

Review

Marine Litter Impact on Sandy Beach Fauna: A Review to Obtain an Indication of Where Research Should Contribute More

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Abstract: In order to identify how research contributes to the knowledge of marine litter as a pressure on beaches, we reviewed interactions of beach fauna with this pollutant. Entanglement of pinnipeds in fishing gear, negative correlations between macroinvertebrates abundance and sediment pollution, and the presence of plastic surrounding burrows were primary evidence of beach fauna interacting with stranded litter. Ingestion represents the main body of research; microplastic uptake by invertebrates has been studied by laboratory experiments and field collections to report the presence of polymers in tissues. In the natural context, the higher the urbanization surrounding beaches and sediment pollution, the higher the concentration of microplastics in organs of bivalves. This approach currently constitutes the main research direction, but ecotoxicological assays are emerging prospects to assess the effects of exposure to microplastics. Beached macroplastics entangle and entrap invertebrates and vertebrates, and studies have reported increasing negative interactions with seals and sea turtles. Changes in nesting and feeding behavior of resident and transient organisms have been shown as typical early warning indicators of marine litter impacts. The focus on fauna–litter interactions holds terrific potential for research and citizen science projects, which finally becomes a powerful driver towards environmental awareness on sandy beaches.

Keywords: microplastics; marine litter; sandy beach macrofauna; plastic; human impact; conservation



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1. Introduction

Reports of marine litter analyzing a variety of materials and shapes in the marine environment date back half a century [1,2]. The environmental contamination and the consequent pollution are broadly recognized as a widespread threat, affecting all marine ecosystems from the poles to deep ocean basins [3]. Plastic polymers are materials of broad use; consequently, the chances of environmental spills are higher, and its occurrence in marine litter usually surpass other litter types [4]. Furthermore, under an ecological perspective, all plastic polymers are persistent in the environment, with disappearing rates by natural processes on the scale of decades to centuries [5]. Residing in the environment for a long time, and undergoing breakdown processes, plastics become a nearly irreversible pollutant (throughout a series of fractions, from macro, to fragments, to microplastics). The emerging but urgent need is to gather information about contamination, and relate that with pollution from marine litter plastics and consequences for biodiversity [6].

Research is hence facing the challenge of providing urgently needed information, shifting from the quantification of plastic polymers in the environment (patterns), to the assessment of their effects on organisms (processes). Numerous and serious consequences

of plastics presence in the environment for marine fauna have been assessed and/or hypothesized [6]. The risks are mainly related to the ingestion of micro- and macroplastics [7] and the entanglement and entrapment in large debris causing lethal and sublethal damages [8]. Currently, more than 900 marine species have already been negatively affected by the interaction with marine litter items, and this number is expected to increase exponentially [9].

When it comes to marine litter assessment, sandy beaches are often used as elective sites for studying and monitoring, given their behavior as “sinks” for marine litter, the cost-effectiveness of the studies, and the possibility to engage the society in the process. More in detail, sandy beaches represent the interface between land and sea, comprise half of the world’s ice-free coastlines and support various ecosystem services, of which recreation is of paramount relevance for economies [10]. This often carries along a bias towards its recreational use at the expenses of conservation [11]. For their nature of ecotonal systems, beaches are known to be depositional sites where marine litter from adjacent ocean and land compartments accumulate and are exchanged with still unclear dynamics [12]. In addition, beachgoers’ activities directly contribute to marine litter disposal and accumulation on coastal areas [13]. At the same time, beach visitors seem to react negatively to the presence of marine litter and are usually sensitized to reports of charismatic animals interacting with it [14–16]. However, excepting effects on tourism and on charismatic fauna (e.g., sea turtles and mammals), the consequences of stranded marine litter on beach fauna are usually not a target of management actions [17,18]. This set of characteristics, social and ecological, makes sandy beaches an ideal compound to tackle the assessment of interaction of fauna with marine litter and shed light on the marine litter-related risks to which resident and transient beach fauna (beyond marine megafauna and species of commercial relevance, for a long time prioritized in local research) are exposed.

Science-based information regarding the effects of marine litter on sandy beach resident fauna and its final effect on ecosystem functioning is crucial for supporting social mainstream action, i.e., specific management interventions and environmental education. In parallel, sandy beaches are openly recognized as elective locations of campaigns (e.g., clean-up days) on combating marine litter and monitoring of fauna–litter interactions [19–21]. Undoubtedly, beaches provide an exceptional asset for creating and sustaining a base of empirical evidence and its channeling via scientific outreach and environmental education actions [22]. The number of beached marine litter studies has indeed increased exponentially worldwide [14,23]. The recent outbreak of the personal protective equipment (PPE) litter driven by COVID-19 [24] added dramatically to this. Thus, the awareness of threats associated with beached marine litter beyond tourist deterrence, including the negative effects that this poses to beach fauna and ecosystem functioning is at reach, but should find new directions.

