sized plastics directly contribute to fatalities among marine mammals, fish, birds, reptiles, and plants (UNEP, 2021). The microplastics can cause physical harm such as blockages and injuries, and also lead to toxicological effects due to the leaching of harmful chemicals such as bisphenol A and phthalates (Rochman et al., 2013). The consumption of microplastics can interfere with feeding patterns, hinder growth and development, and impair reproductive health in marine species, leading to broader ecological consequences throughout marine food webs (Galloway et al., 2017). Furthermore, the presence of synthetic polymers in marine environments has been linked to the accumulation of persistent organic pollutants, which further exacerbate the health impacts on marine wildlife (Andrady, 2011).

Plastics as a dominating item causing marine litter

Plastics are widely used in various consumer products, packaging, and industrial use globally. Due to its versatility, low cost, and convenience, plastics have become ubiquitous in modern society, leading to widespread distribution and potential for littering (Kumar et al., 2021). Plastic is used across almost every sector, including but not limited to producing packaging, in building and construction, in textiles, consumer products, transportation, electrical and electronics and industrial machinery (BPF, 2024).

According to the IUCN, over 460 million metric tons of plastic are produced annually for various applications, with an estimated 20 million metric tons of plastic litter entering the environment each year. This amount is expected to rise significantly by 2040, exacerbating the already severe impact of plastic pollution with regard to land, freshwater, and marine ecosystems (IUCN, 2024). As a major driver of biodiversity loss, ecosystem degradation, and climate change, plastic pollution presents a complex and transboundary issue that demands a unified global response.

In addition, plastics are lightweight and buoyant, making them easily transported by wind and by water currents. Rivers, streams, and storm-water runoff can carry plastic debris from inland areas to coastal regions, where they can accumulate on beaches (Su et al., 2022).

The problem is not limited to macroplastics. It also relates to microplastics (between 100 nm and 5 mm in size), or even smaller nanoplastics (defined as being less than 100 nm). Microplastics are classified as primary (intentionally manufactured to be small) or secondary (degraded from larger plastics) (OC, 2023). Microplastics are found in growing quantities in the ocean. According to the UN, there are as many as 51 trillion microplastic particles in the seas, 500 times more than stars in our galaxy (UN, 2017). They may travel great distances. For example, a special characteristic of many microplastics is their low density (e.g. PE and PP), which may lead to accumulation at or near the water surface where they can be transported by water currents, e.g. from freshwater to the ocean. Because they are lightweight, microplastic particles might be carried by air currents to remote areas (Dris et al., 2016). Additionally, their small size allows microplastic particles to be easily ingested and potentially transferred through food chains from prey to predator (Carbery et al., 2018).

As for chemical contamination, plastics can leach harmful chemicals and additives into the environment, especially under certain conditions such as exposure to sunlight and seawater. These chemicals may include plasticizers, flame retardants, and other additives used in plastic manufacturing. They can bioaccumulate in organisms and transfer through food webs, posing risks to human health and ecosystem integrity (Cole et al., 2013).

The global community has increasingly recognized the urgent need to combat plastic pollution, leading to the development of the Plastic Treaty (UNEP, 2021). This landmark treaty aims to address the pervasive issue of plastic waste through comprehensive international cooperation and stringent regulations. By setting ambitious targets for reducing plastic production and enhancing recycling efforts, the treaty seeks to minimize the environmental impact of plastics on oceans, wildlife, and human health. It also promotes innovative approaches to sustainable packaging and waste management practices.

In turn, plastics can potentially undergo degradation and fragmentation processes under various environmental abiotic conditions, e.g., UV light, pH, salinity, and temperature. These processes will lead to the creation of tinier pieces of plastics known as microplastics which range between 50 µm and 5 mm (Andrady, 2011; Kalogerakis et al., 2017; Wang et al., 2016) making them challenging to detect. Nevertheless, they are abundant in marine environments, contributing to the dominance of plastics in beach litter.

Unlike organic materials such as paper, wood, or food waste, plastics do not readily biodegrade in natural environments. Instead, they undergo photo-degradation and fragmentation into smaller pieces, persisting in the environment as microplastics for extended periods (Baccar Chaabane et al., 2022).

Alternatives to plastics

In recent years, the increase in plastics production has far surpassed the growth of any other manufactured material. The very properties that give plastics their versatility across countless applications also make them challenging or impossible for nature to break down and assimilate. Thus, without a well-designed and tailor-made management strategy for end-of-life plastics, humans are conducting a singular uncontrolled experiment on a global scale, in which billions of metric tons of material will accumulate across all major terrestrial and aquatic ecosystems on the planet. To effectively address the environmental challenges arising from the massive and ongoing increase in global plastics production and use, it is essential to carefully evaluate the relative benefits and drawbacks of various strategies, including dematerialization, substitution, reuse, material recycling, waste-to-energy, and conversion technologies (Geyer et al. 2017).

Monitoring efforts that highlight the dominance of plastics on beaches underscore the urgent need for coordinated action to mitigate marine litter and plastic pollution (Jambeck et al., 2015). This includes implementing policies to reduce plastic production, promoting sustainable alternatives, improving waste management infrastructure, and raising awareness about the environmental impacts of plastic pollution. However, there is a lack of studies on the valorization of marine plastic litter, which is important for advancing the concept of circular economy (Mejjad et al., 2023).

The majority of plastics are non-biodegradable, which means that they do not decompose naturally over time, leading to prolonged environmental effects. Only 10% of the world's plastic landfill waste undergoes recycling, while 12% is subjected to incineration, and a significant 79% finds its way into oceans (EU, 2020). In 2021, only 5.5 million tons of postconsumer recycled plastics were reintegrated into the European economy (Plastic Europe, 2022), which means only one-tenth of the total plastic debris (Narayanan, 2023).

Recent research has focused on materials that can be an alternative to plastic. This refers to all non-conventional plastics including, but not limited to, bioplastics, bio-based, biodegradable, compostable and oxo-degradable plastic. In fact, the terms bioplastics or bio-based plastics are often used interchangeably, though there are differences between them. Bioplastic can be defined as a plastic that is either bio-based or biodegradable, or has both properties (European Bioplastics, 2020), though there are some slightly conflicting definitions.

More precisely, bio-based plastic is made in part or in full from feedstocks other than petroleum products, known as biomass - some form of plant or animal matter. Mostly, bio-based plastics means that it is partly plant based, which may include organic waste or crops cultivated specifically for use as feedstock. For example, sugar cane can be processed to produce ethylene, which is then used to manufacture polyethylene (used for applications such as food packaging) (Plastics Europe, 2018). Bio-based polylactic acid (PLA), polyethylene terephthalate (PET) and polytrimethylene teraphthalate (PTT) made from corn or other biomass can be used to make fibers for textiles (Textile Exchange, 2018). The structure and performance of bio-based plastics is either identical or very similar to that of conventional plastics.

An important term mentioned in this thesis is biodegradable plastics. This is a term that refers to plastics that are capable of breaking down to the basic components of water, biomass and gas, with the aid of microorganisms (SAPEA, 2020). Under appropriate conditions, biodegradable materials can break down either fully or partially into hydrogen, oxygen, and carbon molecules. These plastics can be produced from either renewable (i.e., bio-based) or fossil fuel sources. Their rate of biodegradation depends on the additives used in their manufacture, and the environmental conditions they encounter.

According to recent studies, another material considered to be a good replacement for plastic is “compostable plastics”. This is defined as being capable of undergoing biological decomposition in a compost site, such that the material is not visually distinguishable and breaks down into carbon dioxide, water, inorganic compounds, and biomass, at a rate consistent with known compostable materials (Fauna & Flora International Report, 2022). Compostable plastics can be produced from renewable feedstocks, fossil fuels, or a blend of both. For example, PLA made from a blend of corn starch and petroleum-derived polymers is used to make bags for the collection of food waste (BASF, 2011), with the goal of ensuring that both the bag and its contents can be composted together, and fully decomposed within four weeks in specific industrial environments.

Global efforts to combat marine litter

The first global accounts of plastic debris in the marine environment were reported in the 1970s (Carpenter & Smith, 1972; Carpenter et al., 1972; Cundell, 1974). A brief history of marine litter research reveals that concerns about the potential impacts of marine litter began to emerge in the 1960s. Initially, there were anecdotal reports of entanglement and plastic ingestion, which were followed by scientific publications in the 1970s. These led to a series of meetings on marine debris in the early 1980s which led to a better understanding of marine litter problems and for the generation of possible solutions by the end of the twentieth century (Ryan, 2015). Those early reports offered the initial signs of an awareness of the environmental crisis that was unfolding (Arabi et al., 2023).

The global plastic pollution crisis has prompted significant international dialogue, culminating in the development of the United Nations Plastic Pollution Treaty. Adopted in March 2022, this landmark agreement aims to address the full lifecycle of plastic, from production and design to disposal and recycling. The treaty's goal is to significantly reduce plastic waste and pollution by implementing measures such as improving waste management systems, promoting sustainable alternatives, and enforcing regulations to limit plastic production (UNEP, 2022). This global accord builds on earlier initiatives such as the Basel Convention, which focused on the transboundary movement of hazardous wastes, and represents a comprehensive approach to mitigating the environmental impact of plastics (UNEP, 2021). The treaty reflects a growing recognition of the urgent need for collective action to tackle plastic pollution, emphasizing the role of international cooperation and policy innovation in safeguarding ecosystems and human health (Schäli, 2022).

Coastal Zones: study areas diversification in terms of characteristics and activities

The world's coastal environments feature a diverse array of landforms, varying greatly in size and shape, from gently sloping beaches to steep cliffs. However, these coastal landforms are most effectively categorized into two main types: erosional and depositional (Bird, 2008). The overall characteristics of any coast can typically be described by one of these categories. However, it is important to recognize that both erosional and depositional landform types can be present along the same stretch of coastline (Davis, 2021).

Coastal areas are often the focus of significant government investment due to their attractiveness for tourism and economic development. Therefore, it's important to highlight the importance of these investments and their impact. In a report published by the World Bank (2016), the economic benefits of investing in coastal areas is discussed, emphasizing their role in tourism, fisheries, and trade.

UNEP highlights the need for balanced investment to protect the environment while promoting economic growth. Pollution, particularly plastic pollution, poses a significant threat to coastal areas, impacting ecosystems, human health and economies (Satta et al., 2009).

Plastic litter and the blue economy in Tunisia

Marine litter is a growing environmental issue in Tunisia, significantly impacting its coastal ecosystems and marine biodiversity. Recent studies indicate that Tunisia, like many Mediterranean countries, faces considerable challenges with regard to marine pollution. According to the Tunisian Ministry of Environment, approximately 70% of marine litter in the Mediterranean comes from land-based sources, with plastics being the most prevalent (Ministry of the Environment, 2022).

Plastic waste in Tunisia represents, on average, 9.4% of the household and similar waste generated. Around 75% of the total municipal waste are generated in the coastal governorate, particularly in large cities such as Tunis, Bizerte, Sousse and Sfax (ANGed, 2020). According to the World Bank, the Tunisian coast experiences a daily flow of plastic waste, estimated at 9.5 kg of plastic per km of coast each day, with the main waste fraction being identified on beaches. This research showed that plastic represents the main item identified, with a percentage that varies between 54% and 70% of the total number of items generated (World Bank, 2022(b)).

According to the same reference, plastic pollution represents a significant threat to Tunisia's blue economy. The Tunisian economy suffers a loss linked to plastic pollution estimated at between 170 and 561 million US dollars per year. Plastic also contributes to climate change by emitting greenhouse gases throughout its life cycle. The fight against plastic pollution is therefore part of the fight against climate change, which constitutes a significant threat for Tunisia. According to a WWF report by (Dalberg, 2019), the cost of the estimated impact of plastic pollution on tourism in Tunisia is about $16.6 Million, in the form of $1.7 million on fisheries, $1.6 million on maritime trade, and $4.2 million in terms of the cost of cleanup operations. The same report highlighted that the blue economy loses over $20 million annually due to the effects of plastic pollution (Dalberg, 2019).

Inadequate waste management practices, the excessive use of single-use plastics, and littering contribute to the accumulation of plastics on beaches and the coastal environment in Tunisia, and can consequently lead to growing costs and increasing economic damage.

For many years the Tunisian government has been developing strategies and regulations to fight marine litter and plastic pollution at the national level. Tunisia's efforts to reduce pollution and reinforce the circular economy started early, via the establishment of ECO-Lef, a public system for the recovery and recycling of packaging waste which was created in 2001 and implemented in partnership with the private sector and local authorities. It is regulated by Decree No. 97-1102 of June 2, 1997, setting the conditions and modalities for the recovery and management of packaging bags and used packaging, as amended by Decree No. 2001-843 of April 10, 2001 having, as its legal basis, Article 12 of Law No.° 96-41 of June 10, 1996, relating to waste and the control of its management and elimination. The system focuses on the collection of packaging waste under conditions and agreements with the ANGed, and the recycling of plastic waste under certain conditions and agreements to obtain monthly quotas of materials collected from ANGed.

Recently, Tunisia has developed its National Ecological Transition Strategy (SNTE), which comprises 5 key areas and 53 measures. This strategy involves not only the Ministry of the Environment but also other institutions. It is a strategy that covers all public institutions (at the central, regional and local level) and is also intended to address the economic actors, associations, citizens, etc. One of the 53 key measure of this strategy is measure 31, entitled the "National strategy for circular, global and sectoral waste management", validated on May 16, 2023 by the Council of Ministers. This measure includes 4 components - the National Strategy for integrated and sustainable management of household and similar waste (SNGID-DMA) 2020-2035, the Plan to combat plastic pollution (which in turn includes the Plastic-Free Coastal Strategy – LISP-), the "Tourism and marine litter" program" entitled TouMaLi, and other initiatives suggested by the Ministry of the Environment (TouMaLi, 2022).

In addition to this, a draft decree on "selective sorting" at the national level is being developed by the Ministry of the Environment. In its preliminary version, the project emphasizes that the purpose of sorting household and similar waste at source is to contribute to the establishment of a circular economy through a process of rational waste management. This is an essential preliminary step, involving establishing the compulsory sorting of household and similar waste on the part of their producers and holders, and by organizing their collection operations. Among the crucial aspects mentioned in the project are the reduction in the quantity of waste to be eliminated to a strict minimum, and ensuring that only non-recoverable final waste is sent to controlled landfills. There it is to be converted into economic resources to promote waste recovery and the waste management sector, and to integrate the informal sector into the formal waste management sector.

With regard to the single-use plastics aspect, on January 16, 2020 the Tunisian government published a decree prohibiting the use of single-use plastic bags. This was registered in number 32 of the Official Journal of the Tunisian Republic (JORT) for year 2020. This decree lays down a series of preparatory measures. However, the implementation of this decree faces various challenges, including the adaptation of manufacturers to the new law, and the fight against the informal sale of plastic bags. Since March 23, 2023, the use of single-use plastic bags has also been banned in Tunisian bakeries.

Today, the government of Tunisia is willing to develop the different waste stream sectors, and has started with analyses of the current situation, with the aim of identifying the potential from establishing a new model based on extended producer responsibility (EPR) for potential waste streams, in particular for packaging. In addition, the government is focusing on improving plastic consumption and management in tourist areas by establishing several initiatives in Hammamet (Bemed, 2023), Hammam Sousse (TouMaLi, 2022), Djerba and Monastir.

Germany as benchmark country

Through its extensive experience in waste management, the circular economy and fighting litter, Germany serves as a benchmark due to its significant contribution to these environmental efforts. Research on Baltic Sea beaches reveal high levels of pollution with regard to micro- and meso-litter, predominately in the form of artificial polymers (Winterstetter, 2023). Beach surveys in the North Sea region demonstrate the presence of marine litter, with plastics being the most commonly-found material, originating from sources such as fishery activities in the North Sea and neighboring islands (Haseler et al., 2020).

Additionally, Germany contributes to our understanding of transport patterns of marine litter through the deployment of satellite-tracked drifters in coastal and estuarine systems, showcasing a low-cost and robust design for studying the complex pathways and dynamics of floating litter (Unger et al., 2021).

The OSPAR method was employed for beach litter monitoring in Germany. This method involves various approaches and considerations focusing on macro-litter (> 25 mm) but showing limitations in dealing with smaller litter classes (<25 mm) in the Baltic Sea beaches (Haseler et al., 2018).

Moreover, Germany has taken several measures to improve waste management, introduce a circular economy and avoid marine litter, such as a ban with regard to single-use plastic bags, the development of a deposit system for PET bottles and cans, warning and disposal instructions for single-use plastic products since July 2021, reinforcing and financing the cleaning of streets and beaches, ensuring more recycling of plastic packaging, incentivizing environmentally-friendly packaging, creating plastic from recycled products and ensuring 97% less microplastics in cosmetic products.

Finally, considering the current context in Tunisia, there is a need to reinforce the decision-making process in such a way as to provide sustainable and adapted solutions to avoid coastal and marine litter. For this purpose, it has been necessary to develop a beach litter monitoring campaign in different areas in Tunisian coastal areas to determine the composition of the waste in different points from the North to the South. In addition, an analysis of the different indicators impacting the coastal litter situation in the country has been carried out.

The results of the beach litter monitoring campaign have also been compared with the results of the campaign carried out in recent years in the Baltic Sea beaches in Rostock in Germany, in addition to identifying the primary measures and policies aimed at preventing marine litter.

This study also analyzed the effectiveness of various alternatives to tableware single-use plastic items. For these, an in-situ assessment combined with a laboratory experiment was carried out to analyze the degradability of some alternatives to replace some selected single-use plastic items in the main events in Rostock.

To address the existing knowledge gaps, and to identify possible future measures for dealing with marine litter, the following hypotheses are formulated:

Hypothesis 1

The identification and development of key indicators for marine litter will enhance the effectiveness of management recommendations, leading to reduced litter levels.

Hypothesis 2

The amount and composition of marine litter in a region will correlate with existing regional and national regulations, indicating that prevalent terrestrial sources significantly influence litter characteristics, despite potential long-distance transport in marine environments.

Hypothesis 3

Alternative materials for single-use items, designed for faster decomposition at landfills also exhibit faster degradation under marine and brackish conditions

To prove the validity of these hypotheses, a combination of field observations as well as laboratory experiments were conducted, details of which will be outlined and discussed in the following sections.

2. MATERIALS AND METHODS

Marine litter and plastic pollution represent a major environmental issue affecting marine ecosystems and biodiversity (Jambeck et al., 2015). The focus on coastal areas and beaches in this study is driven by several key factors. Firstly, coastal regions are often densely populated and serve as centers for tourism, recreation, and commerce, resulting in higher levels of waste generation and the possibility of mismanagement, which can contribute to marine litter. Secondly, coastal zones act as critical interfaces between land and sea, making them primary recipients of terrestrial waste that can be easily transported to the ocean through rivers, streams, storm drains, and direct dumping. Lastly, coastal areas are of significant economic importance due to their roles in fisheries, tourism, and transportation, all of which can be adversely affected by marine litter. For instance, litter on beaches can deter tourists, leading to economic losses for coastal communities. Similarly, marine debris can damage fishing gear and boats, affecting the livelihood of fishers.

This work focuses on the following aspects:

- Indicator identification and development,
- Beach litter monitoring in Tunisian coastal areas,
- Benchmark analyses involving German coastal litter monitoring results,
- Decomposition behavior of biodegradable and single-use tableware items in the Warnow Estuary (Baltic Sea) in Germany.