With the goal of synthesizing the available scientific information regarding the interaction of sandy beach fauna with marine litter, we screened the literature related to indirect and direct interactions of different taxonomic groups with beached marine litter, including entanglement, entrapment, ingestion and their consequences for different ecological organization levels. Previous syntheses on organisms with indicator roles and suggested for biomonitoring [25,26] were used as background for the queries. The results from the queries to literature were discussed in terms of (1) synthesis, (2) toxicity of marine litter to beach fauna and correlation with potential drivers such as contamination of the sediment and proximity to urban infrastructure, and (3) the interface with social tissue towards beach conservation and litter pollution mitigation.

2. Materials and Methods

We searched for articles that evaluated indirect, direct or putative interaction of sandy beach invertebrates and vertebrates with marine litter in Google Scholar database. We choose Google Scholar because it is broader than other specific search bases and can be accessed without needing subscription. We used the following keywords present in title:

“beach” OR “surf zone” AND “marine litter” OR “marine debris” OR “waste” OR “plastic(s)” OR “microplastic (s)” OR “macroplastic (s)” AND “ingestion” OR “entanglement” OR “entrapment” OR “interaction” OR “benthic fauna” OR “turtle” OR “bird (s)” OR “fish”. We considered the last three terms together with “beach” word to avoid articles reporting interaction with litter outside beach ecosystem. Afterward, the terms “beach” and “surf zone” were replaced by family and genera of sandy beach indicator species known to characterize the beach and surf zone habitat, along with their common names, as follows: “ghost crab” OR “Ocypodidae” OR “Ocypode” OR “mole crab” OR “Hippidae” OR “Emerita” OR “sandhopper (s)” OR “Talitridae” OR “Talitrus” OR “Orchestia” OR “Atlantorchestoidea” OR “Donacidae” OR “Donax” [25].

Lists of references from papers found in the literature review were further inspected with the aim of finding studies that had not been retrieved from the search platforms ($n = 35$) (Spreadsheet S2, Figure S1). Regarding species that use beaches only for resting and nesting, such as penguins, sea turtles and pinnipeds (i.e., transient organisms), entanglement was retained while ingestion was not included in our dataset, because this latter kind of interaction results most likely from foraging in marine ecosystems other than beaches [27,28]. Accordingly, plastic ingestion assessed from stranded animals was not considered. Marine litter as a vector for bioinvasion was not considered in the literature review because it is not a direct interaction with sandy beach species (i.e., non-incrusting organisms). The full list of papers screened as well as the steps for exclusion were accessed by all authors (Spreadsheets S1 and S2) and steps taking to the final list of items retained were discussed in the framework of the study objectives.

Two other parameters were further extracted from the resulting literature: (i) The concentration of microplastics in sediment, whenever indicated in the papers, was used to test whether the concentration of microplastics in macroinvertebrates (expressed as microplastics per g of wet weight) quantitatively reflects the abiotic pollution level. Thus, the process follows the concept of beach invertebrates as biomonitors [25]. (ii) The urbanization level surrounding each beach (scale of 1000 m) contained in the dataset was used to assess its role as drivers of fauna contamination. The HMc (Human Modification Metric [29]) was applied to represent the urbanization level, using the geo-coordinates provided in the articles surveyed, and applying the packages “raster” [30] and “rgdal” [31] in R software. Details of HMc calculation are provided as Supplementary Material (Doc file S1). These analyses were limited to bivalves and crabs because data is available only for these groups.

Finally, bivariate regression models were built with sediment pollution and urbanization as predictive variables, and the microplastic concentration in organisms as dependent variable [25]. For bivalves, only the concentrations measured from the soft tissues were included in the analyses. The visual inspection of the residues preceded the adjustment of the models with linear function, as well as the confirmation of homoscedasticity, normality, and influence of outliers.

3. Results and Discussion

3.1. Overview

The search, initially performed in October 2021, with latest update on August 2022, returned 57 articles (process in Figure S1 and full dataset in Spreadsheets S1 and S2). The number of articles retrieved for each keywords’ combination ($n = 242$) are provided in Supplementary Material (Spreadsheet S1, Figure S1). Expert judgment was applied as the criteria for selection, and to proceed with further screening.

Most studies were conducted with invertebrates ($n = 34$), followed by pinnipeds ($n = 13$), sea turtles ($n = 4$), surf zone fish ($n = 5$), and birds ($n = 1$) across a range of negative interaction with marine litter (show in the table at the end of text). Of those studies, one was performed with invertebrates and birds simultaneously aiming to evidence microplastic trophic transfer on beaches [32]. One study reported animals and algae trapped in fishing lines deposited on a Mediterranean beach, reinforcing the contribution of marine litter as vector to biological invasions [33], though not explicitly regarding beach fauna. It is

unlikely that floating marine litter contribute to the introduction of exotic beach fauna because most species are not encrusting.

The relatively low number of papers compared to other reviews about marine litter is evidence that knowledge on beach indicator species and their ecology is not being up-taken by plastics studies, and paths of interaction are still scarcely explored. Co-occurrence analysis focusing on sandy beach literature showed that plastic-related keywords interact 100–500 times with fauna-related terms, including mainly invertebrates and turtles [34]. However, the analyses performed by these authors could not define if interaction really occurred on the beach or if the co-occurrence of words source from mere speculation in the papers. Meaningfully, the current focus highlights the main ways of fauna–litter interaction on sandy beaches.

3.2. Putative and Diffuse Interactions: A Starting Point

Studies had long reported pinnipeds entangled with litter when using beaches for resting (i.e., transient species) [21]. These reports emerged in the 1980s [35–39], being usually based on beach monitoring, but without taking into account seals entangled in beached litter (i.e., diffuse interaction). Most entangling litter comes from fishery activities, including plastic packing bands that are also used on bait boxes during angling on beaches [40]. Some authors argue that stricter monitoring of pinnipeds is an important and reliable mitigation action, even because most seals–litter interaction can be easily reported on sandy beaches [21].

To our knowledge, the biological consequences of marine litter to sandy beach resident fauna were firstly conjectured by a correlative study [41]. The authors assessed spatial variability and composition of marine litter in five beaches in southern Brazil, and found negative, but weak correlation between the number of items and the number of ghost crab (Crustacea: Ocypodidae) burrows. The co-occurrence of litter with more profusely studied stressors related to recreational use of beaches actually represents a confounding effect. This was clear in the case of lower burrow densities of two ghost crab species that were observed on more polluted sectors of Cable Beach in Australia, whereas these sectors also receive substantial vehicle traffic simultaneously to litter pollution [42]. In general, urbanization is assumed to be associated with higher littering probability [43,44]. Recent studies remark that a high amount of macroplastics on urbanized beaches exerted confounding negative effects on crustacean abundance, because it is an independent mechanism (yet co-occurring with trampling and vehicle traffic) by which human disturbance affects populations size and community richness [45,46]. The major challenge is to unveil if and how marine litter contributes to the widespread reduction in fauna population sizes in urban beaches [47,48].

The first clear evidence of marine litter usage by ghost crabs was demonstrated by the presence of litter surrounding burrows in south-eastern Brazil [49] (Figure 1). Interestingly, the authors verified that straw, polystyrene Styrofoam, soft plastic, and ropes were more frequent on burrows' entrances than in the drift line. This apparent selectivity and the higher occupation rates of burrows with litter (68%) than without (28%) suggested that litter could be used in homing behavior (as a landmark for burrow placement).

Contradicting possible negative effects [41,45], some authors suggests that large litter items may increase habitat heterogeneity on beach environments, besides increasing sediment stability and burrow abundance at patchy scales [50]. In addition, higher sediment stability may explain the burrow construction by ghost crabs near large plastic items as it does on other physical barriers to sediment transport on beaches [51]. This postulate, similar to the stabilization of sediment substrate in presence of coarse pieces (from pebbles up), remains untested and needs in-depth consideration regarding the effect of differential litter densities on ghost crab behavior.

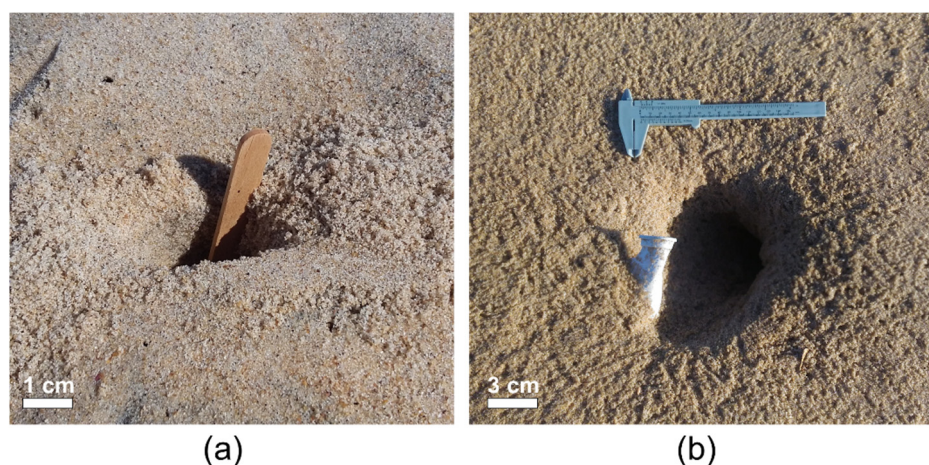


Figure 1. Litter surrounding burrows is evidence of anthropogenic debris usage by the ghost crab *Ocypode quadrata* (Fabricius, 1787). (a) Ice lolly stick; (b) food pack. Pictures by Leonardo Costa.