Figure 1 summarizes the methodology of the research:

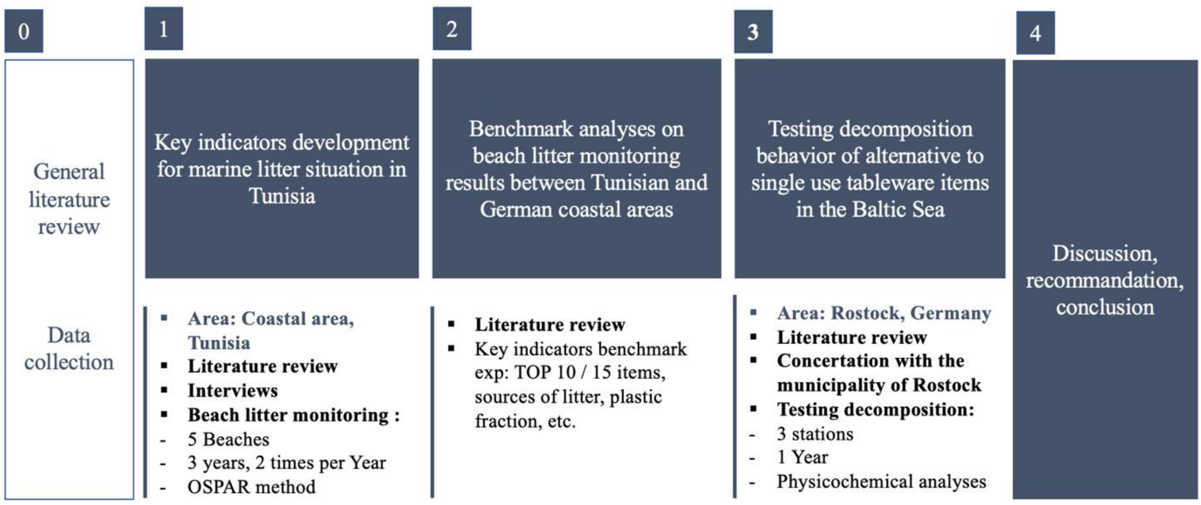

Figure 1. General outline of the methodology to be applied

2.1. Marine litter monitoring in selected Tunisian beaches

2.1.1. Description of the study areas

The study was carried out on five beaches across five cities in Tunisia, representing approximately 5% of the country's total coastline. Given the large number of beaches, a selective approach was adopted to ensure the results were representative while maximizing geographical coverage from north to south. The selection prioritized accessibility and considered variations in beach activities to enhance the study's relevance. The Tunisian coastline is 1670 km in length, of which 575 km consist of sandy beaches (APAL, 2013). Going from the north to south, the study beaches are as follows: Gammarth (Governorate of Tunis), Hammamet (Governorate of Nabeul), Sousse (Governorate of Sousse), Sidi Mansour (Governorate of Sfax), and Gabès (Governorate of Gabès), as shown on the map in Figure 3.

Furthermore, and to better understand the work approach, an illustration of the methodologies adopted for section 2.1 and section 2.2 is given in Figure 2.

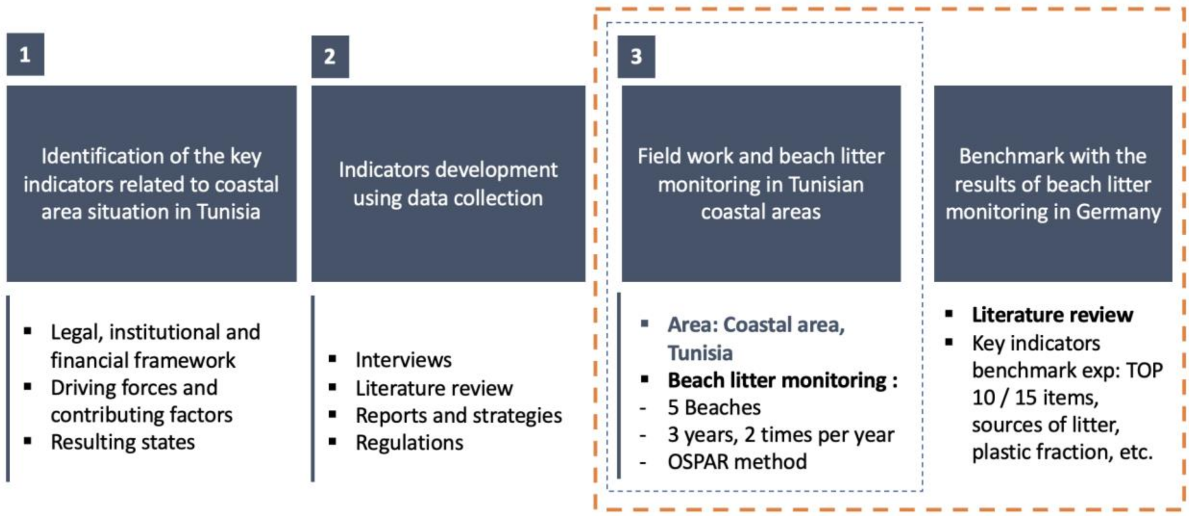

Figure 2. Illustration summary of methodologies for field work in Tunisia as well as the benchmark with Germany (Sections 2.1 and 2.2)

In this study, the OSPAR - 100 meter - method was applied (OSPAR, 2010). Following the criteria defined, the beaches must consist of sand or gravel, be open to the sea, accessible to a team of workers throughout the year, possess a minimum length of several hundred meters, remain devoid of permanent structures year-round, and not be subject to any other litter collection activities such as beach cleaning prior to the sampling campaign.

Before starting the sampling campaign, cities and areas were selected according to the different parameters highlighted in Table 1:

Table 1. Criteria for the beaches selected for the OSPAR 100 m method

Criteria	Description
Abundance of litter	Ideally, the selected sites should represent the extent of litter abundance and composition for a given region. Not all coastal sites were appropriate as they may be limited in terms of accessibility, suitability for sampling (sand or rocks/boulders), and beach cleaning activities.
Length of the beach	A minimum length of 100 m.
Accessibility	Clear access to the sea such that marine litter is not screened by anthropogenic structures. In addition, the site should be accessible to the survey team all year round, although some consideration had to be given to sites that are iced-in over in winter and the difficulty in accessing very remote areas.
Area	Low to moderate slope (15–45◦).
Activities in the area	The location should remain unaffected by other litter collection activities such as cleaning operations.
Species protection	Sampling activities should be conducted so as not to impact any endangered or protected species such as sea turtles, sea birds or shore birds, marine mammals, or sensitive beach vegetation; in many cases, this would exclude national parks, but this may vary depending on local management arrangements.

The following figure 3 shows the cities selected for sampling beaches which are well known for their economic activities, encompassing tourism, fishing, and diversified industries. It is also important to mention that each selected station belonged to one of the 13 coastal governorates from a total of 24 governorates.

Figure 3. Location of the sampling stations in Tunisia's coastal areas

The monitoring was done at different times of the year and using OSPAR monitoring method for 100 m. Each station has the following different characteristics:

- **Gammarth**: belongs to Tunis governorate. Situated on the gulf of Tunis and is known as a business - tourism destination since many hotels are located on this part of the coast.
- **Hammamet**: belongs to the governorate of Nabeul. Also, an area that attracts tourists from all over the world as it is well known for its tourist activities, events and the diversity of hotels (104 hotels) located on this part of the coast.
- **Sousse**: is a touristic city that belongs to the governorate of Sousse. It is situated in the southern part of the Gulf of Hammamet. The city its internationally well-known due to its mass tourism activities, in particular during the summer period.
- **Sfax (Sidi-Mansour)**: the sampling station is located in the governorate of Sfax. It is located in the middle of Tunisia, known for its intensive industrial activities. The sampled beach is an artificial one.
- **Gabès**: the sampling station is located in the southern part of the governorate of Gabès. The city represents the only coastal oasis in the Mediterranean, and is surrounded by sand beaches. This area is well-known for its industrial activities with a limited amount of

tourism.

2.1.2. Description of the beach litter monitoring methodology

In order the qualify and quantify the amount of litter on the selected beaches in the coastal areas of Tunisia, the OSPAR monitoring protocol was adopted (OSPAR, 2010). This methodology is standardized to ensure comparability of data across different regions and times. This includes predefined survey areas and detailed categories for litter items. These categories relate to various types of litter such as plastics, metals, paper, rubber and wood.

The collected data from the different sampled stations of Tunisia is analyzed to identify trends, sources, and hotspots of marine litter. This information is critical for developing targeted interventions. It is defined as a standard method involving software useful for the statistical analysis of beach litter data (Schulz et al., 2017).

The samples collected from each sampling location made it possible to collect all fractions of waste as well as all types. The choice of sampling locations was based on selected criteria, as highlighted in Table 1.

On-site, the monitoring focused on 100-meter stretches of beach encompassing the entire area from the seafront to the back of the beach. Initially, all visible items were collected by hand. Subsequently, the OSPAR guide was used to aid in the identification and classification of litter items. Most of the collected litter fell into the macro-litter category, with sizes above 2.5 cm. However, smaller meso-litter particles (0.5–2.5 cm) were also partially included.

2.1.3. Data collection and indicator development

Following a literature review, based on existing documents, studies and reports, the current situation of marine litter in Tunisia was analyzed in order to identify suitable indicators. This assessment covered selected coastal cities and governorates in Tunisia, considering most of activities that might generate waste.

To obtain precise information about marine litter in the Tunisian coastal area, various indicators were developed (see Table 2) and were classified into legal, institutional, and financial frameworks, driving forces and pressures, and resulting states. Each indicator provides insights into the current situation and enhances the decision-making process.

Table 2. Indicators related to marine litter in Tunisian coastal areas

Indicators	**Description**
Legal, institutional, and financial framework	This indicator provides a comprehensive structure for managing waste and addressing marine litter in Tunisia's coastal areas, ensuring coordinated efforts and sustainable practices.
Driving forces	Driving forces refer to the underlying causes and contributing factors that lead to the presence of marine litter in coastal areas. By identifying and analysing these driving forces, it becomes possible to understand the sources of marine pollution (from land-based activities or on the beaches and coastal zones) and to develop targeted strategies for mitigation.
Pressure and resulting states	As result of the previous indicators, the main required findings are: - Focus on plastic litter fractions on beaches. - Identification of the top 10 plastic items. - Sources of different litter: land- and ocean-based sources of litter. - Quantity of plastic litter: measuring the amount of plastic materials along a 1 km stretch at each sampling station in the coastal areas of Tunisia. - Percentage of packaging litter composed of plastic in the sampling areas.

2.2. Benchmark of the beach litter monitoring between the Tunisian and German beaches

The benchmark analyses focused on the results of beach litter monitoring in German coastal areas over recent years, employing the OSPAR 100-meter method. The primary objective of this benchmark study was to understand the differences in litter presence between Tunisian and German beaches. By using the OSPAR method, the study aimed to provide a detailed comparison of litter types, quantities, and distribution patterns. The indicators subject to the benchmark are as follows:

- Identified plastic litter fractions on beaches;
- Identified top 10 / 15 plastic items;
- Sources of different litter: land- and sea-based sources of litter;
- Number of litter items per 100 m

The same sampling and monitoring methodology was adopted on selected beaches along the coastal zone of Tunisia.

2.3. Decomposition behavior of biodegradable and single-use tableware items in the Warnow Estuary in the Baltic Sea

In collaboration with the municipality of Rostock, different tableware items were provided for testing in the water. The aim is to reduce tableware single-use waste that ends up in the sea or among others the Warnow estuary during the events organized in this location. In order to better understand the work process, Figure 4 summarizes the different aspects of the methodology that was used.

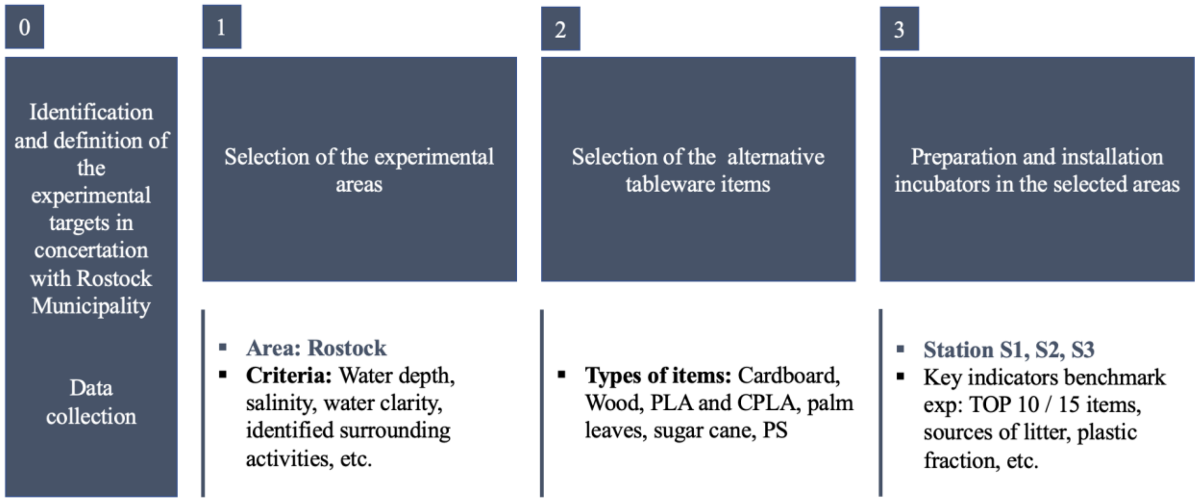

Figure 4. Diagram summarizing the methodology for testing the biodegradability of tableware items in the Warnow estuary.

The samples considered for these experiments are commercialized and used at some coastal events (festivals, markets, street-food events, Hanse Sail, etc.) in Rostock and were selected by the Municipality of Rostock to test possible sustainable solutions. Documentation with the description and the characteristics of each sample was collected. The selection of the study area was based on some specific criteria:

- Water depth: The depth of water in marine and freshwater environments significantly impacts various ecological, chemical, and physical processes. In terms of the ecological effect, depth affects light penetration in that it decreases with increasing water depth, affecting photosynthesis in aquatic plants and phytoplankton. Water temperature often decreases with depth, leading to the formation of a thermocline; a layer where the temperature changes rapidly. This stratification can impact nutrient mixing and the distribution of marine organisms (Mann et al., 2013). As for the chemical effect, this includes oxygen levels. Oxygen concentration generally decreases with depth due to reduced light penetration and photosynthetic activity, leading to hypoxic or anoxic conditions in deeper waters. The IUCN (2019) reports that the ocean's oxygen content has declined by approximately 2% since the 1950s and is projected to decrease by another 3–4% by 2100, posing significant threats to marine biodiversity, fisheries, and ecosystem stability. Furthermore, upwelling and mixing processes transport nitrogen and phosphorus from deeper waters to the surface, enhancing primary productivity, as observed in the East China Sea (Wei et al., 2024) and through mesoscale eddy-driven nutrient transport (Marshall et al., 2023). Finally, water pressure increases with depth, and deep-sea organisms have evolved specialized adaptations such as flexible skeletal structures and cellular chemicals to survive extreme pressures (Notre Dame University, 2024; University of Leeds, 2024). In addition, water temperature decreases with depth, often reaching near-freezing levels, while thermoclines, influenced by seasonal and environmental factors, create rapid temperature shifts in the ocean (Stewart, R. H. 2024; lumen.learning, 2025). Besides, many marine species exhibit vertical migration, moving up and down the water column daily to feed and avoid predators, influenced by light and depth. In addition, and regarding the human impact, depth-related factors must be considered in activities such as deep-sea mining, fishing, and waste disposal to mitigate the environmental impact.

- Salinity, the concentration of dissolved salts in water, can vary significantly with depth in marine environments. This variation affects many ecological and chemical processes, including the biodegradability of organic materials. High salinity can inhibit the activity of non-halophilic microbes, reducing overall biodegradation rates in environments where these organisms predominate (Ventosa et al., 1998).
- Access to the research station is a crucial criterion for ensuring the safe and effective conduct of experiments, as well as for monitoring the materials installed in the water. Easy access to the stations where the incubators are suspended is essential for continuously tracking the water's physicochemical parameters and to allow cleaning the incubators to remove impurities that could obstruct water circulation.
- Water clarity, or transparency: this refers to how much light can penetrate a water column. It is influenced by factors such as the presence of suspended particles, dissolved substances, and biological activity. Water clarity typically decreases with increasing depth due to the attenuation of light by different factors. In shallow, clear waters, light availability supports

phototrophic microorganisms (e.g., algae, cyanobacteria) which contribute to biodegradation through photosynthesis and the production of organic matter (Azam et al., 1983). Deeper waters with reduced clarity rely on heterotrophic microorganisms that degrade organic matter without sunlight. Biodegradation rates can be slower due to lower temperatures and reduced oxygen levels at greater depths (Jørgensen et al., 2007).

- The identification of the surrounding activities of the experimental area is an important aspect to note. At the Warnow Estuary in the city of Rostock, several activities occur all the year round, and especially during summer. Activities include, but are not limited to, shipping and port activities, fishing, tourism and recreation, industrial activities, agriculture and urban development.

The incubators were set up in accordance with the research protocol. They were periodically maintained to ensure cleanliness and proper operation throughout the experiments. Additionally, the degradation rate (DR) of the items was monitored alongside the water's physicochemical parameters.

2.3.1. Description of study sites and incubator installation

The incubation of different samples took place in the Warnow River estuary splitting Rostock city, which is located in the German Federal state of Mecklenburg-Western Pomerania on the Baltic German coast (Lange et al., 2015).

In order to run the experiments in different conditions, three different stations were chosen in which to hang the incubators. The stations were named according to the locations respectively from North to South along the Warnow River estuary as follows: S1. Hohe Düne, S2. IGA Park and S3. Gehlsdorf.

The left part of Figure 5 shows the exact location of each chosen station on the map. The right part shows where the incubators were hung.

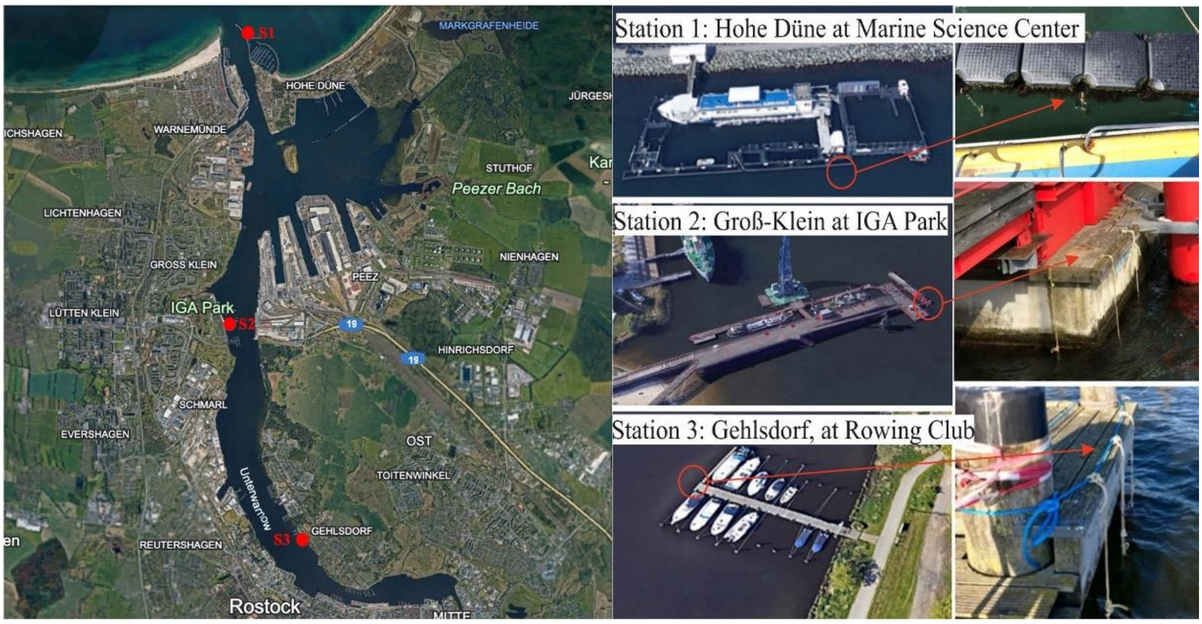

Figure 5. Location of selected stations S1, S2 to S3 in the Warnow River estuary at Rostock City in addition to the incubators hanging in the water column

The geographical location and some characteristics, as well as the incubators emplacement are detailed as follows:

- S1 is at the Marine Science Center in the Marina of Hohe Düne right on the Warnow's east breakwater. The water depth is 5 meters and the incubators are hung on plastic floating buoys which surround the seal and penguin cages. The exact geographic coordinates are 54_11002.4''N,12_05043.4''E.
- S2 is at the IGA Park located at Schmarl Dorf, known for a range of different activities. The water depth is approximately 4 meters and the incubators were hung at the extremity of a platform. The exact geographic coordinates are 54_08027.4''N,12_05021.2''E.
- S3 is at the rowing club opposite Rostock City. The water depth is approximately 3 meters and the incubators were hung at the extremity of the dock where many boats were present year-round. The exact geographic coordinates are 54_05047.8''N,12_07054.1''E.

The coastal area of the Warnow River estuary is divided into different sections: shipping industries, Rostock ports, waste industries, other industries, tourism and recreation, beaches, green areas, reed belts, local transport ferry and military areas.