3.3. Ingestion

The negative effects of marine litter on health and fitness of beach fauna are probably preponderant, particularly regarding the ingestion of microplastics. Information about other litter types ingested by beach fauna and potential sources are generally lacking. The first evidence that microplastics could be swallowed by a beach species was demonstrated in laboratory experiments, where the sandhopper *Talitrus saltator* (Montagu, 1808) feeds on polyethylene microspheres (diameter 10–45 μm) mixed in fish food [52]. This preliminary investigation did not show any consequence of microsphere ingestion on the survival capacity in the laboratory. Accordingly, in situ manipulative experiments show that some invertebrates, such as the ghost crab *Ocypode quadrata* (Fabricius, 1787), misidentify large litter items (e.g., cigarette butts, straws, popsicle sticks, paper napkins and polystyrene Styrofoam) as food sources [53] (Figure 2), evidencing that ingestion of plastic occurs mainly during active foraging.

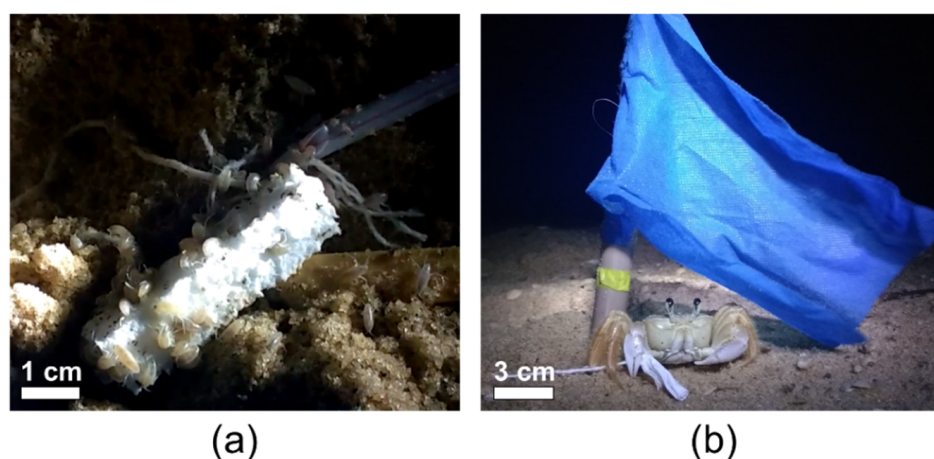


Figure 2. Sandy beach invertebrates misidentify marine litter with food. (a) Talitrid amphipods feeding on styrofoam; (b) ghost crab feeding on paper and string. Pictures by Julyana Madureira.

Thereafter, various studies have reported macro- and microplastics ingestion (mainly in the shape of colored fibers) by invertebrates. Almost 50 beach invertebrate species were reported to ingest micro- and macroplastics at natural context. This included sandhoppers [54,55], ghost crabs [56–58], meiofaunal polychaetes and nematodes [59,60], mole crabs [61] and mainly clams [62–69]. However, these works did not investigate possible effects of ingestion at any biological level.

Negative consequences of plastic ingestion by beach fauna at organism level have been demonstrated in laboratory assay [70]. For instance, the survival of the talitrid *Platorchestia smithi* Lowry, 2012 decreases 35%, and jump height decreases ~1.6 cm after 120 h exposure to microplastics [70]. Jumping impairment due to microplastics ingestion may reduce the ability of individuals to respond to predators, and the resilience to human trampling [70]. The mole crab *Emerita analoga* (Stimpson, 1857) exposed to polypropylene fibers in laboratory assay presented increased mortality and decreased retention of egg clutches after ingesting microfibers, causing variability in embryonic development rates [71]. The exposure of *Donax trunculus* Linnaeus, 1758 to polyethylene and polypropylene mixture (0.06 g/Kg of sand) induced a significant inhibition of Acetylcholinesterase activity (a neurotoxicity biomarker) in both gills and digestive gland and oxidative stress (measured by Catalase and Gluthation-S-Transfereases enzymatic activities) in all organs, which has been studied [72]. The clam *Atactodea striata* (Gmelin, 1791) reduced the filtration rates (and energy uptake) when exposed to high microplastic concentrations, avoiding the incorporation of particles without nutritional value [73]. These are mechanisms that could contribute to the reduction in macroinvertebrate population size on urban beaches worldwide synergically with other physical and chemical stressors.

Even pristine beaches are exposed to marine litter pollution [74,75], posing a challenge to unveil the role of plastic as a causative agent of human-induced changes in diversity patterns. Recent studies have tested whether microplastics incorporation by beach fauna varies according to the proximity of beaches to urbanized areas. Urbanization level on beaches in Morocco and India significantly influenced the concentration of microplastics in clam tissues [62,63]. Oppositely, microplastics ingestion by ghost crabs was not related to urbanization in south-eastern Brazil [57]. Correspondingly, relationships between microplastics concentration in invertebrate tissues and urbanization surrounding beaches are not statistically significant ($r^2 < 0.05$; $p > 0.10$) when considering data from reviewed studies together (Figure 3). These contrasting, species-dependent, and local-dependent results challenge the assessment of microplastics beach pollution as overall paradigms [25].

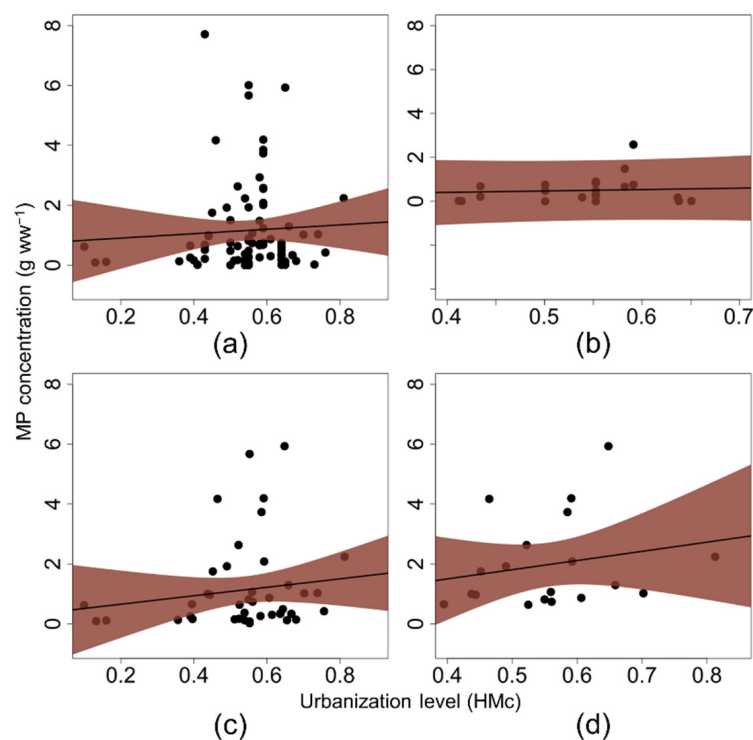


Figure 3. Microplastics (MP) concentration in soft tissues (grams of wet weight) of sandy beach invertebrates (y-axis) and in relation to urbanization level (HMc—Human Modification Metric) surrounding the beaches (x-axis). (a) All invertebrates; (b) crabs; (c) bivalves; (d) Donacidae clams.

Sentinel species should accumulate a pollutant in their tissues without major adverse effects on population size. They can be regarded as biomonitors when the individuals concentrate the target pollutant in the proportion it is found in the environment [25,76]. Studies on decapod crustacean species did not find significant correlation between microplastics density in sediment and prevalence of contaminated crabs (Figure 4a). However, microplastics concentration in soft tissues of beach clams seems to reflect the sediment and water pollution level (Figure 4b). Notable ingestions of microplastics by clams inhabiting sandy beaches in India [63], Thailand [67], China [64], Argentina [66], United States of America [65], South Korea [77], and Morocco [62] were recently reported. In fact, specifically donacid clams are commonly used in environmental monitoring studies as sentinel species for the biomonitoring of sandy beaches [78].

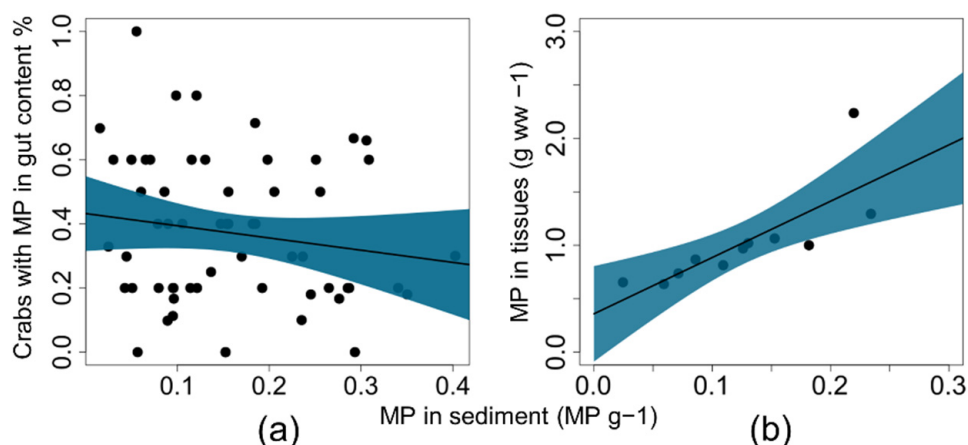


Figure 4. (a) Relationship between the frequency of individuals of decapod crabs with microplastics (MP) in the digestive tract in relation with MP concentration in the sediment is not significant according to regression model ($r^2 = 0.01$; $p = 0.231$); (b) Relationship between MP concentration in soft tissues of *Donax cuneatus* Linnaeus, 1758 and MP concentration in the sediment is significant ($r^2 = 0.66$; $p = 0.001$).