2.3.2. *Incubator preparation*

To ensure a secure placement of the experiments in the water column, it was essential to develop a specially-designed and rigid tool that ensured the natural circulation of the water and the contact with the product. Therefore, incubators were designed and constructed within the workshop of the Leibniz Institute for Baltic Sea Research (Oberbeckmann et al., 2018).

1. Incubator before assembly
2. Incubator after installation of the mesh
3. Incubator after fixing the metal rings and side bars
4. Incubators at final stage : fixed to ropes and hung in water

Figure 6. Steps of assembling an incubator ready to use in testing the biodegradable items

The incubators were made of a circular hard plastic cage (the black part in the photograph) and a 2 mm mesh size plastic net which was used to build the walls of each incubator. The mesh size allowed good water circulation, which is considered an important mechanical parameter. The assembly of the incubators, as well as their installation in the water, is documented in the photographs in Figure 6.

2.3.3. *Used tableware items*

The tableware items provided range in size, shape, color and density. They were made of PLA, CPLA, palm leaf, sugar cane bagasse (bleached/unbleached), wood, paper/cellulose and single-use fossil-based conventional plastics (PS). Some examples of the tableware items used are presented in Figure 7.

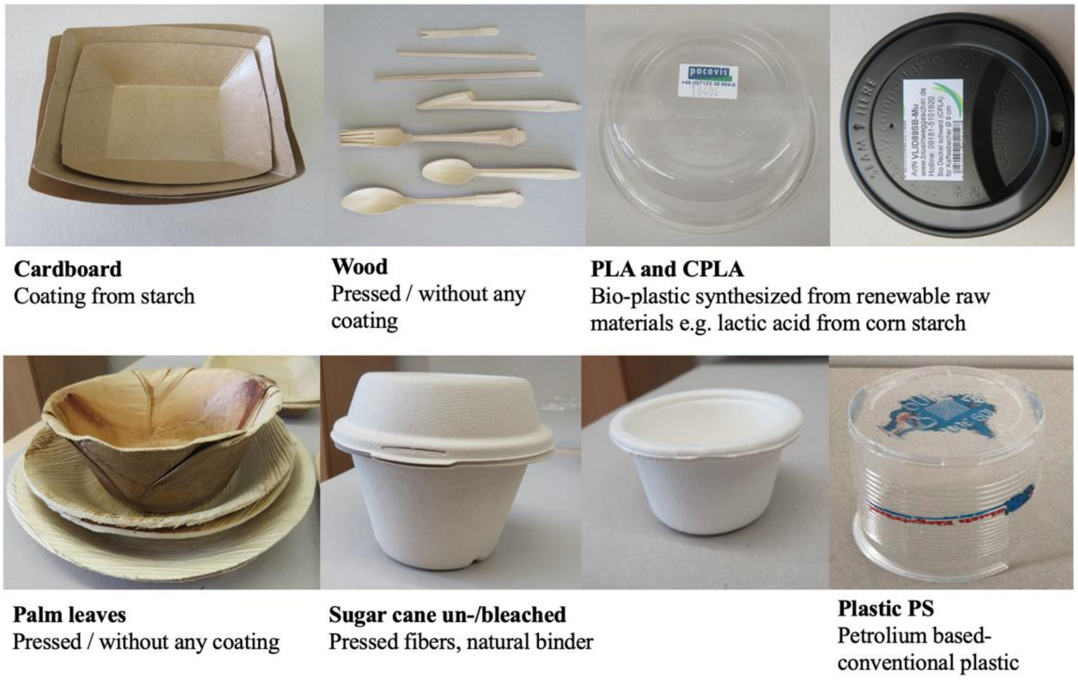

Figure 7. Used tableware items for the test experiments

According to the technical file relating to the items used for the experiments:

- PLA or polylactic acid is a biodegradable polyester which is very versatile and is derived from 100% renewable resources (Dumright et al., 2009). It is produced from corn, starch and sugars (Fukushima et al., 2004; Timbuktu et al., 2006). It has a density value of between 1200 and 1450 kg/m3, and is used for packaging food products given its high permeability to water (Alaerts et al., 2018). According to Ohkita et al., 2006, soil burial tests show that the degradation of PLA is slow, and that it takes a long time for degradation to start. For instance, no degradation was observed on the material sheets after 6 weeks in soil. CPLA or crystallized polylactic acid is obtained through sugars and corn starches. When producing PLA, lime is added. The material then becomes crystallized and resistant to heat.
- CPLA, when used for tableware, is considered to be a bioplastic. In a natural environment such as soil, it starts to degrade in 5 to 6 months, with complete decomposition after 12 months. If composted with food garbage, it begins to decompose after 2 weeks (Popa et al., 2011).
- The plates and bowls were made from discarded and pressed palm leaf from the "Adaka" nut palm. Depending on the source of the palm leaf used, its density is between 0.7–1.55 g/cm^3 (Pradeep et al., 2015).

- The sugar cane bagasse products used in these experiments are derived from the extraction of sugar from the cane's biomass (fiber), which is typically incinerated. The density of sugar cane is 1.20 g/m^3 (Wahid et al., 2019).
- Paper is composed of lignocellulose. The density of paper is 700 kg/m3 according to Sonntag et al. (1998). The product's technical file indicates that the cardboard cups are made from pure cellulose. To enhance moisture resistance, the interior of the cardboard is coated with a starch film.
- Wood packaging is mainly used for the transportation of goods and is mainly made of cellulose (Mudgal et al., 2012). The wooden tableware used was made or punched from birch wood using a pressing process, having a density of 623 kg/m^3 (Dobrowolska et al., 2020). No additional coating or surface treatment is applied.
- Polystyrene (PS) is a synthetic hydrophobic polymer with a high molecular weight and a density of 1060 kg/m^3 (NIST, 2020). It is recyclable but not biodegradable, and it remains solid at room temperature. Polystyrene, a clear, rigid plastic, is often used for disposable tableware (Tokiwa et al., 2009).

The tableware items were cut into small pieces to fit into the incubators, where they were weighed and measured. For each item, a sample was placed in an upper incubator (exposed to more sunlight and pelagic organisms) and a lower incubator (closer to the bottom, with less sunlight and more demersal organisms).

In total and at each station, 12 incubators were placed in the water in 3 groups of 4 incubators and were attached to ropes. They were hung from the top and fixed with chains to the bottom as shown in Figure 8. Regarding the label attributed to each incubator, and as an example, at station S1, paper samples were divided into two fragments, one in the upper incubator (U), hence labelled M.1.1.U, and the other in the lower one (D) and labelled M.1.3.D.

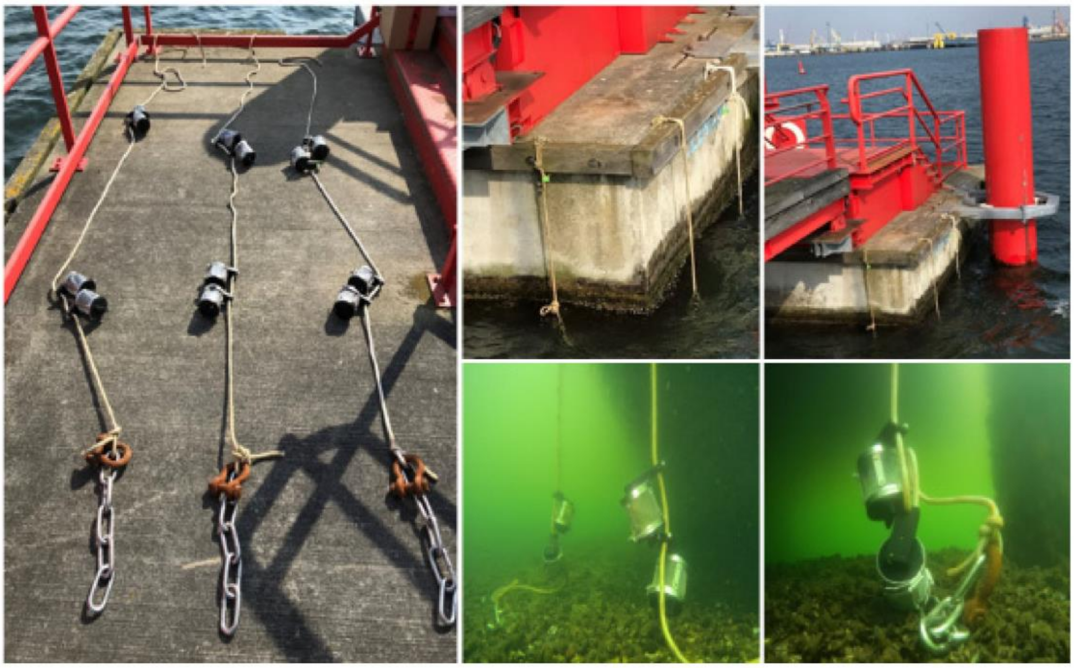

Figure 8. Preparation and installation of the attached incubators to ropes

The incubators were installed at a precise spot at each station in order to ensure easy access for parameter monitoring and incubator opening. The ropes were attached at each station into different boarders. The experiments started at the same time in order to undertake the experiments in the same weather conditions.

2.3.4. Parameter monitoring tools

In order to obtain the required data regarding the measurements of DO, temperature, pH and salinity, specific tools were used involving cables and measuring device from the Hach HQD digital multimeter which combines reliability, flexibility and ease of use. The devices used for measurement in the water are the Premium Field Kit for Environmental Monitoring with a 5 m Cable and a CTD48M gear. The kit is composed of an HQ40D Portable pH, Conductivity/TDS and Dissolved Oxygen Meter.

The monitoring of these parameters followed a specific schedule: initially, measurements were taken two to three times per month. Towards the end of the experimental period, the frequency was reduced to once or twice per month, depending on equipment availability and access to the stations.

3. RESULTS

3.1. Marine litter monitoring in selected Tunisian beaches

3.1.1. Key Indicators: solid waste management and marine litter in Tunisia

3.1.1.1. Main solid waste management practices in Tunisia

The amount of solid waste in Tunisia is increasing in line with the growing population. The waste generation is increasing at a rate of 2.8% per year (ANGed, 2018). According to ANGed, the average waste production is around 0.8 kg per inhabitant per day, with significant disparities between urban and rural areas. According to ANGed, landfilling is the predominant method for the disposal and treatment of solid waste in Tunisia, accounting for 95% of the total. However, only 5% of the generated waste is recycled or composted. Plastics represents 9.4% of the total waste generated. According to the WWF (2019), Tunisia released 8,500 tons of plastic into the Mediterranean in 2016, with 33% of it washing back ashore within a year. The World Bank highlight that the annual quantity of poorly-managed plastic waste has been estimated at 55.5 kt per year and the amount of plastic deposited in the sea is estimated at around 17 kt/year (World Bank, 2022(b)).

The collection systems implemented by municipalities typically adhere to a uniform pattern: bins are used for mixed waste, as there is no practice of separating waste at the source. Source-based waste separation is only implemented in a few specific areas and municipalities with a very low quality of segregation. According to ANGed, the municipal waste collection rate across Tunisia is almost 84%. Since 2018, the entire Tunisian territory, including the rural areas, is covered by municipal services, especially the waste collection service, as waste management has become a devolved competence that is managed by the local authorities. Currently, Tunisia has nine operational sanitary landfills and fifty-six transfer stations. However, a number of landfills and transfer stations have been closed for a number of technical or social reasons.

The processing of specific materials in Tunisia depends significantly on informal waste pickers who gather recyclable and valuable materials from mixed waste and from landfills. The informal sector is instrumental in facilitating waste sorting and recycling activities. Referring to ANGed, about 4% of the total waste generated is recovered as recyclable materials including polyethylene terephthalate (PET), polyethylene high-density (PEHD), and metals. Waste pickers sort and collect these materials from street waste containers as well as landfills and dumpsites. According to ANGed, waste pickers ensure the collection of 80% of collected recyclable materials.

The national system for the collection and recovery of used packaging, known as ECO-Lef, serves the public in facilitating the recovery and reclamation process. This initiative is carried out by small companies that are approved and authorized by ANGed. These companies purchase materials from informal collectors, commonly referred to as “Barbechas”, and compensate them directly based on the weight of the materials. The collection companies sell the collected amounts to ANGed. At the ECO-Lef points, materials are collected, registered, compacted, and prepared to be sold to recycling companies. However, many ECO-Lef points have been closed due to logistical problems and disagreement with local authorities, and quantities collected by the system have decreased considerably in recent years.

3.1.1.2. Financial framework

Financial factors play a crucial role in developing an effective and sustainable approach to tackling marine litter issues in coastal areas of Tunisia. The financial framework related to such marine litter is closely linked to the solid waste management system, which is mainly funded by the government via local authorities. The primary sources of funding are:

- The government through the national budget or via the depollution fund managed by the Ministry of Finance, which covers the financing of 80% of the landfilling costs and the financing of different waste flow systems operations;
- A percentage of 1% of the hotel’s turnover per year is paid to the municipality, and 1% to the tourism protection fund. The tax does not cover the waste management and cleanliness issues only, but also provide other services such as security and lighting in the tourist areas.
- The producers of packaging in the case of the national system for ECO-Lef packaging, who place packaging goods on the Tunisian market, should contribute financially through an annual contribution to the ECO-Lef system. However, ANGed reports that only around 4% of packaging producers in the Tunisian market, including those dealing with plastic packaging, contribute to the public system.
- Importers of products on the Tunisian market participate financially in terms of imports by paying 7% of their turnover to the Ministry of Finance to finance the depollution fund. The Ministry is then responsible for distributing the funds in accordance with the government program.

3.1.1.3. Legal framework

From a legal standpoint, the solid waste management sector in Tunisia is primarily governed by two framework laws: the first is Law No. 96-41, enacted on June 10, 1996, which addresses waste management and its regulation and the second pertains to the local government code of 2018.

Law No. 96-41 defines the overarching philosophy of waste management and its implementation methods, guided by three key principles: waste reduction, recovery of valuable materials, and landfilling of unrecoverable waste.

The local authorities code of May 9, 2018, outlines responsibilities for waste management, stating that the collection, sorting, and transportation of household and similar waste to controlled landfills are the responsibility of municipalities. Additionally, central government is obligated to provide necessary environmental infrastructure, such as controlled landfills.

Regarding packaging waste and plastics, Tunisia has established the ECO-Lef system, a specific framework for the collection, treatment, and valorization of packaging materials. The Tunisian government is today working to develop regulations for several waste streams such as E-waste, textiles, glass, paper, cardboard, by designing and putting in place extended producer responsibility (EPR).

3.1.1.4. Institutional framework

The current institutional framework related to marine litter in Tunisia involves several actors, each of whom have different responsibilities and influence on the sector. In this study, these different responsibilities are classified according to the institution involved:

- Institutions related to waste management,
- Institutions with marine litter activities,
- Other institutions with indirect relations to marine litter.

Institutions related to waste management

Solid waste management requires the involvement of public entities at both national and local levels, as well as the private sector. Numerous organizations and institutions play an active role in this area. The interactions between the different stakeholders are represented in Figure 9.

At the national level, the Ministry of the Environment and ANGed have a direct link to the topic due to their relationship with the solid waste management sector. ANGed is the national waste management operator in charge of waste transport from the transfer stations to the landfills, the management of the landfills, and the treatment of leachate through private operators. It is also tasked with providing the necessary infrastructure, such as transfer stations, landfills, and other treatment facilities. Additionally, ANGed oversees the operation of various waste stream systems, including packaging.

At the local level, municipalities are the first responsible bodies for solid waste management collection and street and beach cleaning in the territory. They are responsible for collecting and transporting mixed waste to transfer stations. As part of the decentralization process, the number of municipalities has increased to 350 to ensure coverage across the entire country.

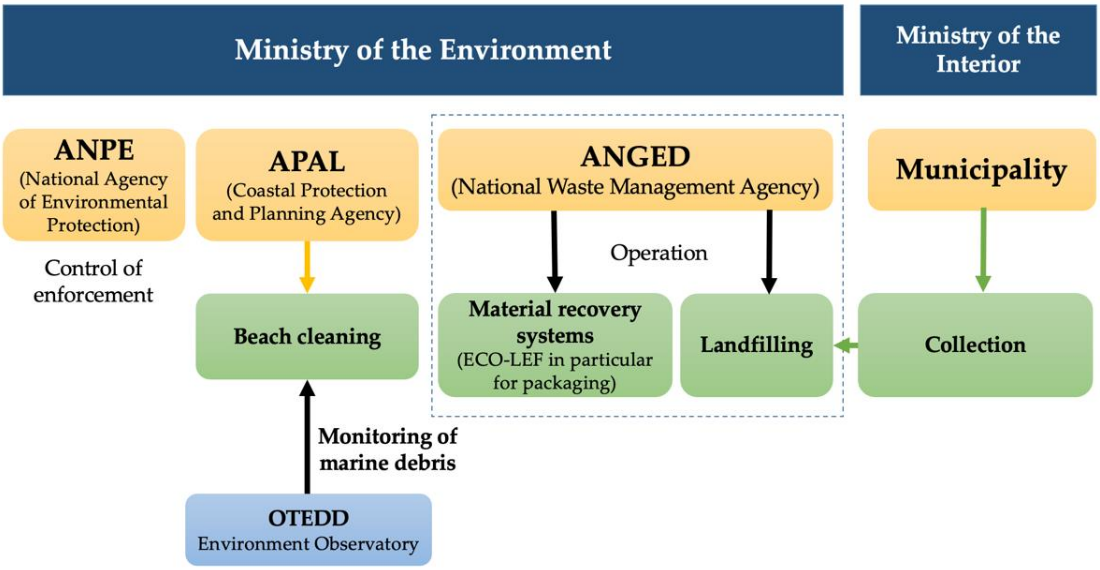

Figure 9. Legal responsibilities of the main institutions related to solid waste and marine litter

Other institutions are also involved, including:

- The National Agency for the Protection of the Environment (ANPE). This agency is responsible for overseeing the adherence to waste management regulations on the part of institutions, citizens, and industrial entities. It has the authority to prosecute and impose penalties on offenders.
- Coastal Protection and Planning Agency (APAL) is a non-administrative public institution created by Law no. 95-72 promulgated on 24 July 1995. APAL is tasked with executing state policy regarding coastal protection and development, as well as safeguarding the maritime public domain from illegal encroachment and occupation. It is

also tasked with giving its approval to any development and equipment project on the coast prior to its execution. These duties exist within the framework of consultation with the stakeholders. APAL ensures, in consultation with the coastal municipalities, beach cleaning operations.

- The International Center of Environmental Technologies of Tunis (CITET) provides technical assistance to help companies better manage their waste and implement environmental management, training, and information systems.

Institutions contributing to the mitigation of marine litter activities

A number of institutions in Tunisia were created with a specific task related to marine litter, including but not limited to:

- The General Secretariat for Maritime Affairs: a position, filled for the first time, in accordance with Decree no. 2019-144 of 18 February 2019, creating a Ministerial Commission and a General Secretariat for Maritime Affairs;
- The Tunisian Observatory for the Environment and Sustainable Development (OTEDD) constitutes the basis of a permanent mechanism for the observation, collection, production, analysis, management, and dissemination of information on the condition of the environment and sustainable development, to support decision-making.

Other institutions indirectly related to the mitigation of marine litter

Alongside the institutions previously mentioned, several other stakeholders play a role in addressing the issue of marine litter management:

- The Ministry of Finance ensures the collection of eco-taxes and participates in solid waste management financing, particularly the financing of part of ECO-Lef activities and other waste stream systems, and financing 80% of the waste treatment in landfills.
- The Ministry of Public Health, for its part, monitors and manages waste from healthcare establishments and assesses the health impacts of products.
- The Ministry of Industry, Energy and Mines (MIME) is responsible for the development of sectoral strategies, programs, and national guidelines to support the sector and the development of policies and adequate legislation including (i) the optimal exploitation of resources, (ii) incentivizing innovation and the encouragement of scientific research and its development, and (iii) establishing and facilitating discussions and consultations with

all government and parliamentary bodies, authorities, the private sector, and civil society on issues related to energy and mining resources.