Microplastics uptake through ingestion can propagate to predators such as surf zone fish and shorebirds, as microplastic abundance nearshore increases. Indeed, ingestion of plastic by transient vertebrates foraging on beaches such as fishes and shorebirds has already been reported [79–83]. Similar composition of plastic fibers in invertebrates' tissues and shorebirds' scats, for instance, suggests secondary ingestion and trophic transfer of microplastics [32].

A typical prediction of microplastics studies is that the feeding mode affects microplastic ingestion by fishes. Unsurprisingly, surf zone fishes (typical predators of invertebrates on sandy beaches) ingest microplastics, but this pollutant incorporation does not always differ among trophic guilds, weakening the prediction that functional traits affect microplastics ingestion [79]. Oppositely, the abundance of microplastics in invertebrates of sandy beaches and mudflats was related with feeding mode, with deposit feeders and grazers being more susceptible to microplastics ingestion [64]; the authors, however, argued that patterns are very local specific. Indeed, the effect of feeding mode of organisms on microplastics ingestion is still inconsistent in the literature [64]. Sandy beaches are excellent study grounds for filling this gap, given the variety of trophic guilds found on sandy shores and food resource zonation across the littoral active zone [10,84].

Plastics are admittedly a vector of trace elements, persistent organic pollutants, and polycyclic aromatic hydrocarbons for beach invertebrates. Microplastics ingested by beach clams have dozens of chemical elements adhered to their surface [62]. Notoriously, microplastics in the beach environment can adsorb persistent organic pollutants that can potentially be assimilated by organisms. The presence of microplastics seems to cause greater proportional uptake of polybrominated diphenyl ethers, as found with the surf

zone amphipod *Allorchestes compressa* Dana, 1852 [85]. However, microplastic ingestion can both transfer and remove polybrominated diphenyl ethers from organisms collected on beaches, indicating a partial balance among positive and negative effects [86]. Thus, future studies combining knowledge from both food web, plastics and other adsorbed pollutants and their chemical impacts at individual level are required to depict paths of biomagnification along trophic networks connecting land and sea.

3.4. Entanglement

Entanglement is often caused by ghost fishing gear, being one of the most damaging effects of litter particularly for the megafauna [40,87,88]. We have only limited knowledge about the risks of entanglement that marine litter on the sand surface exert on less charismatic invertebrates inhabiting beaches. However, many invertebrates are mobile and have surface activity (e.g., ghost crabs), being at imminent risk of entanglement on derelict fishing gear, for instance (Figure 5). A recent study quantified the density of fishing lines and hooks deposited on a Mediterranean beach and found 120 animals entangled belonging to seven taxa, though most of them were not sandy beach species [33].



Figure 5. Invertebrates entangled in fishing gear. (a) *Pachygrapsus marmoratus* (Fabricius, 1787); (b) *Ocypode quadrata* (Fabricius, 1787). Pictures by Maurizio Pinna and Leonardo Costa.

In particular, vertebrates that use sandy beaches for resting, nesting, staging and foraging are exposed to being entangled in large debris [89,90]. For instance, turtle hatchlings emerging from nests have been entangled in fishing nets and entrapped in plastic containers (experimentally deployed), possibly causing a significant decrease in nest numbers in the long term [91]. Worryingly, turtle hatchlings are not able to avoid contact with litter or reverse their direction to escape, increasing risks of adverse effects [91]. Several studies reporting pinnipeds entangled in fishing gear on sandy beaches exist, dating back to the 1980s (shown in the table at the end of text). Some of those studies presented very insightful approaches, linking the patterns recorded with the implementation of strategies (e.g., MARPOL annex V) from Government and industry to reduce the problem of derelict fishing gear. Recent and specific reviews have been published on pinnipeds entanglements, so further discussion was not expanded in this manuscript [21,40].

3.5. Entrapment

Similar to studies that report entrapment of turtle hatchlings on containers during manipulative experiments [91], some authors have shown that invertebrates are becoming stuck inside plastics. For instance, large amounts of litter created a significant barrier in which the strawberry hermit crab *Coenobita perlatus* H. Milne Edwards, 1837 encounter during their daily activities [92]. The authors quantified the number of hermit crabs entrapped in plastic containers in Australia, estimating that an average of 2 crabs/m² and 1 crab/m² become entrapped in debris and die each year on Henderson Island and

the Cocos Islands, respectively. Decaying hermit crabs inside containers can attract other individuals to replace their shells (and possibly to scavenge on dead crabs), thus amplifying the observed negative effects. Similarly, discarded containers on beaches act as pitfall traps for sand-dwelling beetles [93]. A total of 18 sand-dwelling beetle species from various trophic guilds were found entrapped, mostly in glass bottles, capturing more than 50% of the individuals found.

3.6. Individual Trait Changes and Consequences on Populations

Stranded or half-buried marine litter is a barrier for surface activity of organisms crawling on sand. An innovative in situ baiting experiment was applied to quantify the efficiency of the gastropod *Nassarius pullus* (Linnaeus, 1758) in locating and moving toward food according to the level of plastic cover [94]. The authors found prolonged food searching time and decreasing accuracy of orientation towards the bait as the level of plastic cover increased. The consequence seems to be the reduction in the gastropod abundance frequently observed during periods of deposition of large amounts of litter on the intertidal sandflat areas of Talim Bay, Philippines [94]. Changes in surf zone fish feeding behavior had also been supposed, because of a positive correlation between litter pollution and insect ingestion by pompanos (*Trachinotus* spp.) [95]. This is evidence that human disturbances deplete natural prey, and the amount of litter is instead attracting synatropic insects for the beach.

Large debris deposited on the sand also impose adverse effects on sea turtle nesting females and hatchlings [90,96,97]. The ratio between the amount of hatchling tracks reaching the end of the permanently wet area line and the total number of eggshells was used as a proxy of success rates of the green turtle *Chelonia mydas* (Linnaeus, 1758) in Turkey beaches [97]. A strong negative correlation between litter amount and the number of hatchlings reaching the sea was found [97]. Disorientated turtle hatchlings may be easier prey, with litter playing a role in reducing seawards orientation, though this hypothesis remains untested. Similarly, the highest concentrations of plastics along the tracks of looping (i.e., females crawling on sand and returning to the sea without nesting) green turtles was observed, compared to tracks where turtles successfully nested (i.e., eggs laid in a completed chamber) [90]. Large natural and anthropogenic debris were experimentally removed from one of three sections of loggerhead sea turtle *Caretta* Linnaeus, 1758 nesting beaches in northwest Florida, and as a consequence, the number of nests increased by 200% [96]. These is strong evidence that macroplastics have adverse impacts on sea turtle nesting behavior, and removal of large debris from nesting grounds could be an effective management action.

3.7. Marine Litter, Beach Fauna, and Active Citizenship Populations

Beach cleaning is an important requirement, especially when it comes to beach quality awards and beach perception [15]. Certainly, the removal of marine litter benefits both tourists and fauna [98]. However, ecological concerns were raised, especially when (i) there is no discrimination between marine litter and natural inputs such as stranded wrack or carrion, and (ii) beach cleaning is carried out using mechanical machinery to rake and sieve the beach sand (grooming), usually to the size of a cigarette butt [99,100]. Indeed, ecologists report that grooming with wrack removal and heavy machine traffic has an impact on the beach biodiversity. These impacts are usually neglected for the sake of aesthetic benefits and public health aims without considering the importance of benthic biodiversity along beaches in sustaining functional environments.

Zielinski et al. (2019) [98] reviewed the ecological effects of beach cleaning and argued that most studies are centered on the impact of wrack removal (habitat loss and food depletion). However, when beaches with low macroalgae inputs are targeted in impact assessments, the negative effects of cleaning are weakened. This corroborates a meta-analysis conclusion that taxa such as talitrid amphipods, which include both sand-associated and wrack-associated sandhoppers and beachhoppers, respectively [101], are for

now the unique robust indicators of beach cleaning disturbance on sandy beaches [26]. Mechanical beach cleaning further includes the impact of beach compaction, and carries along confounding effects of stressors. Therefore, this is considered an unreliable management action to mitigate litter pollution, even though the most applied to recreational beaches.

Beach cleaning imposes a social–ecological conflict [102] that could be partially solved with scientific studies disentangling the effects of fauna–litter interaction with specific attention to the conceptual discrimination between anthropogenic and natural litter. It is well accepted that manual clean-up is more reliable than grooming to reduce litter pollution and improve aesthetic condition of tourist beaches without exerting dramatic ecological degradation [98]. This kind of action was also found extremely efficient in connecting people with beaches, strengthening emotional values [103]. However, even if this is desirable to raise awareness, it was noted that clean-up events with a high audience can attract hundreds of people to a single beach, and acute trampling can exert negative ecological effects from resident invertebrates to nesting and foraging vertebrates [104]. In addition, removal of debris without sieving could cause substantial sand loss [105].

The role of active citizenship is intertwined with all those aspects, though research should mark the path to reveal such potential. For instance, citizen science performed through clean-ups was found to be a major contributor to global repositories and with data quality comparable to research scientists [106]. Microplastics studies for citizen science were less developed, also due to instrumental impediments such as the unavailability of analytical tools to citizens, though recent initiatives target to overcome this obstacle [107,108]. When it comes to the study of interaction between beach fauna and marine debris, reviews point at a relevant activity of citizen scientists and monitors ($n = 7$ studies) involving citizen science and targeting the interaction of marine litter with biota (after reference [106]). The information on species affected by marine litter, in the aforementioned review, was documented on an interactive website [109]. However, these results do not make it into scientific literature and were not found in this bibliometric analysis. Whether this depends on a scarce confidence of research scientists on citizen-sourced data, or on citizen science protocols to be improved, it remains clear that a tighter dialogue between science and society is needed, and sandy beaches are a paradigmatic case for that, including their unique fauna as important tools.