- The Technical Center for Chemistry is responsible for carrying out diagnostic studies aimed at determining the strategic choices and the material and non-material resources required. The Center is also tasked with evaluating companies' circumstances and pinpointing areas where improvements can be made with regard to technology, organization, environmental compliance, and occupational safety.
- The Packaging Technical Center (Packtec) performs physio-mechanical and chemical analyses and tests on various materials, as well as physical, mechanical, and optical tests and barrier properties using high-tech equipment to control the quality of plastic packaging.
- The Ministry of Agriculture, Water Resources and Fisheries is responsible for supporting efforts with regard to reducing pollution in the form of agricultural waste and from sources such as fishing ports, in addition to protecting water resources.
- The National Institute of Sciences and Technologies (INSTM) is a public institution in the field of research, working under the Ministry of Agriculture, Water Resources and Fisheries. INSTM is active in different projects related to marine litter and fighting pollution in coastal areas.
- The Agency for the Promotion of Industry and Innovation (APII) deals with the promotion of products and projects related to the industrial sector, particularly the plastics sector.

In addition to the institutions mentioned earlier, various other stakeholders are actively engaged in solid waste management, and play a direct or indirect role in combating marine litter:

- The private sector is mainly active in waste collection and cleaning, particularly in coastal and tourism cities during summer periods where waste generation reaches very high levels. Small collection and recycling companies are also active in recyclable material collection and recycling.
- Informal waste collectors are not visible in the current ECO-Lef official system despite their significant contribution to preserving the ecosystem and ensuring sustainable development. The involvement of informal collectors in the Tunisian economy could significantly benefit this population, particularly in terms of social, health, economic, and

environmental aspects, as well as with regard to the national economy. Within the ECO-Lef system, “Barbechas” cannot currently directly access the system’s collection points, which are open only to holders of commercial licenses, who also must be approved by ANGed. As a result, most of the "Barbechas" are unable to take advantage of the high prices guaranteed by ECO-Lef, and are forced to rely on intermediaries who offer lower rates.

- Producers of packaging under the framework of Law no. 96-41 (Polluter Pays Principle) financially contribute to the public system for the recovery and recycling of ECO-Lef packaging waste.
- Importers pay 7% of turnover on their imported materials to the depollution fund, managed by the Ministry of Finance.

3.1.2. Key Indicators: driving forces

3.1.2.1. Waste generated from land-based activities

Population in Tunisia and its coastal areas

The coasts of Tunisia, bounded to the north and east by the Mediterranean Sea, are subject to increasing pressures, including the concentration of the population and visitors. The distribution of the population is continually increasing. In 2014, 70.7% of the population was concentrated on the coast, and it is estimated that this has increased to 71.8% in 2021 compared with 67.7% in 2004 and 64.7% in 1956, following a migratory dynamic from inland areas. Currently, according to the National Institute of Statistics (World Bank, 2022(b)), the total population of the 13 governorates opening onto the Mediterranean Sea is 7.768 million inhabitants (estimated to be 8.607 million in 2021). Following the extension of municipal boundaries in 2018, these regions now encompass 130 coastal municipalities, covering the entire territory of Tunisia. These coastal municipalities rare home to 45% of the total population of Tunisia (Chaabane et al., 2019), which currently stands at 11.8 million (SWEEP-NET, 2014).

Waste management operations in Tunisian coastal areas

As mentioned in the national strategy for the integrated management of household and similar waste, the average amount of waste generated per capita is 0.8 kg/person/day. According to ANGed, the plastic content in household waste is estimated to average 9.4%, with variations in waste composition across different municipalities.

Mismanaged solid waste refers to waste that is either not collected or is disposed of inappropriately, such as in uncontrolled landfills, ultimately finding its way into the natural habitat and the sea via rivers, waterways, winds, storms, and tides. Currently, eleven landfills are active in the coastal governorates. However, three of these - Djerba, Mahdia, and Monastir - have been closed or are non-operational as presented in Figure 10.

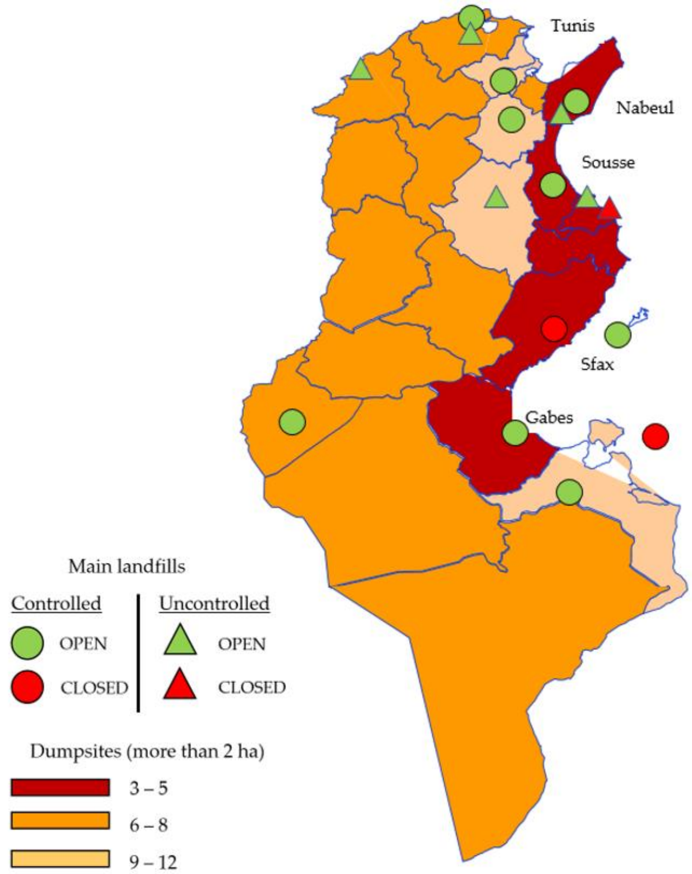

Figure 10. Controlled landfills and planned centers in Tunisia (Data collected from ANGed and designed by the author)

Waste generation from the land-based tourism sector

Tourism is a key economic driver for Tunisia. The Ministry of Tourism reports a rise in tourist numbers, surging from 8.2 million in 2018 to approximately 9.3 million in 2023 (Ministry of Tourism, 2024). Notably, 95% of Tunisia's tourist activity is concentrated in the coastal regions (World Bank, 2022(a)).

Most tourist facilities are located along the country's coastline. Major tourist hotspots, especially during the summer season, produce substantial amounts of waste. This situation places additional pressure on local authorities to manage waste effectively given their current logistical resources. Currently, more than 76% of hotels and restaurants, particularly those serving tourists, are located in coastal governorates, with only 24% situated in interior governorates. These establishments produce substantial amounts of waste, as demonstrated by the waste characterization studies conducted in hotels in Hammamet and Gammarth. Notably, the plastic fraction comprises between 14% and 20% of the total waste generated in these locations. A majority of Tunisian hotels, constituting 83%, dispose of waste without any source sorting, adopt an indiscriminate approach. On the other hand, the other hotels have initiated sorting measures to minimize waste and enhance recycling efforts.

Waste generated from the agricultural sector

The annual estimate of agricultural waste is 4 million tons. This waste is processed for recovery and reuse, serving as livestock feed, for food preparation, and heating. Additionally, it can be composted on both private and state farms (World Bank, 2019).

Waste generated from industries

The Tunisian coastline is characterized by a significant concentration of urban and tourist activities, with approximately 65% of urban agglomerations (equivalent to around 4.5 million inhabitants) and nearly 95% of hotel capacities (exceeding 200,000 beds) situated in this region. Additionally, almost all of Tunisia's industrial activities, including heavy industries and the majority of energy-related industries, are clustered along the coast. These industrial activities contribute to various forms of pollution, particularly in coastal areas such as Gabès, Menzel Bourguiba, Bizerte, Goulette Radès, Sousse, Monastir, and Sfax-Skhira (Ministry of Transport, 2024).

3.1.2.2. Waste generated on the beaches and in coastal zones

Recreational activities

According to APAL (2013), the overall coastal length is 1670 km, comprising 68% continental length, 20% island length, and 12% artificial length. The state of the coast greatly influences both manual and mechanical cleaning operations. Currently, there are over 142 beaches along the Tunisian coast. In the sampled cities, the number of beaches is as follows: 7 in Tunis, 12 in Sousse, 34 in Nabeul, 5 in Sfax, and 11 in Gabès. The average dimensions of these beaches range from 1 to 7 kilometers in length and 5 to 70 m in width.

These coastal cities are renowned for their diverse recreational activities, hosting various events on their beaches throughout the year, especially during the summer season. Tunisia possesses significant advantages for the development of pleasure boating. Its proximity to

Europe is a key factor, complemented by natural attractions that appeal to boaters, such as its central Mediterranean location, extensive coastline, picturesque landscapes, mild climate, and abundant sunshine. There are currently six operational marinas with a total capacity of 2,150 berths: Port El Kantaoui, Monastir, Tabarka, Hammamet, Bizerte, and Sidi Bou-Saïd.

Tourism activities

The tourism industry is a vital pillar of the Tunisian economy, generating foreign exchange and significantly impacting trade, transportation, communication, crafts, and other sectors. It accounts for 13.1% of the Tunisian gross domestic product (amounting to 13.928 MTD/year in 2018). The country has a hotel capacity of over 237,000 beds, with more than 86% located along its beaches (World Bank, 2022(a)). Additionally, 95% of tourist activities are centered in the coastal regions.

In 2018, the tourism sector created approximately 100,000 direct jobs and 289,000 indirect jobs, totaling 389,000 jobs, of which 98,000 were permanent positions (G. JRC Technical Report, 2016). This positions tourism as the second-largest employer following agriculture. The economic contribution of tourism is significant, especially when compared with other countries in the Mediterranean basin (World Bank, 2022(a)).

Commercial port activities

Maritime transport is essential to the national economy, as commercial ports and shipping significantly contribute to national development, and enhance Tunisia's position in foreign trade. As per data from the Ministry of Transport, 98% of the country's foreign trade is conducted via the sea, utilizing eight commercial ports that serve as pivotal hubs in the national economy. Annually, these commercial ports manage the transit of over 30 million tons of goods, 500,000 containers, 140,000 trailers, 720,000 passengers, and 300,000 cars. Tunisia is connected to the main Mediterranean ports through nearly 40 regular maritime lines (World Bank, 2022(a)).

Fishing and aquaculture

According to the Ministry of Agriculture, Water Resources and Fisheries (2020), there was a 2% increase in the production of fishery and aquaculture products in Tunisia, reaching 41,562 tons by the end of the initial five months of 2021. This marks a rise from the 40,673 tons recorded during the corresponding period in 2020.

The fisheries sector holds a crucial position in Tunisia, serving as a vital source of animal protein and contributing significantly to foreign currency earnings. As of 2017, approximately 52,000 individuals directly depend on fishing for their livelihood. Over the years, from 2009 to 2019, Tunisia's annual fish production has hovered around 125,094 tons, with the central and southern maritime areas contributing nearly 80% of the overall total. In 2019, the Gulf of Gabès, accessible directly by three governorates (Sfax, Gabès, and Médenine), housed 23,085 fishermen, constituting nearly 45% of the country's fishing population. Coastal fishing in this region accounted for approximately 70% of the national production in this sector, totaling around 38,000 tons of marine products. The fishing fleet in the same year comprised approximately 12,993 active units, with 93% being coastal boats. The fishing and aquaculture sector provided 50,621 jobs, distributed as follows: 71.5% in coastal fishing, 12% in bluefish fishing, 12.5% in trawling, 2% in shore fishing, and 2% in aquaculture (Ministry of Agriculture, 2020).

The percentage distribution of fishing activity across the Tunisian governorates in recent years is as follows (see Table 2): Jendouba and Beja (1%), Bizerte (5%), Tunis and Ben Arous (2%), Nabeul (14%), Sousse (4%), Monastir (20%), Mahdia (17%), Sfax (15%), Gabès (6%), Medenine (14%), with the remainder distributed across other governorates.

Each year, fishing and aquaculture activities generate solid waste, mainly consisting of plastic materials. This includes items such as nets, fishing lines, cages, traps, ropes, crab traps, shipping containers, and packaging waste such as PET. The utilization of traditional fishing tools is in decline, and faces the risk of disappearing due to various factors, primarily associated with pricing, material durability, product availability, and other related considerations.

Tunisia has a total of 42 fishing ports located throughout the country, classified into three main categories: (1) offshore ports with sufficient depth and quay length for most maritime forms of transport, (2) coastal ports with more basic specifications, and (3) sheltered sites. Additionally, there is a significant number of artisanal fishing landing sites (SWEEP-NET, 2014).

3.1.3. Pressures and resulting states

3.1.3.1. Plastic litter fraction

The OSPAR tables for classifying litter items were designed to reflect the common litter types encountered in the countries that developed the OSPAR methodology for beach litter monitoring. Each litter type was assigned a general code and an OSPAR ID.

For Tunisian beaches, a different classification system was implemented to streamline the number of categories and group items to allow a statistical analysis of data from various surveys, based on a specific classification derived from the types of items typically found on the beaches.

Figure 11 shows the percentage of plastics identified during the beach litter monitoring on the different beaches during the different sampling campaigns. Plastic represents the main item identified and varies between 54% and 70% of the total number of items generated.

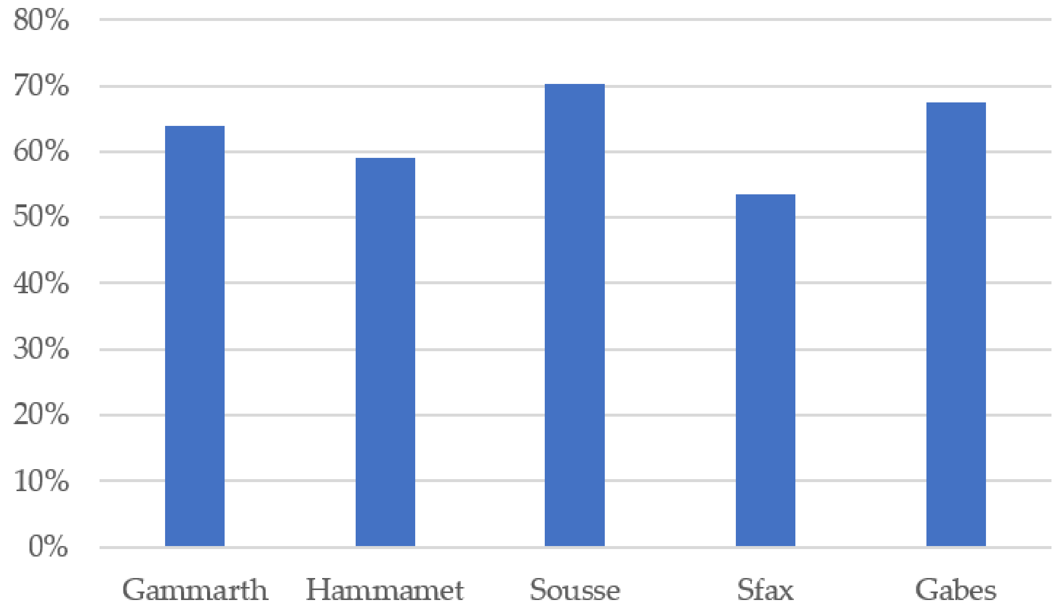

Figure 11. Percentage of plastic in terms of total waste identified on the sample beaches

The results indicate that plastic represents the highest fraction of beach litter, including items such as bottles, cutlery items, and bags. Additionally, various plastic items associated with fishing activities, such as nets and fragments of nets, cords, and similar materials, have been found on the majority of beaches. Sousse, an important tourism destination with a high level of commercial beach activity, had the largest proportion of plastic and single-use plastic items, with 70% of the total identified waste.

The second greatest proportion is observed in Gabès, accounting for 68% of plastics in relation to the overall monitored waste, followed by Gammarth with approximately 64%. In the tourist area of Hammamet, a slightly lower percentage of 59% is observed, likely due to effective plastic waste management practices. Finally, Sfax exhibits the lowest proportion of plastic waste, comprising around 54% of the total waste.

3.1.3.2. Number of items identified at sampling beaches during different seasons

To establish a connection between the littered items identified and waste management and cleaning practices, monitoring campaigns were conducted throughout the various seasons of the year. This approach ensured that various levels of visitor intensity in the area were addressed.

The findings shown in Figure 12 indicate that the number of items identified on the sample beaches from September to May was higher than the number of items identified in the period from May to September. Beach cleaning operations are not conducted with consistent frequency throughout the year, nor do they cover all coastal regions of the country. This inconsistency stems from limited financial resources and differing financial conditions among municipalities. APAL and the municipalities increase the frequency of cleaning operations before and during high tourism seasons, particularly in tourism municipalities (from May until September). This explains the decrease in the amount of litter identified in this period. However, as cleaning activities decline during the off-peak seasons, this leads to a buildup of litter on the beaches for a certain period.

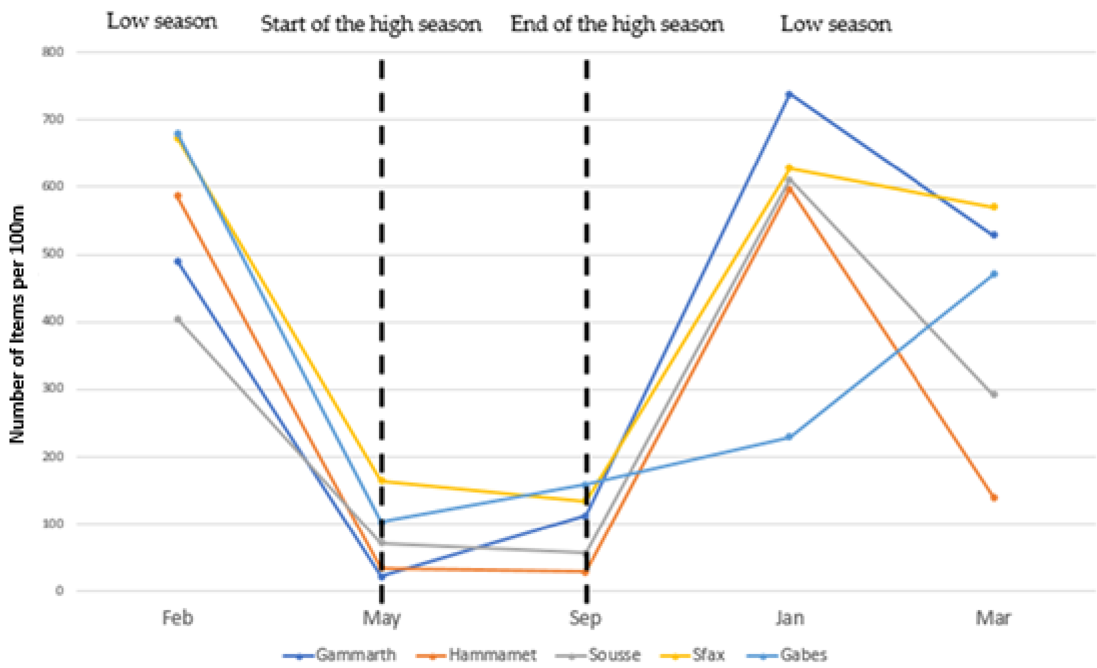

Figure 12. Fluctuation of the number of items identified (per 100m) during different seasons

The significant variation in sampling results highlights the differences in beach waste management and cleaning frequency.

3.1.3.3. Top 15 plastic items

To identify the predominant litter types on each beach, a list of the fifteen most common litter items was compiled based on the beach litter monitoring campaigns. This list will aid in selecting and implementing the most effective reduction strategies.

These lists are based on the classification of the litter items following the OSPAR categorization of each piece of litter, including fragments (G. JRC Technical Report, 2024).

The items listed in the following table (Table 3) highlight the most frequently found type of litter in each station on the 100 m monitored.

Table 3. Top 15 items identified in target cities in coastal areas in Tunisia.

	Gammarth	Hammamet	Sousse	Sfax	Gabès
1	Plastic/polystyrene pieces 0–2.5 cm	Plastic/polystyrene pieces 2.5 cm–50 cm	Plastic/polystyrene pieces 0–2.5 cm	Cigarette butts	Caps/lids
2	Cigarette butts	Cigarette butts	Cigarette butts	Bags (e.g., shopping)	Cigarette butts
3	Caps/lids	Plastic/polystyrene pieces 0–2.5 cm	Caps/lids	Plastic/polystyrene pieces 0–2.5 cm	Drinks (bottles, containers, and drums)
4	Plastic/polystyrene pieces 2.5 cm–50 cm	Food wrappers	Bags (e.g., shopping)	Caps/lids	Plastic/polystyrene pieces 2.5 cm–50 cm
5	Drinks (bottles, containers, and drums)	Bags (e.g., shopping)	Drinks (bottles, containers, and drums)	Cutlery/trays/straws	Bags (e.g., shopping)
6	Bags (e.g., shopping)	Drinks (bottles, containers, and drums)	Cutlery/trays/straws	Plastic/polystyrene pieces 2.5 cm–50 cm	Food wrappers
7	Toys and party poppers	Caps/lids	Crisp/sweet packets and lolly sticks	Crisp/sweet packets and lolly sticks	Plastic/polystyrene pieces 0–2.5 cm
8	Food wrappers	Food containers incl. fast food containers	Food wrappers	Cleaner (bottles, containers, and drums)	Cigarette lighters
9	Foam sponge	Cutlery/trays/straws	Foam sponge	Drinks (bottles, containers, and drums)	String and cord (diameter less than 1 cm)
10	String and cord (diameter less than 1 cm)	Foam sponge	Other plastic/polystyrene items	String and cord (diameter less than 1 cm)	Cutlery/trays/straws
11	Cutlery/trays/straws	Industrial packaging, plastic sheeting	Plastic/polystyrene pieces 2.5 cm– 50 cm	Cups	Other bottles, containers, and drums
12	Nets and pieces of net <50 cm	String and cord (diameter less than 1 cm)	Cups	Food wrappers	Small plastic bags, e.g., freezer bags
13	Rope (diameter more than 1 cm)	Other plastic/polystyrene items	Food containers incl. fast food containers	Nets and pieces of net <50 cm	Food containers incl. fast food containers
14	Crisp/sweet packets and lolly sticks	Crisp/sweet packets and lolly sticks	Nets and pieces of net <50 cm	Industrial packaging, plastic sheeting	Foam sponge
15	Plastic bag ends	Rope (diameter more than 1 cm)	Containers/tubes	Small plastic bags, e.g., freezer bags	Industrial packaging, plastic sheeting

3.1.3.4. Sources of Plastic Litter

Beach litter and marine litter can originate from various sources. In addition to failures in waste management practices, several activities have been identified as contributors in the waste in Tunisian coastal areas. In this study, sources of beach litter were classified into four categories: tourism and recreational activities, fisheries, construction waste, and others (including shipping, medical waste, E-waste, etc.). The findings in this case study showed an uneven percentage for the different sources as presented in Figure 13.

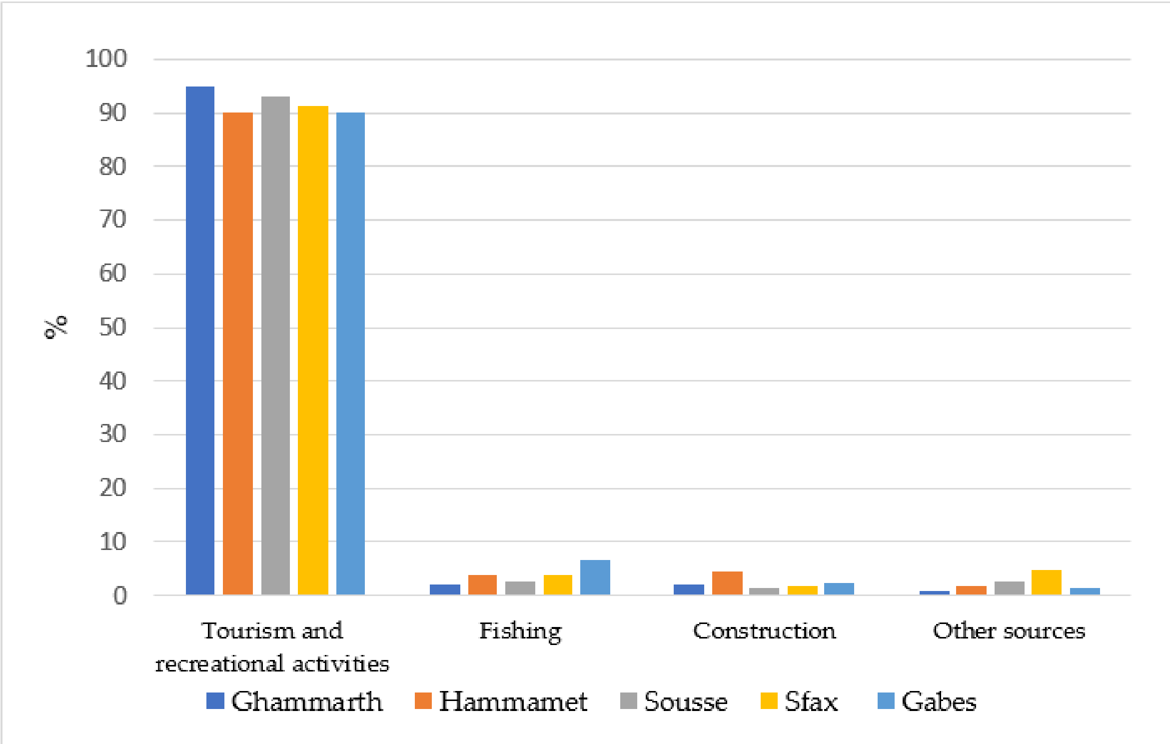

Figure 13. Percentage of identified litter in terms of source

Tourism and recreational activities sector

Tourism in Tunisia contributes to various forms of pollution, primarily water pollution, solid waste generation, and aesthetic pollution. Effective waste management is a significant challenge in tourist areas.

The waste produced by hotel guests each day exceeds the amount generated per resident or household each day in tourism municipalities across Tunisia. According to Chaabane (2020), the average waste generated in hotels is about 2.6 kg, compared with 1 kg generated by households.

Fisheries activities

In addition to the waste generated by extensive recreational activities along the Tunisian coast, fishing activities produce varying quantities of waste depending on the intensity in different areas. For instance, plastic waste is particularly prevalent in busy fishing ports such as Nabeul (including Hammamet), Mahdia, Monastir, Sousse - which serves as a major commercial and tourist port - Sfax, and Médenine near Gabès (World Bank, 2022(b)).

Construction sector

As many entertainment projects such as cafés, restaurants, and clubs, operate near the beaches, a significant amount of construction waste is often left behind. While inspecting the monitored beaches, numerous pieces of metal rods, brick fragments, plastic tubes, and other debris were observed.

Other sources

Litter on the beaches has not only clearly defined in terms of waste, but also other kinds of waste, such as, but not limited to, medical waste, sports activities waste, and industrial waste (tires, electronic waste, etc.) exist.

The results in Figure 13 indicate that tourism and recreational activities represent the main sources of beach litter in the sample cities in Tunisia (with more than 90% of the sources). The coastal cities of Tunisia are well-known for their seaside activities. In addition to hotels, Tunisian tourism includes a wide array of offerings such as restaurants, beach bars, and both formal and informal businesses.

Tourism and recreational activities account for the highest percentage of litter, followed closely by fishing activities, particularly in southern Tunisia. In Hammamet, construction-related litter is also significant due to the numerous new beach bars and restaurants being developed. The remaining litter sources are often linked to unspecified and sometimes unidentifiable origins, rather than being associated with regular or recent activities.

3.1.3.5. Quantity of plastic items on 1 km of beach in the monitored beaches

Expanding the interpretation of the results from 100 meters to 1-kilometer enabled the researchers to approximate the condition of the beaches in terms of litter during peak seasons in relation to local activities. Gammarth, Hammamet, and Sousse are recognized as tourist cities where cleaning efforts are more frequent compared to other locations such as Sfax and Gabès. The diagram in Figure 14 explains the low amount of plastic litter, with an average of

4.16 kg/km/day (Gammarth: 4.8 kg/km/day; Hammamet: 2.9 kg/km/day; Sousse: 4.8 kg/km/day) and a higher average of 15.9 kg in the case of the other cities (Sfax: 16.2 kg/km/day; Gabès: 15.6 kg/km/day).

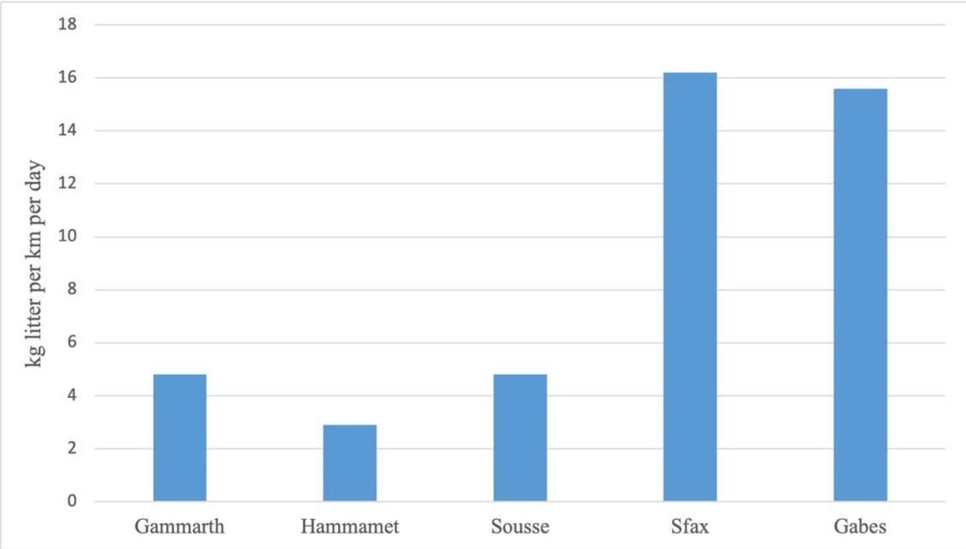

Figure 14. Average amount of plastic waste in kg in sampled cities per km per day

3.1.3.6. Beach Litter Packaging Percentage

Visually, packaging is very apparent on beaches in Tunisia. When browsing the beaches during the sampling procedure, it was remarkable that the fraction of packaging was dominant compared with other types of existing waste. Figure 15 highlights the results of the analyses, depicting the proportion of packaging waste within the total identified litter on the designated beaches.

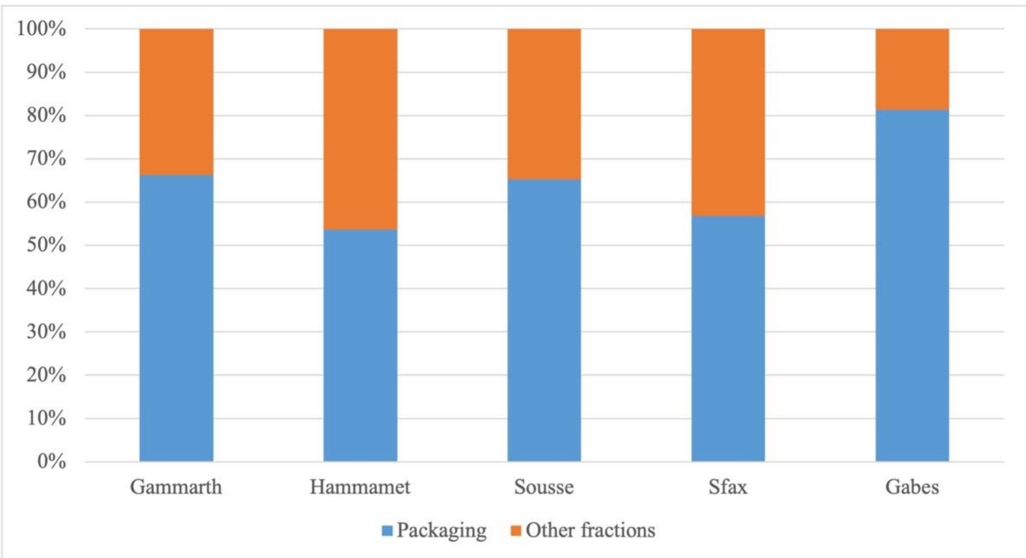

Figure 15. Percentage of the packaging fraction vs other fractions in the beach litter

The overall results indicate that packaging is the predominant waste stream found on the sampled Tunisian beaches, accounting for 53% to 81% of the total waste monitored. The primary items identified include various types of packaging, both with and without market value, such as food wrappers, plastic bottles, films, plastic bags, drink containers (including bottles and drums), cans, multilayer packaging, crisp and sweet packets, and lolly sticks. Some of these materials are too small or low in value to be collected, while others are gathered for recycling. Notably, a significant number of recyclable materials were found on the target beaches, despite their high market value.

Plastic packaging poses environmental concerns due to its persistence and non-degradability, contributing to visual pollution for both local visitors and tourists. This indicator is crucial for future decision-making processes aimed at establishing an extended producer responsibility system for packaging in Tunisia. Identifying the proportion of packaging waste in various tourism destinations and cities can aid in calculating the budget needed for effective cleaning operations in each area.

3.2. Benchmark with results of beach litter monitoring in Germany

The beach litter monitoring in Tunisia took place at 5 stations spread throughout the coastal zone during different periods during 2019, 2020 and 2022.

The main findings of this beach litter monitoring study are centered around several critical indicators. These include the assessment of waste generated from land-based activities that ends up directly on the beaches and in coastal zones, highlighting the pressures exerted on these environments and the resulting states of degradation. A significant focus was placed on the plastic litter fraction, given its prevalence and persistence in marine ecosystems. The number of items identified at the sample beaches across different seasons provided insights into temporal variations in litter accumulation. Furthermore, the analysis identified the top 15 plastic items, pinpointing the primary sources of plastic litter. The study also quantified the quantity of plastic items found per kilometer of beach, offering a measurable indication of pollution intensity. Additionally, the percentage of beach litter attributed to packaging materials was calculated, emphasizing the role of consumer goods in coastal pollution.

This chapter aims to benchmark the results of the identified indicators based on beach litter monitoring campaigns carried out in Tunisia and Germany. By comparing the data from these two distinct regions, the objective is to understand the current situation in both countries. Such a comparison will provide insights into the main types of identified litter, their spread and sources.

Comparison of top 15 items between Tunisia and Germany

The results of the monitoring showed that cigarette butts are top of the litter list in Tunisia compared with the beach litter situation in Germany between 2017-2019 and in 2013.

Indeed, cigarette butts are one of the most commonly-found items in marine litter. They are small, often improperly disposed of, and can easily be carried into waterways through runoff, wind, and storm drains. Once in the marine environment, cigarette butts pose several problems such as toxicity (Anna et al., 2012). In fact, they contain chemicals such as nicotine, lead, arsenic, and other harmful substances that can leach into the water, harming marine life and ecosystems. Moreover, cigarette filters are made of cellulose acetate, a type of plastic that can take years to degrade, contributing to long-term pollution. The most dangerous fact is that marine animals can mistake cigarette butts for food, leading to ingestion that can cause internal blockages, poisoning, and even death (Gladstone, 2023).

Plastic pieces between 0.5 – 2.5 cm in size have been identified in Tunisian and German beaches. The items are the results of degradation of larger (macro) litter items such as plastic bags.

Caps and lids are present in the list of top 15 items in Germany, but were not identified in the top 10 items in the experiments of 2017 and 2019. In Tunisia, caps and lids are in total amount 529 for all stations and during all samplings, and are identified in the top 5 items.

There is an absence of plastic PET bottles in Germany whereas large amounts are present in Tunisia. It is important to note that the PET bottles collection system is based on collection via the informal sector. However, the system in Germany is based on a deposit system, with a high collection rate.

Germany has a well-established deposit system for plastic bottles, known as the "Deutsche Pfandsystem", which has been in place since 2003. The system imposes a mandatory deposit on most single-use beverage containers, including plastic bottles and cans. The deposit is typically 0.25 EUR per container. Consumers pay this deposit when purchasing a beverage and can reclaim it by returning the empty container to a reverse vending machine, usually found in supermarkets.

The system is highly effective, with Germany achieving one of the highest return rates for beverage containers in the world, exceeding 90%. This success is largely due to the convenience of the system and the environmental awareness it fosters. The returned containers are then recycled, contributing significantly to reducing plastic waste and promoting a circular economy (DPG, 2024).

The consumption of plastic bottles in Tunisia and Germany highlights significant differences due to the varying levels of economic development, environmental policies, and consumer behavior in each country.

Table 4 summarizes the classification of marine litter after sampling of beaches according to the OSPAR method in both Germany and Tunisia during different years.

Table 4. Top 10 /15 beach litter items found on both Tunisian and German beaches

N°	TOP 15 items identified in Germany	TOP 10 items identified in Germany	TOP 15 items identified in Tunisia
	Galgani et al. (2013)	Haseler et al. (2020)	Baccar Chaabane et al. (2024)
1	Plastic/polystyrene pieces 2.5 cm > < 50cm	Cigarette butts	Cigarette butts
2	Cigarette butts	Plastic pieces 0.5 – 2.5 cm	Plastic/polystyrene pieces 0 – 2.5 cm
3	Caps/lids	Bottles incl. pieces	Plastic/polystyrene pieces 2.5 cm > < 50 cm
4	Foam sponge	Other glass items	Caps/lids
5	Other ceramic/pottery items	Slack/coal	Bags (e.g. shopping)
6	Bags (e.g. shopping)	Firework plastic pieces	Drinks (bottles, containers and drums)
7	Food incl. fast food containers	String and cord (< 1 cm)	Food wrappers
8	Bottle caps	Plastic pieces 2.5 > < 50 cm	Cutlery/trays/straws
9	Cutlery/trays/straws	Food waste	Crisp/sweet packets and lolly sticks
10	Wood Crates	Paper fragments	String and cord (diameter less than 1 cm)
11	Crisp/sweet packets and lolly sticks		Foam sponge
12	Cups		Toys & party poppers
13	Rope (diameter more than 1 cm)		Food containers incl. fast food containers
14	Other textiles		Cleaner (bottles, containers and drums)
15	Other paper items		Other plastic/polystyrene items

Tunisia has been experiencing a steady growth in the demand for plastic bottles, driven primarily by an increasing population and growing economic activities. The market is characterized by significant imports of plastic bottles, with a substantial portion of these bottles being used in the beverage industry. However, the country is also facing challenges related to waste management and recycling, which are not as advanced as in more developed countries.

On the other hand, Germany has a well-established system for managing plastic bottle consumption. The country has implemented a deposit return system, which has been highly effective in promoting the recycling of plastic bottles. In Germany, consumers pay a deposit when purchasing beverages in plastic bottles, which is refunded upon returning the empty bottles. This system has resulted in a high recycling rate and a more circular approach to plastic usage.

In terms of consumption patterns, Germany's approach has led to a more controlled and environmentally-sustainable use of plastic bottles compared to Tunisia, where the recycling infrastructure is still developing. The results of the comparison between the identified items in both Tunisia and Germany as shown in Table 4 indicates that cutlery items are listed among the items of litter in Germany (class number 9) and in Tunisia (class number 8, with 203 cutlery items identified on the beaches in Tunisia). In 2020, tableware items were not included in the list of top 10 items. Therefore, and for this reason, a study of biodegradable cutlery was carried out to test their lifespan in water as a final destination after discharge.

Introduction of the benchmark of sources

As shown in Table 5, the classification with regard to “Tourism and recreational activities sector” sources identified in Tunisia covers the “Improper waste disposal”, “plastic items such as bags, bottles, and packaging materials, often discarded irresponsibly and which can be carried by wind or water into the sea” and “Recreational and tourism activities” highlighted in the classification of the reference 2 provided by Râpă et al. (2024), and is comparable with “Tourism and recreational activities, including beach-based water spots” highlighted in reference 1 by Schäfer et al. (2019) (Germany).

Table 5. Comparison of source of litter between in Tunisian and German beaches

Sources of litter in German coastal areas	**Sources of litter in German coastal areas**		**Source of litter in Tunisian coastal areas**
Reference 1 Schäfer et al. (2019)	**Reference 2** Râpă et al. (2024)		**Reference 3** Baccar Chaabane et al. (2024)
	Land-based	**Sea-based**	
Fishing (incl. fishing ports)	Improper waste disposal	Fishing operations	Tourism and recreational activities sector
Aquaculture	Sewage and wastewater discharge	Marine tourism sector	Fishing
Ferry and excursion boats	Plastic items such as bags, bottles, and packaging materials, which are often discarded irresponsibly and which can be carried by wind or water into the sea	Shipping	Construction
Recreational boating (incl. marinas)	Recreational and tourism activities	Abandoned fishing gear such as nets, lines and traps	Other types: medical waste, sports activities waste, industrial waste including tires, electronic waste, etc.
Cargo and other shipping	Industrial and construction activities	Aquaculture	
Tourism and recreational activities (including beach-based water spots)	Harbour activities	Offshore oil and gas platforms	
Harbour operations and facilities			
Other maritime industries			
Land-based industry and commerce			
Sewage outlets and rainwater overflow			
Garbage collection and disposal			

The results of the benchmark between the sources of litter in Tunisia and in Germany show that tourism and recreational activities and fishing are considered the main sources of litter when it comes to land-based activities (classified in the top 5 types for the case of the German references, and the first type in Tunisia). Fishing is considered an important source of beach litter in both countries.

Benchmark between Tunisian and Germany analyses in terms of number of litter items found on tourist beaches

In Tunisia, on the Mediterranean coast, the stations were sampled 5 times as was the case in Germany in the 2 stations belonging to the city of Rostock on the coast of the Baltic Sea (Hohe düne and Warnemünde) (Schernewski et al., 2018).

The main findings showed that at average number of litter items in 100 meters of beach monitored at the Hohe düne beach was 62 items, while at Warnemünde beach it was 74 items, while in Tunisia the number of items at Hammemet it was 1,917 items whereas at Gammarth it was 3,293 items. The selected stations for comparison are located in tourist coastal towns with intense summer activity.

Additionally, according to the same references, the benchmark indicate that plastics are the dominant type of litter at all the sample stations in both Tunisia and Germany. Therefore, finding solutions to prevent plastic littering has become a current focus in the fight against maratime pollution. In the following section of this thesis, one of the solutions was developed and tested in terms of the biodegradability of selected items in water.

As a summary to the benchmark analyses, it’s worth highlighting the following points:

- Plastics represent the main items of litter in beaches in both countries, and products made of plastic are classified in the top 10 / 15 items identified.
- Tourism activity represents a potential source of litter in both countries. This is mainly due to weaknesses in the waste management system.
- Tableware items were identified as items of litter in both countries, with a reduced number of items in Germany in 2020.

3.3. Degradation rate monitoring experiment results

The incubators located at Hohe Düne were periodically taken out of the water column for cleaning and to assess the condition of the materials after 50, 202, and 339 days; from IGA Park after 65, 165, and 399 days; and from Gehlsdorf after 64, 148, and 356 days. At the conclusion of the experimental period, the incubators were removed opened at the IOW laboratory, where the results were documented. Samples were weighed and placed in labeled bags for further analysis. Tables 5, 6 and 7 show the difference between the initial and the final weight of the samples after the experimentation period. The degradation rate was calculated using the following formula:

$$(1)\ \text{Degradation Rate}\ (DR) = (Wo - Wt / Wo) \times 100$$

where W0 and Wt are the weights of the initial and degraded items, respectively.

Table 6. Results of the degradation of selected items in Station S1, Hohe Düne (HD)

Incubators and content	Initial weights of samples	Final total weight	Degradation rate (DR) (%)	Final status of the item
HD.1.1.U Paper	Plate (1.6 g), small cup (0.3 g)	1.1 g (- 0.8 g)	42.1%	Soft to the touch
HD.1.2.U Plastics	Cup (1 g), box (2.1 g)	4.3 g (+ 1.2 g)	0 %	Not degraded
HD.1.3.D Paper	Plate (1.8 g), small cup (0.4 g)	1.5 g (- 0.7 g)	31.8%	Soft to the touch
HD.1.4.D Plastics	Cup (1 g), box (1.8 g)	3.5 g (+ 0.7 g)	0 %	Not degraded
HD.2.1.U Wood	Spoon (2.5 g), fork (2 g)	4.8 g (+ 0.3 g)	0 %	Soft to the touch
HD.2.2.U Palm leaf	Plate (3.3 g)	0.6 g (- 2.7 g)	81.8 %	Small fibers
HD.2.3.D Wood	Spoon (1.6 g), fork (2 g)	5.8 g (+ 2.2 g)	0 %	Soft
HD.2.4.D Palm leaf	Plate (2.9 g)	0 g (- 2.9 g)	100 %	Totally degraded
HD.3.1.U PLA / CPLA	PLA (lid 0.9 g, cup 1.2 g)/ CPLA (lid 1.9 g, spoon 2.4 g)	6.6 g (+ 0.2 g)	0 %	Not degraded
HD.3.2.U Sugar cane	Bleached (1.1 g)/unbleached (1.2 g)	0 g (- 2.3 g)	100 %	Totally degraded
HD.3.3.D PLA / CPLA	PLA (lid 1 g, cup 1.1 g)/ CPLA (lid 1.7 g, spoon 2 g)	6 g (+ 0.2 g)	0 %	Not degraded
HD.3.4.D Sugar cane	Bleached (1 g)/ unbleached (1.3 g)	0 g (- 2.3 g)	100 %	Totally degraded

At S1, the results show that the DR of sugar cane and palm leaf placed in the upper and lower incubators was high. Paper was relatively resistant to the water conditions (42.1% and 31.8%), but its morphology changed considerably and it tended to degrade. However, PS, PLA/CPLA and wood in both upper and lower incubators were not degraded (DR: 0%). In addition, it was noted that barnacles were growing on its surface, which explain the gain in weight (+0.2 to +2.2).

Figure 16 includes images that summarize the initial state as well as the final state of the materials of the upper incubators of station S1.

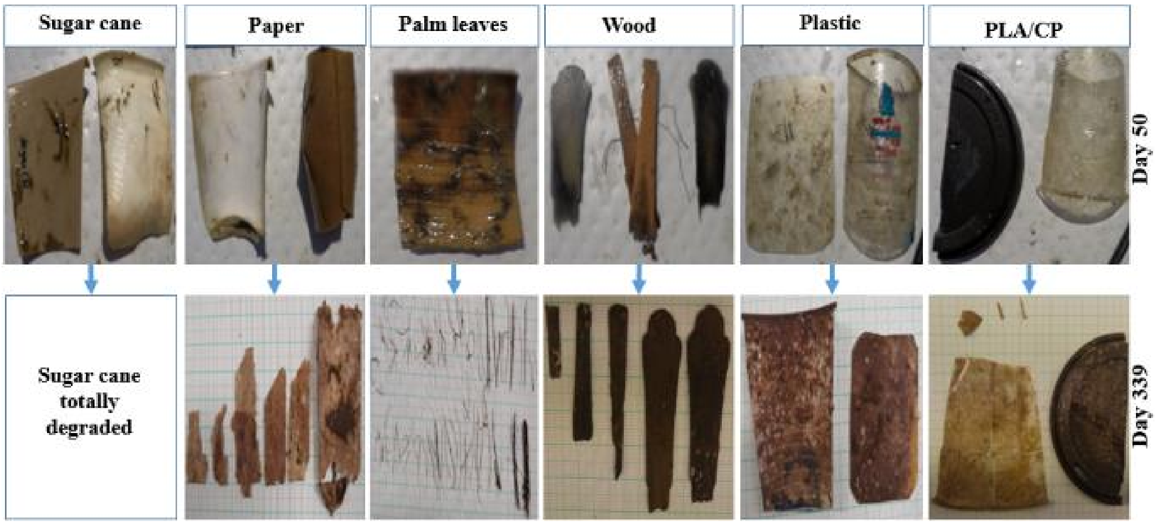

Figure 16. Examples of degraded items from the upper incubators at S1

In fact, as larvae, barnacles have a size of between 0.35 and 1 mm (Carlton, 2007), and can easily get inside the incubators which have a 2 mm mesh size. Barnacles were then able to fix themselves to materials.

Table 7. Results of the degradation of selected items in Station S2, IGA Park (I)

Incubators and content	Initial weights of samples	Final total weight	Degradation rate (%)	Final status of the item
I.1.1.U Plastics / CPLA	Cup (0.6 g), box (1.5 g), knife (1.6 g)	4 g (+ 0.3 g)	0%	Not degraded
I.1.2.U Sugar cane	Bleached (2.8 g)/ unbleached (1.3 g)	0 g (- 4.1 g)	100%	Totally degraded
I.1.3.D Plastics / CPLA	Cup (0.6 g), box (1.5 g), knife (1.8 g)	4.5 g (+ 0.6 g)	0%	Not degraded
I.1.4.D Sugar cane	Bleached (2.8 g)/ unbleached (1.3 g)	1.4 g (- 2.7 g)	65.8%	Soft to the touch
I.2.1.U Wood	Tableware (1.3 g)/ (2.2 g)	7.1 g (+ 3.6 g)	0 %	Soft to the touch
I.2.2.U Palm leaf	Rectangular plate (1.5 g)	0 g (- 1.5 g)	100%	Totally degraded
I.2.3.D Wood	Tableware (1.8 g)/ (1.7 g)	6.8 g (+ 3.3 g)	0 %	Soft to the touch
I.2.4.D Palm leaf	Plate (1.6 g)	1.1 g (- 0.5 g)	31.2%	Small fibers
I.3.1.U Paper	Plate (1.7 g), cup (2 g)	0 g (- 3.7 g)	100%	Totally degraded
I.3.2.U PLA/CPLA	PLA (cup 2.5 g)/ CPLA (knife 2.3 g, lid 1.7 g)	18.2 g (+ 11.7 g)	0 %	Not degraded
I.3.3.D Paper	Plate (1.7 g), cup (1.9 g)	0 g (- 3.6 g)	100%	Soft to the touch
I.3.4.D PLA/CPLA	PLA (cup 2.5 g)/ CPLA (knife 2.3 g, lid 1.7 g)	9.1 g (+ 2.6 g)	0 %	Not degraded

The results at S2 showed that the DR of paper, palm leaf and sugar cane items of the upper incubators was high (100%) and were relatively important in most lower incubators. Palm leaf degraded to small fibers which explain the registered weight.

Figure 17 includes images summarizing the initial and final states of the materials of the upper incubators of station S2 (where sugar cane, paper and palm leave totally degraded).

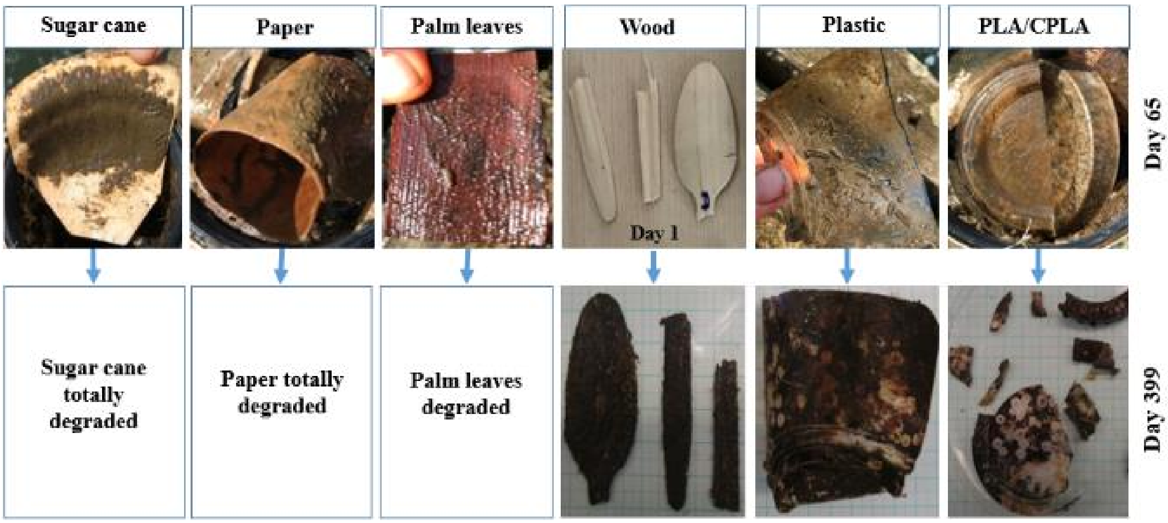

Figure 17. Examples of degraded items from the upper incubators at S2

However, PS, wood and PLA/CPLA were resistant to the water conditions, and degradation did not take place during the experimentation period. In fact, the process of degradation seemed to start at that period of time.

Table 8. Results of the degradation of selected items in Station S3, Gehlsdorf (G)

Incubators and Content	Initial weights of samples	Final total weight	Degradation rate (%)	Final status of the item
G.1.1.U Sugar cane	Bleached (1.6 g)/ unbleached (1.9 g)	0 g (- 3.5 g)	100%	Totally degraded
G.1.2.U PLA / CPLA	PLA (cup 1 g, box 1.8 g)/ CPLA (lid 1.5 g, spoon 3.1 g, knife 2.5 g)	11.6 g (+ 1.7 g)	0 %	Not degraded
G.1.3.D Sugar cane	Bleached (1.6 g), unbleached (1.8 g)	0 g (- 3.4 g)	100%	Totally degraded
G.1.4.D PLA / CPLA	PLA (cup 1 g, box 1.8 g)/ CPLA (lid 1.6 g, spoon 2.7 g, knife 1.9 g)	10.6 g (+ 1.6 g)	0 %	Not degraded
G.2.1.U Palm leaf	Plate (4 g)	0 g (- 4 g)	100%	Totally degraded
G.2.2.U Wood	Spoon (2.3 g), stick (0.7 g)	6.7 g (+ 3.7 g)	0 %	Soft to the touch
G.2.3.D Palm leaf	Plate (4.2 g)	1.3 g (-2.9 g)	69 %	Small fibers
G.2.4.D Wood	Spoon (1.5 g), stick (0.8 g)	4.6 g (+ 2.3 g)	0 %	Soft to the touch
G.3.1.U Paper	Plate (1.6 g), cup (1.7 g)	0 g (- 3.3 g)	100%	Soft to the touch
G.3.2.U Plastics	Cup (0.8 g), box (1.6 g)	3.3 g (+ 0.9 g)	0 %	Not degraded
G.3.3.D Paper	Plate (1.7 g), cup (1.7 g)	1.3 g (- 2.1 g)	61.7%	Soft to the touch
G.3.4.D Plastics	Cup (0.9 g), box (1.7 g)	3.2 g (+ 0.6 g)	0 %	Not degraded

At S3, sugar cane, palm leaf and paper items in the upper incubators totally degraded (DR: 100%). However, palm leaf items placed in the lower incubator degraded to a form of small fibers resulting in a DR of 65%. In addition, paper items in the lower incubators lost weight and changed their morphology. However, they didn't degrade totally. No change was registered regarding PLA/CPLA, wood and PS items in terms of DR. However, their color changed, showing also a growth of barnacles, algae and mussels on top (figure 18).

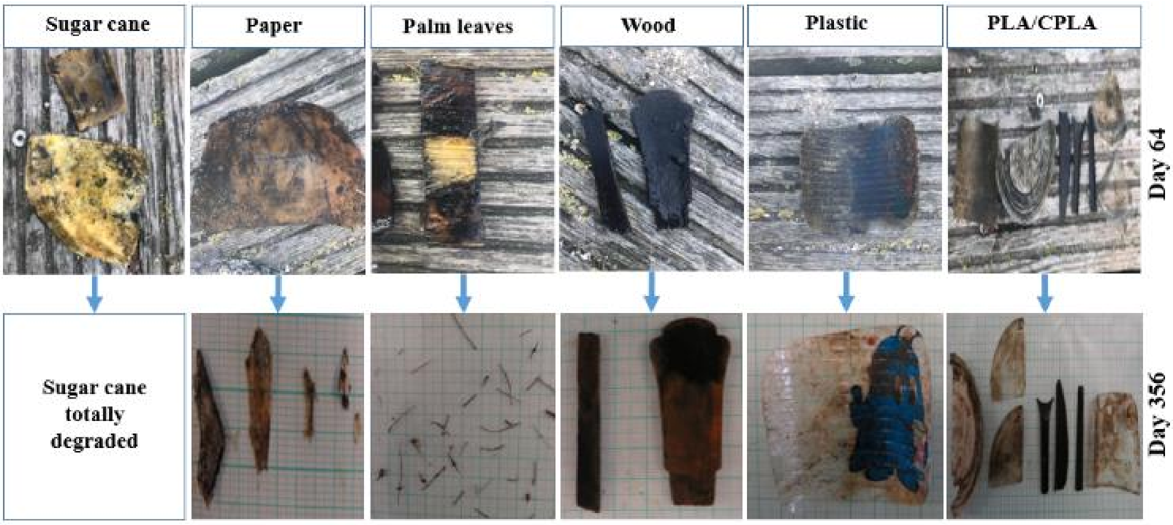

Figure 18. Examples of degraded items from the upper incubators at S3

Parameters variations and DR monitoring

In this research it was not possible to follow the DR (%) of items periodically through weighing. In fact, most items were very wet, fragile and soft to the touch. The weighing operation could have lost some parts of the material and distorted the results. However, and in order to assess the influence of the monitored parameters on the DR, an estimation of the degradation is noted, based on the photographs taken during the field visits. The results of the parameter monitoring and the DR of the materials used are presented in Figures 19, 20 and 21:

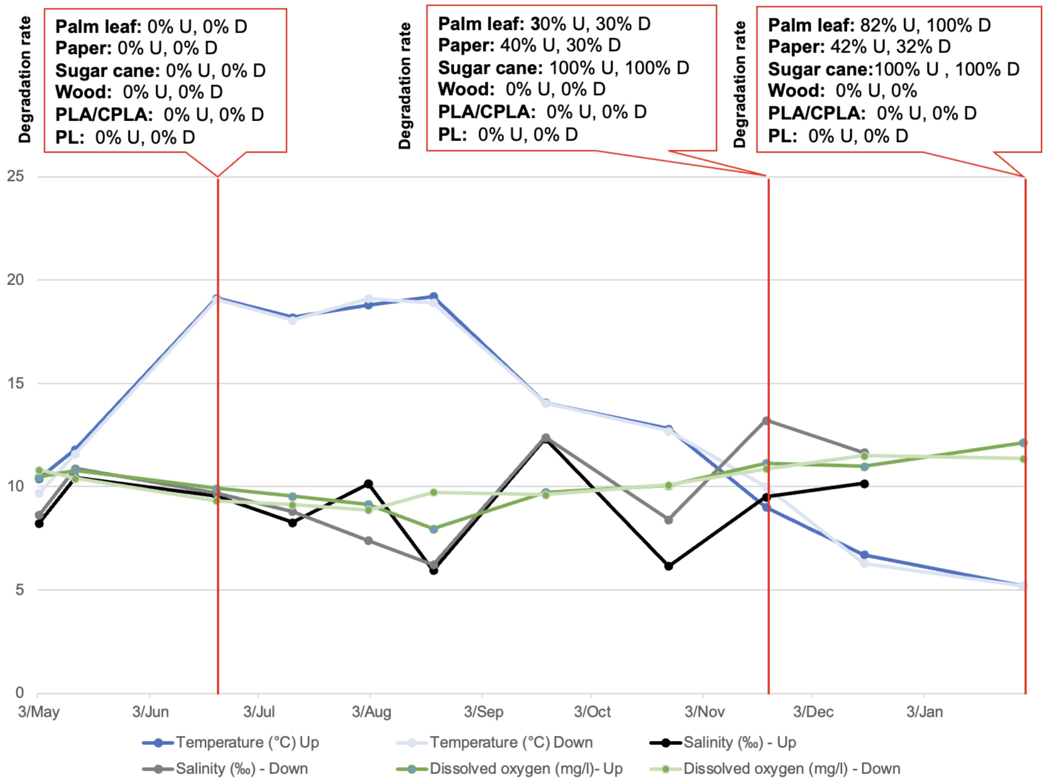

Figure 19. Parameters variation and DR in Upper and Lower incubators at S1

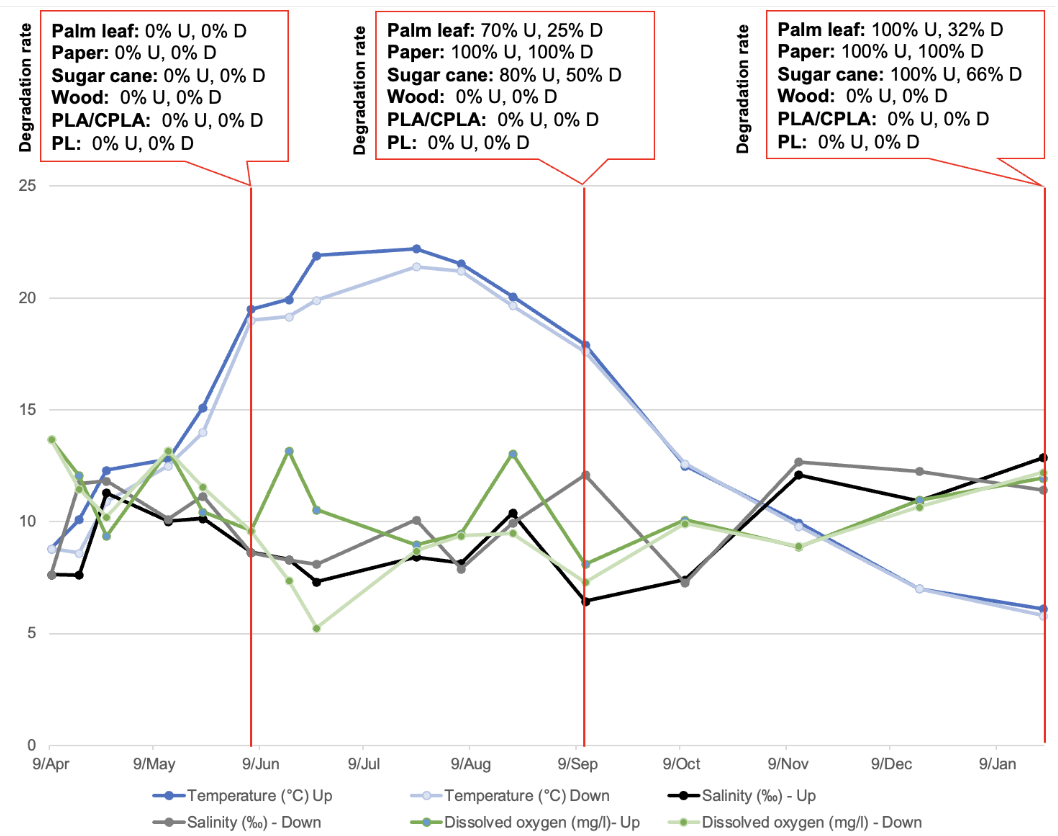

Figure 20. Parameters variation and DR in Upper and Lower incubators at S2

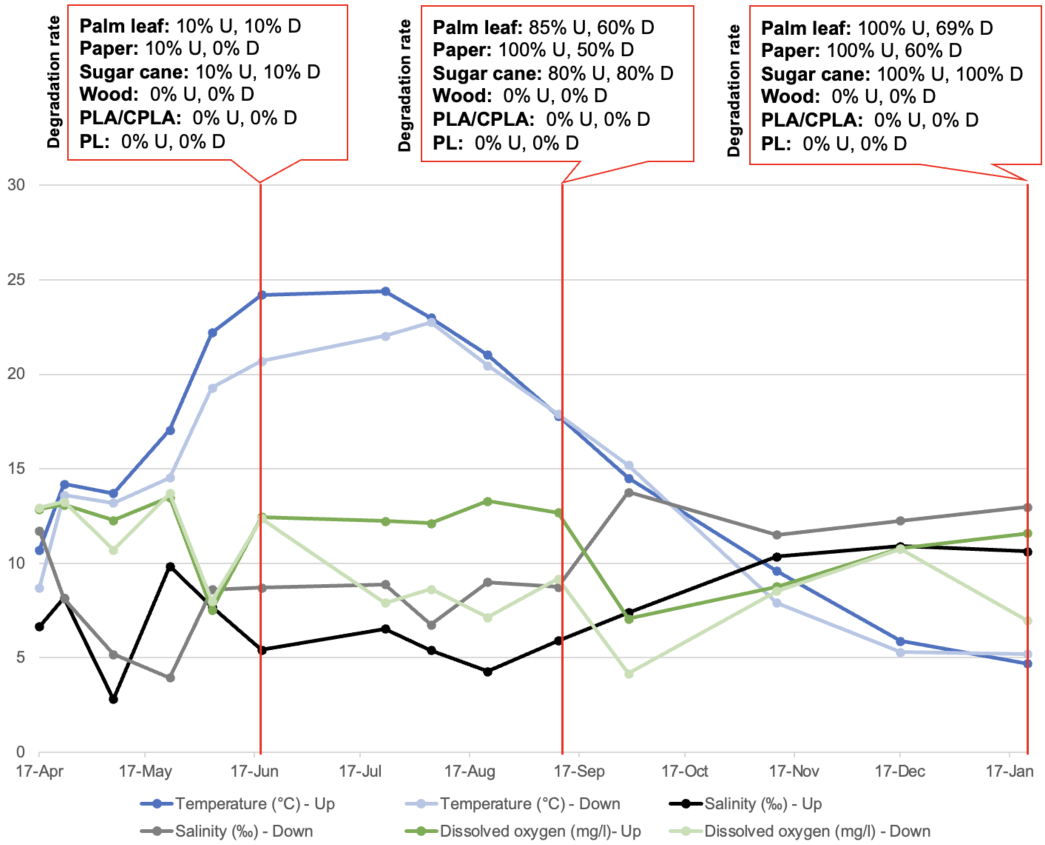

Figure 21. Parameters variation and DR in Upper and Lower incubators at S3

The characteristic parameters of natural water have a certain fluctuation caused by seasonal changes. Among them, water temperature shows the most obvious fluctuation between 4.7°C and 24.4°C (in the upper layer) and 5.2°C and 22.7°C (in the lower layer). The pH does not change significantly. The same is true in terms of salinity, with average values of 2.8% and 12.8% (in the upper layer) and 6.7% and 13.2% (in the lower layer) respectively. The DO was not stable in either the upper or lower incubators.

The density values provide insights into the behavior of biodegradable items in water, with some sinking and others floating. This variation influences their fragmentation and the interaction with living organisms, which may have used these materials as habitats or sources of nutrition during the experimental period. For instance, PLA and sugar cane tend to sink over time, whereas wood, paper, and PS items typically float. In the case of palm leaf materials, differences in density margins mean that they can either float or sink.

4. DISCUSSION

The problem of beach and coastal litter is evident not just in Tunisia but also in numerous developing and developed nations. Many countries are enacting strategies and measures to prevent littering in coastal regions and subsequent transfer to the marine environment. The study undertaken by Brinkmann et al. (2022) indicates that despite the efforts and measures taken, litter on beaches continues to pose several challenges worldwide. Addressing the issue necessitates the implementation of a set of cohesive and combined measures tailored to the specific context of each country and to the nature of the problematic items.

In order to understand the coastal litter situation in Tunisia, this research has developed a series of key indicators encompassing the legal, institutional, and financial framework, as well as the driving forces, pressures, and resulting states associated with marine litter. These indicators act as key factors that can inform decision-making processes and which can be valuable at both national and local levels. Nevertheless, these indicators should be utilized and regularly updated based on the data collected and analyzed. In fact, decisions ought to rely on tangible data, which constitute the fundamental element of indicator development and serve as the cornerstone of information.

The results of the key indicator analyses related to solid waste management in Tunisia shows that the current model is characterized by poor organization and a general lack of coordination among the stakeholders and institutions concerned. Furthermore, the insufficiency of financial resources and organization results in an ineffective waste collection system (with an average collection rate of 84%, much lower in rural municipalities), which in turn exacerbates the problem of litter accumulation along coastal areas.

The results show that despite the creation of a national system for packaging recovery (ECO-Lef) and the resulting development of small and medium enterprises related to the waste operation activities, a substantial percentage of packaging waste has been identified on Tunisian beaches. The findings indicate that the lowest percentage of recorded packaging on beaches was in Hammamet tourism area (53.6%), while the highest percentage was observed in Gabès (83.3%) considered a non-touristic city. The current packaging recovery national system is largely shaped by the informal sector, and the absence of traceability for the quantities collected outside of the formal system. Furthermore, the materials that are collected are primarily those that hold market value, either within Tunisia or for export. Furthermore, the current system only covers a number of packaging products where the volume exceeds 100 mL. Consequently, a number of items that are not covered by the system remain uncollected, in particular single-use plastics items.

The indicators show that the increase in the quantity of household waste in Tunisia is more intense in coastal areas where urbanization is prevalent. The concentration of population in coastal agglomerations leads to a change in production and consumption patterns, the production of more waste, and a change in its composition. The increase of the quantities of waste generated lead to the increase in landfilling operations, considered the main treatment method in Tunisia. The research highlights those three landfills located in Djerba, Mahdia, and Monastir are either closed or not operational, and many others are classified as dumpsites. The presence of inactive or poorly- managed landfill sites can contribute to increased leakage and migration of waste into surrounding areas, including marine environments.

In fact, the link between poor waste management systems and marine litter is well-documented and considered significant. Research indicates that mismanaged solid waste and inadequate waste collection systems are major contributors to the high levels of plastic pollution in marine environments (Jambeck et al., 2015). This issue is exacerbated in regions with limited resources for waste management, or where regulatory frameworks are weak or poorly enforced (Lebreton et al., 2017). This is applicable for the case of Tunisia, where the level of cleanliness depends on the importance of the tourism area, the engagement of the municipalities to enforce the regulations and to ensure the control of related operations, and the ability to take measures and initiatives and to engage in collaboration to reduce litter.

Legally, Tunisia's waste management regulatory framework is structured through a multifaceted system comprising various jurisdictions designed to address different aspects of waste management. This includes a general regulatory framework that governs waste management across all sectors, specific regulations tailored to particular types of waste (such as municipal, industrial, and hazardous waste), and a dedicated coastal management framework aimed at protecting marine environments. Despite the existence of these diverse regulatory components and institutions, the effectiveness of the system is hindered by inefficiencies in coordination and unclear delineation of responsibilities among the various entities involved.

The institutional framework for addressing marine litter in Tunisia involves several key actors, each with designated roles and responsibilities, yet the interaction between these actors often reveals significant inefficiencies. At the forefront is the Ministry of the Environment, which oversees national policies and regulations related to waste management and marine pollution. This Ministry collaborates with various specialized agencies such as the National Agency for Waste Management (ANGed), which focuses on the implementation and enforcement of waste management strategies. Additionally, local municipalities play a crucial role in waste collection and local environmental protection. Coastal areas, particularly those with high tourist activity, are also managed under frameworks that involve the Ministry of Tourism and local tourism boards, aiming to balance environmental concerns with tourism development. Despite these layered responsibilities, the interaction between these entities is frequently hampered by overlapping mandates, lack of clear communication channels, and insufficient coordination. This fragmented approach can lead to gaps in enforcement, delays in implementing effective measures, and inadequate responses to the growing issue of marine litter. To improve the management of marine litter, there is a pressing need for enhanced collaboration among these actors, clearer delineation of responsibilities, and more integrated policy frameworks that facilitate coordinated action across all levels of governance.

Tunisian coastlines, stretching 1,670 km, are vital to the nation's economy and daily life, influencing various sectors including tourism, commercial activities, and fisheries. However, the substantial waste generated by these sectors poses significant challenges for waste management and environmental protection, particularly in coastal and marine environments. Moreover, many other sectors contribute to the coastal litter in Tunisia, including the agriculture and the industrial sectors.

Tourism is a cornerstone of Tunisia's economy, contributing 13.1% to the GDP and providing around 389,000 jobs. The concentration of tourist facilities along Tunisia's coastlines significantly impacts waste management systems, particularly during peak tourist seasons. Coastal areas, which host over 76% of the country's hotels and restaurants, face unique challenges in handling the substantial waste generated by these establishments, including single-use plastics. Despite efforts to manage waste, the volume produced by the tourism industry, combined with the lack of waste sorting at sorting in many hotels (83% of which dispose of waste indiscriminately), complicate the issue (Chaabane et al., 2019). This scenario increases the pressure on local authorities and the waste management infrastructure, which must cope with increased waste volumes using existing logistical resources. Effective waste management in tourist hotspots is essential for preventing the accumulation of waste on beaches and in the marine environment, which can detract from the natural beauty of the coast and negatively impact local wildlife.

The majority of Tunisia's beaches, totaling over 142 along the coast, experience considerable waste generation due to diverse recreational activities. Cities like Tunis, Sousse, Nabeul, Sfax, and Gabès host a large number of these beaches, with lengths ranging from 1 to 7 kilometers and widths varying from 5 to 70 meters. During the summer season, the influx of tourists and recreational events results in increased litter, including plastics and other non-biodegradable materials. The popularity of Tunisia as a destination for pleasure boating further compounds this issue. With six operational marinas and a combined capacity of 2,150 berths, waste from boating activities adds another layer of complexity to coastal waste management. The combination of high visitor numbers, recreational events, and boating activities underscores the need for effective waste management strategies to mitigate the environmental impact.

Considered as one of the driving forces, maritime transport is critical for Tunisia's economy, with 98% of foreign trade conducted via sea routes. The eight commercial ports handle substantial cargo volumes and passenger traffic, contributing to significant waste production, including shipping containers and packaging materials. The efficiency of waste management in these ports is crucial to prevent operational waste from reaching the marine environment.

It is also important to mention that the fishing sector is integral to Tunisia's economy, with significant contributions from coastal and offshore fishing activities. However, this sector also generates considerable waste, primarily in the form of plastics such as nets, lines, and traps. The Gulf of Gabès, a major fishing area, contributes significantly to the country's fish production, but also faces challenges related to the disposal of fishing-related debris. The presence of 42 fishing ports and numerous artisanal landing sites further complicates waste management efforts in Tunisian coastal areas. The decline in traditional fishing tools and the increased use of plastics in fishing gear highlight the need for improved waste management practices and the promotion of more sustainable materials.

Marine litter on Tunisian beaches, as well as on other coastal beaches, presents a growing environmental concern that necessitates further investigation into the biodegradability of various waste items. Specifically, the accumulation of plastic cutlery and similar items in marine environments highlights the need to test their biodegradability within the water column. Understanding how these materials break down over time in seawater is crucial for assessing their long-term environmental impact. The aim of evaluating the degradation rates of cutlery items is to determine the effectiveness of these materials as alternative items to replacing current polluting products and in reducing marine pollution.

As already mentioned, and shown in the results, the biodegradability of certain cutlery items and food containers, recognized as being among the first items on the list of waste found on beaches, can be a solution to combatting their persistence in water. Testing the biodegradability of these cutlery items provides valuable insights into their environmental impact and suitability for reducing pollution. Thus, the degradation is assessed by measuring the decay of relevant physical properties, such as changes in molecular weight mass and molecular mass distribution, tensile properties, mass loss, morphological changes, etc. (Rutkowska et al., 2002 (a) ; Rutkowska et al., 2002 (b), Rutkowska et al., 1998).

This research examined both mass loss and morphological changes to characterize the degradation rates of various bio-based materials. These materials have potential applications in several economic activities along coastal areas, where the sea may serve as their eventual end-of-life destination.

The study was conducted over a one-year incubation period for the items in the Warnow River estuary. The study confirms the results highlighted by Law et al. (2014), that prolonged exposure to environmental factors such as heat, light or microbial action causes polymers to be degraded into smaller pieces.

Upon concluding the experiment, the main findings revealed that palm leaf, sugar cane bagasse, and paper/cellulose nearly fully degraded at most incubator locations, though the rate of degradation varied. This variation was influenced by the specific site and the position within the water column (upper or lower level). According to Jambeck et al. (2015), exposure to UV radiation and oxygen contributes to photodegradation. These processes occur to a depth of 50–100 µm and result in molecular weight reduction. In addition, the morphology of some partially-degraded materials changed, either slightly or considerably.

These changes depend on the material and its characteristics. For instance, most of the partially-degraded palm leaf samples were transformed into fibers or soft pieces. Similarly, the undegraded parts of sugar cane became very thin and decomposed into brown fragments. Additionally, the incubators containing wood items were partly inhabited by barnacles and mussels, which used the samples as habitats. The morphology of the wood items changed slightly, with their color darkening, and the items becoming somewhat softer to the touch, indicating that the degradation process may have begun.

At some stations, paper samples were covered by a thin layer of biofilm and barnacles.

This material became very soft and easily crushable, leading to a complete loss of mechanical properties.

Finally, no changes were noted in terms of the shape of PLA with some change of color, which was the case for Huang et al. (2020). The same was true for the common plastic PS and CPLA. An important growth of mussels and barnacles on top of the samples and inside the incubators was noted.

The degradation of the items placed at all stations began in June, coinciding with a significant increase in temperature. Prior to June, the degradation rate (DR) was typically 0% for all tested materials, but it reached higher percentages by the end of the summer. The experimental findings highlighted the crucial role of temperature in accelerating the degradation of palm leaf, sugar cane, and paper, especially in the upper incubators, which experienced relatively higher temperatures due to increased sun exposure. However, the results indicated that temperature did not impact the degradation of PLA, CPLA, and PS tableware.

For instance, the results confirm the finding of Huang et al. (2020) that, for example, PLA, which exhibits excellent degradation performance in controlled industrial composting, showed no degradation in the ocean. The main reason behind this is that the temperature in seawater is considered relatively low and the specific microbial species and number are less, resulting in obvious inhibition of the degradation process. This is also the case of CPLA and plastic items tested in the context of this research.

The results of the research carried out by Bagheri et al. (2017) on different materials including PLA, aimed to test their biodegradability in sea water and freshwater in a thermostatic chamber at 25◦C and under fluorescent light (16 h light and 8 h dark) for one year. They showed that PLA did not show any significant degradability under the testing conditions.

The impact of weathering on various materials is a complex issue. The degradation of materials is influenced by several factors including temperature, mechanical forces, sunlight, and sample depth, making the analysis of these influences complex (Ter Halle et al., 2017; Chubarenko et al., 2018).

This study on the degradation of tested items in the water column of the Warnow River estuary highlights the significant role that certain environmental parameter such as seawater temperature, sample depth, and sunlight, can have in accelerating or inhibiting degradation. The effects of other parameters remain unclear and warrant further investigation.

Paper cutlery demonstrated the fastest breakdown due to its fiber-based structure, which disintegrates readily in water. Wood cutlery, while more resistant, showed gradual degradation as it absorbed water and weakened structurally. Sugar cane cutlery, made from bagasse, decomposed relatively quickly, but not as swiftly as paper, reflecting its denser, fibrous composition. Palm leaf cutlery, crafted from naturally-fallen leaves, also exhibited significant degradation, but this varied depending on leaf type and processing. PLA cutlery, though designed to be biodegradable, remained largely intact in water, highlighting its dependence on industrial composting conditions for effective degradation. CPLA cutlery, with its increased crystallinity, was the most resistant to water, showcasing a slower degradation rate compared to PLA. This testing underscores the varying rates and mechanisms of biodegradability among these materials, revealing that while natural and organic options break down more quickly, bioplastics such as PLA and CPLA require specific conditions to decompose effectively.

These findings emphasize the importance of choosing the right material based on its environmental impact and the context in which it will be used.

These same items were later tested in compost to show their biodegradability under different conditions. This opens a new avenue for research, enabling us to explore how biodegradation rates and effectiveness differ between the water column and organic matter under various conditions.

Thus, and based on the data and information available, there are multiple measures to be considered when it comes to preventing and reducing coastal litter, and could include but are not limited to establishing extended producer responsibilities (EPR), developing a "deposit system" or a "return bonus system", and banning some single-use plastic items while making available the necessary alternatives.

It is therefore recommended that a national framework that encourages local authorities to prioritize actions and make informed decisions regarding the distribution, commercialization, and use of single-use cutlery by citizens, particularly in commerce and businesses, be established. Local regulations addressing problematic single-use plastic items should take into account the specific characteristics of each area, guided by targeted monitoring campaigns. To gradually implement these regulations, municipalities should develop pilot projects at specific events or locations to assess the results, explore alternatives to current materials, and replicate successful practices.

Enhancing awareness is a vital activity that must be strengthened across all levels of the value chain, involving producers, consumers, and decision-makers.

While recognizing the significance of exploring circular solutions to address the problems posed by marine and beach litter, the importance of cleaning operations remains pivotal in minimizing litter density along shorelines. The results indicate a significant reduction in waste observed on the sampled beaches during the summer season, directly linked to proactive beach cleaning initiatives. In contrast, during the winter months, these efforts are often minimal or entirely absent, resulting in increased levels of waste accumulation.

Based on the results of this research, and in order to effectively reduce coastal litter in Tunisia, several key measures could be implemented, as developed in Table 8.

Table 9. Summary table of the main recommended measures to reduce coastal litter in Tunisia

Measure (name)	Areas of application (National / Local)	Status (Extension of existing action / New action to start / New action in progress)	Main actor (s)	Partner (s)	Possible results	Application in Germany
Development of the packaging system (ECO-Lef) by establishing the Extended Producer Responsibility (EPR) principle at the national level.	- Regulations need to be actualized and adapted at the national level. - They need to be gradually applied at the national level. - They need to involve local authorities.	Extension of the existing action (Existing ECO-Lef) public system.	- Ministry of the Environment - National Waste Management Agency (ANGed)	Ministry of the Interior, municipalities, private sector (producers, collectors, recyclers, startups, etc.), Ministry of Finance.	- Increase the collection rate of packaging products. - Reduce the packaging litter	An EPR system for packaging is operational. Despite its complexity, the system contributes to the increase of the recycling rate and reinforce circular economy and its related infrastructure.
Reinforce the single-use plastic bag ban regulation (to cover other single-use plastic items) and its enforcement at the national level	- The ban regulation (decree) is under revision - Local regulation developed in Djerba Islands to ban single-use plastic bags - Enforcement needs to be strengthened.	Extension of existing action (current regulation)	Ministry of the Environment	- UTICA / CONECT - MIME - CITET	- Decrease of litter via plastic bags and reduce pollution - Incentivize the production of alternatives to plastic bags. - Reduce litter via other single-use plastic items.	- The regulation is in place. - The enforcement is reinforced

Identify biodegradable alternative to single-use plastic tableware items	Local initiatives, starting with local coastal events or commercial areas	New action to start	Municipalities	- Ministry of the Environment - CITET - ANGed - Research institutions	Decrease of the tableware single-use items pollution in the marine environment	- A pilot is operational in Rostock city - On 3 July 2021, the single-use plastic regulation came into force
Develop a national coastal area cleaning mechanism and reinforce the property system of the cities.	- National model - Operations at local level	Extension of existing action	APAL and municipalities	- Ministry of the Environment - ANGed - National systems (ECO-Lef for packaging in particular)	Decrease the level of pollution in beaches (in particular the top 15 items identified) via increasing the cleaning operations frequencies.	- Operational via the municipalities - Financial contribution from producers for cleaning operations.
Reduce the use of single-use plastic items in coastal tourism establishments (Hotels, Restaurants, Coffee shops)	- Operation at the private company level - Voluntary engagement (1-5 years) - Certification / label (5-10 years)	Extension of existing action	- Ministry of the Environment - Ministry of Tourism	- CITET - ANGed - Federation of hotels (FTH) - UTICA/CONECT	- Reduce pollution with single-use plastic items - Decrease waste generated and collection costs	Partially operational / plans to ban

Closure of dumpsites in coastal areas and improve the management of sanitary landfills	Local level	Extension of existing action	ANGed	- Ministry of the Environment - Ministry of Finance - Municipalities - Private sectors (waste management companies).	Reduce the pollution transfer of lightweight packaging to the coastal and marine environment	Operational

5. CONCLUSIONS AND FUTURE RESEARCH

Marine litter is a global issue, originating from a range of different sources, both land- and sea-based. This work shows that the problem has been identified in coastal areas in both Tunisia and Germany, with different levels of pollution and different types of waste identified. In Tunisia, it has been identified that solid waste management remains one of the challenges currently facing the Tunisian government in order to promote services, satisfy citizen expectations in terms of property and collection, develop a circular economy, reduce land pollution, and avoid coastal and marine litter.

Plastic was clearly identified as the main form of coastal litter in Tunisia. The research revealed an average of 4.16 kg/km/day of plastic litter in the sample tourism areas. In contrast, Sfax and Gabès exhibited a higher average of approximately 15.9 kg despite having low beach tourism activity. In particular, the results of the analyses of the top 15 litter items show the presence of cigarette butts, plastic / polystyrene pieces 0 – 2.5 cm followed by 2.5 cm > < 50 cm, caps/lids, bags (e.g. shopping bags), drinks (bottles, containers and drums), food wrappers, cutlery/trays/straws, crisp/sweet packets and lolly sticks, string and cord (diameter less than 1 cm), foam sponge, toys & party poppers, food containers including fast food containers, cleaner (bottles, containers and drums) and other plastic/polystyrene items. The identified items are in particular single-use plastic products, used one time in the coastal areas or moved via the sea or the wind to reach the beach.

In addition, the results of this study clearly show that tourism and recreational activities are the main contributors to beach litter in coastal areas of Tunisia, comprising between 90% and 95% of the total sources of litter, followed by fishing activities. In contrast, construction, and other economic activities generate a smaller proportion of the items identified during this research.

Solutions to coastal litter issues should be based on sustainable organizational and legal concepts that are adapted to the country’s specificities, current strategies and existing regulated and non-regulated waste recovery systems. Fighting coastal litter, in particular that caused by packaging materials, requires the implementation of integrated solid waste management systems and structured financing that targets the circularity of the products of the whole value chain. Therefore, considering the dominance of packaging and plastics of the waste identified in coastal areas, it is highly recommended the current packaging recovery system (ECO-Lef) be optimized by establishing an adequate and sustainable financial mechanism via the EPR system that covers packaging waste management operations, and including beaches and coastal area cleaning operations (including rocky beaches).

Furthermore, local authorities, including rural municipalities such as those created in 2018 should play a crucial role and enhance their waste collection operations to boost collection rates beyond the current 84% in order to effectively prevent plastic pollution. In addition, mismanaged landfills or dumpsites represent an important source of marine litter, particularly when they are located close to coastal areas. Therefore, the existing infrastructure for waste treatment (sanitary landfills) should be improved, and old open dumpsites should be rehabilitated and closed to avoid the transfer of lightweight packaging to the coastal areas and beaches. Local authorities should prioritize the reinforcement of the cleaning operations on beaches by allocating necessary financial resources and ensuring a better coordination with the Coastal Protection and Planning Agency (APAL), the existing cleaning mechanism (Mechanism 41) and the future Producer Responsibility Organization (PRO) of the packaging EPR system.

Single-use plastic bags still represent a major issue in Tunisian coastal areas and are identified among the top 5 items. Despite the single-use plastic bags ban enacted on March 1, 2020, under Decree No. 32 dated January 16, 2020, which prohibits the production, importation, and use of conventional single-use plastic bags in supermarkets, this problematic item is still causing issues at economic, social, and environmental levels. The results in the case of the sample beaches in the target cities in Tunisia show that plastic bags are still in the top six items identified. Plastic bags are more particularly present in non-tourism areas (Gabès and Sfax) than in tourism areas (Sousse and Gammarth). The decree is still not adequately enforced, and incentives and control mechanisms should be reinforced to reduce the prevalence of single-use plastic bag litter and presence in the environment.

Furthermore, the monitoring campaign highlighted that cigarette butts make up the top two items identified in the sample coastal areas in different seasons and years during the elaboration of this research in Tunisian coastal areas. They were also identified in German coastal areas and in many other countries. Adapted solutions and reinforced education and awareness-sharing needs to be considered to reduce the amount of such litter.

Plastic cutlery and single-use items of litter were also present on the Tunisian beaches and coastal areas. Those items are difficult to collect and are considered to be problematic as they do not have any value at their end of life and, thus, cannot be reintegrated into the economic value chain via recycling. They remain abandoned in the environment without any collection, either on the part of the authorities or by the informal sector. This presents several environmental issues. Results of beach litter monitoring campaigns show that a number of single-use plastic items were identified and are classified as the top 15 plastic items, including such items as caps and lids, drink bottles, food wrappers, cutlery/trays/straws, crisp/sweet packets, lolly sticks, etc. This type of litter was also present in German coastal areas, in particular during coastal events.

Therefore, and in order to develop effective solutions, experiments were carried out in the framework of this work to monitoring the degradation behavior of alternative items to tableware single-use items in the coastal areas of Germany, with the aim of duplication or future testing in the Tunisian coastal conditions. The main findings of this research indicate that tableware items composed of palm leaf, sugar cane and paper are less resistant to the seawater physicochemical parameters than wood, PLA, CPLA and plastic (PS) items, which showed a certain resistance during the experimentation period. Furthermore, items placed in the upper incubators degraded relatively faster in most cases than those of the same material and placed in the lower incubators. Furthermore, the results showed that temperature and exposure to sunlight could be the main factors that accelerate the degradation of such materials. The degradation could also be related to the presence of water currents and a greater number of pelagic organisms. However, in this study, the potential of these parameters on the DR has not been proved. Therefore, further studies will be needed to complete and fully check the test methodology used, in terms of the determination of the causes of both physical and biological degradation. In addition, it is also recommended that more tableware items be tested, particularly those recently put on the market.

From these experiments, a number of lessons learned could be transferred to future studies as per the research methodology, such as:

- While selecting the areas of experimentation, ensuring accessibility to the incubators as well as the safety of the incubators.
- The field work requires a regular check-up of the installed equipment in order to ensure the continuity of the experiments without disturbing the degradation process.
- Mechanical destruction experimentations within the laboratory and under controlled conditions could be relevant to testing the effect of water movements and currents on

the DR of the items.

- The impact of specific factors and conditions such as temperature, UV light, pH and salinity in accelerating the degradation of items in the water column are still largely unknown.

In order to prevent and reduce the amount of tableware single-use items litter, the results of the experiments carried out in the Germany should be duplicated and tested in the Tunisian coastal areas. Variations in physicochemical conditions, especially seasonal changes in water temperature, and the presence of diverse living organisms, may influence the degradation behavior of alternative items, potentially leading to varying degradation outcomes.

APPENDIX

Table 10. Results of monitoring of physicochemical parameters of station S1, Hohe Düne (HD)

Date	Level	Temperature (°C)	pH	Salinity (‰)	Dissolved oxygen (mg/l)	Transparency
03/05/2019	UP	10.4	8.16	8.23	10.46	2.33
	DOWN	9.7	8.06	8.63	10.81	
13/05/2019	UP	11.8	7.05	10.44	10.8	4
	DOWN	11.6	7.05	10.88	10.39	
21/06/2019	UP	19.13	8	-	9.91	-
	DOWN	19.06	7.96	-	9.32	
12/07/2019	UP	18.2	8.28	8.26	9.53	-
	DOWN	18.05	8.14	-	9.12	
02/08/2019	UP	18.8	8.5	10.12	9.15	-
	DOWN	19.1	8.22	7.39	8.87	
20/08/2019	UP	19.2	7.96	5.96	7.96	-
	DOWN	18.9	8.29	6.22	9.73	

Table 11. Results of monitoring of physicochemical parameters of station S2, IGA Park (I)

*On the 30th of July 2019, there were no measurements taken. In fact, the incubators were cleaned and opened to check to status of the tested elements.

Date	Level	Temperature (°C)	pH	Salinity (‰)	Dissolved oxygen (mg/l)	Transparency (m)
09/04/2019	UP	8.8	8.32	7.64	13.68	1.88
	DOWN					
17/04/2019	UP	10.1	8.13	7.62	12.06	2
	DOWN	8.6	8	11.7	11.47	
25/04/2019	UP	12.3	7.91	11.29	9.36	-
	DOWN	10.9	7.78	11.82	10.21	
13/05/2019	UP	12.8	8.31	10.01	13.17	2.2
	DOWN	12.5	8.31	10.11	13.18	
23/05/2019	UP	15.1	8.24	10.14	10.43	0.95
	DOWN	14	8.19	11.14	11.55	
06/06/2019	UP	19.5	8.2	8.63	9.59	0.6
	DOWN	19	8.16	8.62	9.58	
17/06/2019	UP	19.93	8.51	8.31	13.18	1
	DOWN	19.16	8.46	8.3	7.38	
25/06/2019	UP	21.9	8.47	7.32	10.54	-
	DOWN	19.9	7.78	-	5.26	
08/07/2019	UP	16.9	7.9	8.17	7.84	-
	DOWN	17	7.86	-	7.77	
24/07/2019	UP	22.2	8.18	8.42	8.97	-
	DOWN	21.4	8.14	10.08	8.7	
30/07/2019*	UP	-	-	-	-	-
	DOWN	-	-	-	-	
06/08/2019	UP	21.53	8.25	8.15	9.47	-
	DOWN	21.2	8.16	7.9	9.38	
21/08/2019	UP	20.06	8.58	10.39	13.05	-
	DOWN	19.66	8.28	9.94	9.49	

Table 12. Results of monitoring of physicochemical parameters of station S3, Gehlsdorf (G)

Date	Level	Temperature (°C)	pH	Salinity (‰)	Dissolved oxygen (mg/l)	Transparency (m)
17/04/2019	UP	10.7	8.08	6.66	12.87	1
	DOWN	8.7	7.77	11.72	12.94	
24/04/2019	UP	14.2	8.16	8.16	13.09	-
	DOWN	13.6	8.17	8.14	13.25	
08/05/2019	UP	13.7	8.45	2.82	12.27	-
	DOWN	13.2	8.16	5.19	10.72	
24/05/2019	UP	17.06	8.57	9.85	13.49	0.6
	DOWN	14.53	7.61	3.95	3.7	
05/06/2019	UP	22.2	8.75	7.7	17.53	0.5
	DOWN	19.3	8.11	8.62	8	
19/06/2019	UP	24.2	8.35	5.41	12.46	-
	DOWN	20.7	7.96	8.71	12.37	
10/07/2019	UP	19.4	8.56	4.42	12.55	-
	DOWN	19.2	8.55	-	13.33	
24/07/2019	UP	24.4	8.32	6.54	12.24	-
	DOWN	22.03	7.94	8.89	7.9	
06/08/2019	UP	23	8.32	5.4	12.12	-
	DOWN	22.76	8	6.75	8.64	
22/08/2019	UP	21.03	8.57	4.29	13.29	-
	DOWN	20.46	8.06	9	7.15	

Table 13. Results of the degradation of selected items in Station S1, Hohe Düne (HD)

Incubators and content	Initial weights of samples	Final total weight	Degradation rate (DR) (%)	Final status of the item
HD.1.1.U Paper	Plate (1.6 g), small cup (0.3 g)	1.1 g (- 0.8 g)	42.1%	Soft to the touch
HD.1.2.U Plastics	Cup (1 g), box (2.1 g)	4.3 g (+ 1.2 g)	0 %	Not degraded
HD.1.3.D Paper	Plate (1.8 g), small cup (0.4 g)	1.5 g (- 0.7 g)	31.8%	Soft to the touch
HD.1.4.D Plastics	Cup (1 g), box (1.8 g)	3.5 g (+ 0.7 g)	0 %	Not degraded
HD.2.1.U Wood	Spoon (2.5 g), fork (2 g)	4.8 g (+ 0.3 g)	0 %	Soft to the touch
HD.2.2.U Palm leaf	Plate (3.3 g)	0.6 g (- 2.7 g)	81.8 %	Small fibers
HD.2.3.D Wood	Spoon (1.6 g), fork (2 g)	5.8 g (+ 2.2 g)	0 %	Soft
HD.2.4.D Palm leaf	Plate (2.9 g)	0 g (- 2.9 g)	100 %	Totally degraded
HD.3.1.U PLA / CPLA	PLA (lid 0.9 g, cup 1.2 g)/ CPLA (lid 1.9 g, spoon 2.4 g)	6.6 g (+ 0.2 g)	0 %	Not degraded
HD.3.2.U Sugar cane	Bleached (1.1 g)/unbleached (1.2 g)	0 g (- 2.3 g)	100 %	Totally degraded
HD.3.3.D PLA / CPLA	PLA (lid 1 g, cup 1.1 g)/ CPLA (lid 1.7 g, spoon 2 g)	6 g (+ 0.2 g)	0 %	Not degraded
HD.3.4.D Sugar cane	Bleached (1 g)/ unbleached (1.3 g)	0 g (- 2.3 g)	100 %	Totally degraded

Table 14. Results of the degradation of selected items in Station S2, IGA Park (I)

Incubators and content	Initial weights of samples	Final total weight	Degradation rate (%)	Final status of the item
I.1.1.U Plastics / CPLA	Cup (0.6 g), box (1.5 g), knife (1.6 g)	4 g (+ 0.3 g)	0%	Not degraded
I.1.2.U Sugar cane	Bleached (2.8 g)/ unbleached (1.3 g)	0 g (- 4.1 g)	100%	Totally degraded
I.1.3.D Plastics / CPLA	Cup (0.6 g), box (1.5 g), knife (1.8 g)	4.5 g (+ 0.6 g)	0%	Not degraded
I.1.4.D Sugar cane	Bleached (2.8 g)/ unbleached (1.3 g)	1.4 g (- 2.7 g)	65.8%	Soft to the touch
I.2.1.U Wood	Tableware (1.3 g)/ (2.2 g)	7.1 g (+ 3.6 g)	0 %	Soft to the touch
I.2.2.U Palm leaf	Rectangular plate (1.5 g)	0 g (- 1.5 g)	100%	Totally degraded
I.2.3.D Wood	Tableware (1.8 g)/ (1.7 g)	6.8 g (+ 3.3 g)	0 %	Soft to the touch
I.2.4.D Palm leaf	Plate (1.6 g)	1.1 g (- 0.5 g)	31.2%	Small fibers
I.3.1.U Paper	Plate (1.7 g), cup (2 g)	0 g (- 3.7 g)	100%	Totally degraded
I.3.2.U PLA/CPLA	PLA (cup 2.5 g)/ CPLA (knife 2.3 g, lid 1.7 g)	18.2 g (+ 11.7 g)	0 %	Not degraded
I.3.3.D Paper	Plate (1.7 g), cup (1.9 g)	0 g (- 3.6 g)	100%	Soft to the touch
I.3.4.D PLA/CPLA	PLA (cup 2.5 g)/ CPLA (knife 2.3 g, lid 1.7 g)	9.1 g (+ 2.6 g)	0 %	Not degraded

Table 15. Results of the degradation of selected items in Station S3, Gehlsdorf (G)

Incubators and Content	Initial weights of samples	Final total weight	Degradation rate (%)	Final status of the item
G.1.1.U Sugar cane	Bleached (1.6 g)/ unbleached (1.9 g)	0 g (- 3.5 g)	100%	Totally degraded
G.1.2.U PLA / CPLA	PLA (cup 1 g, box 1.8 g)/ CPLA (lid 1.5 g, spoon 3.1 g, knife 2.5 g)	11.6 g (+ 1.7 g)	0 %	Not degraded
G.1.3.D Sugar cane	Bleached (1.6 g), unbleached (1.8 g)	0 g (- 3.4 g)	100%	Totally degraded
G.1.4.D PLA / CPLA	PLA (cup 1 g, box 1.8 g)/ CPLA (lid 1.6 g, spoon 2.7 g, knife 1.9 g)	10.6 g (+ 1.6 g)	0 %	Not degraded
G.2.1.U Palm leaf	Plate (4 g)	0 g (- 4 g)	100%	Totally degraded
G.2.2.U Wood	Spoon (2.3 g), stick (0.7 g)	6.7 g (+ 3.7 g)	0 %	Soft to the touch
G.2.3.D Palm leaf	Plate (4.2 g)	1.3 g (-2.9 g)	69 %	Small fibers
G.2.4.D Wood	Spoon (1.5 g), stick (0.8 g)	4.6 g (+ 2.3 g)	0 %	Soft to the touch
G.3.1.U Paper	Plate (1.6 g), cup (1.7 g)	0 g (- 3.3 g)	100%	Soft to the touch
G.3.2.U Plastics	Cup (0.8 g), box (1.6 g)	3.3 g (+ 0.9 g)	0 %	Not degraded
G.3.3.D Paper	Plate (1.7 g), cup (1.7 g)	1.3 g (- 2.1 g)	61.7%	Soft to the touch
G.3.4.D Plastics	Cup (0.9 g), box (1.7 g)	3.2 g (+ 0.6 g)	0 %	Not degraded

Table 16. Interview to gather information concerning the investigation into waste management on Tunisian beaches.

Questions	**ANSWERS**
Can you provide information about the legal and institutional framework of waste management in Tunisia?	
What is your opinion: do you think that the marine litter topic has the same legal and institutional framework?	
Are you familiar with the locations of landfills and dumping sites within the country?	
Are they operational or not?	
Who is responsible for overseeing the management of the landfills?	
Which industry do you believe has a greater influence on the issue of marine litter?	
Do you think that the Tunisian government is investing in the right way in the waste management sector and beach cleanness?	
What could be the factors that affect the waste management sector?	
Can you estimate the frequency of beach cleaning?	
Which source do you assume is more polluting?	
Do you have any figures to add regarding waste collection, recycling, collection rate, waste generated per capita?	
Do you have any documentation or report to provide?	

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DECLARATION OF INDEPENDENCY

I hereby declare that the present work is prepared and submitted by me independently without any assistance other than from those cited and acknowledged in the thesis.

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