4. Conclusions

While the production of knowledge on plastics contamination and pollution of beaches is steadily on the increase, specific focus on the interaction between plastic litter and organisms is still in the beginning. Manuals such as the report on the monitoring of marine litter [110] included the “litter in biota” chapter, with a focus on sea turtles and birds and on the two categories “entanglement” and “ingestion”. However, the up-take from the guidelines to published literature seems to be slower than the urgent demand—both social and scientific—for information. Herein, we synthesized the main consequences of litter to beach fauna reported in the scientific literature. Entanglement and entrapment of beach fauna in deposited litter clearly exert direct mortality. The consequences of micro- and macroplastics ingestion on beach crustacean, polychaete, fish and birds are still not well known, though laboratory assays with invertebrates as study models evidence sublethal negative effects. Possibly, there are many and variable interactions to be reported from now on.

Interaction of beach fauna with litter can be depicted through a variety of creative, powerful and logistically viable experimental designs that will yield knowledge beyond speculative causalities. The number of studies investigating ingestion of plastic by marine fauna is growing rapidly and the vast list of species reported to uptake this pollutant remains increasing [9]. On sandy beaches, all resident and transient species are very likely ingesting microplastic from the sand, water and their prey, and thus, descriptive studies reporting this interaction is not a novelty anymore. Certainly, the application of sound methods for inspecting microplastic in digestive tract of beach fauna will often allow the

detection of colored fibers and other small-sized plastic particles also by non-specialists such as citizen monitors.

Even so, beaches are very accessible ecosystems, favoring investigation of general hypotheses such as bioavailability, bioaccumulation, biomagnification, and the role of individual trait variation in microplastic ingestion. Tested hypotheses will then call for integration of beach ecology paradigms into studies on plastics [34], adding a meaningful and necessary information layer. If morphodynamics and touristic pressure drive the littered plastic dynamics as it does with biodiversity, the physical environment probably regulates the interaction of these two components and possible consequences at population and community levels. Bioassays or in situ experiments can disentangle the consequences of plastic ingestion for beach fauna, mainly through the comparison of body condition, survival, fecundity, and behavior between individuals with and without microplastics in their tissues. Possibly, the amount of microplastics available in abiotic compartments of beaches has already surpassed the threshold in which most organisms are able to avoid ingestion. Thus, changes in populations' size and community diversity will hardly be related to litter pollution level in "compare and contrast" approaches and gradient analysis. Further designs should consider shifting baselines, and a background of microplastics continuously bioavailable.

Other interactions of beach fauna with plastic have been reported with creative designs that in general do not require specialized tools. Thus, entrapment, entanglement, and putative interactions (e.g., litter surrounding burrows and incorporated in nests) can be investigated via direct observation and citizen science projects. For that, standardized protocols are of paramount importance, seeking to gather information of fauna–litter interaction in broad scales in synchrony with the measuring of key biotic and abiotic variables that portray a set of information supporting management and mitigation actions. The success of citizen science projects depends on the strength of the message and its social-ecological impact [111]. Emerging approaches such as netnography for the analysis of social media will certainly contribute to support advances in this sense, mainly because beaches have a widespread online engagement, including quantifiable markers (e.g., engagement measurements, images and hashtags, toponyms) [112].

In conclusion, in the "Plasticene" age [113], beach researchers should be prone to provide novel knowledge on beach pollution by litter and consequences on fauna, and keep presenting sound backgrounds for supporting management and citizen actions. In a context of sandy beaches seen as commercial products and the presence of litter as damaging its value, which factors could trigger the behavior of beach users and beach managers? Does the interaction of beach charismatic species with litter have more appealing information than the argument of beachgoers deterrence because of the reduction in quality in coastal scenery? Environmental awareness and active citizenship could be promoted on sandy beaches, particularly via flagship species (e.g., sea turtles, shorebirds and pinnipeds) that naturally engage people in conservation initiatives [76]. However, research in the field of social sciences and conservation marketing is still required to detangle the effectiveness of negative versus positive messages to build engagement towards the conservation of social–ecological ecosystems such as beaches [114].

Table 1 shows different types of interaction between marine litter and sandy beach fauna reported in several studies.

Table 1. Type of interaction between marine litter and sandy beach fauna reported in several studies.

Taxonomic Group	Species Name	Marine Litter Type	Impact Type	Reference
Bivalves	<i>Anadara antiquata</i>	Microplastics	Ingestion	[68]
	<i>Donax trunculus</i>			[62]
	<i>Donax cuneatus</i>			[63]
	<i>Donax semigranosus</i>			[67]
	<i>Donax</i> spp.			[64]
	<i>Amarilladesma mactroides</i>			[66]
	<i>Siliqua patula</i>			[65]
	<i>Ruditapes philippinarum</i>			[77]
	<i>Nutallia obscurata</i>			[69]
	<i>Venerupis philippinarum</i>			[69]
Gastropods	<i>Neopycnodonte cochlear</i>	Fishing lines and hooks	Entrapment	[33]
	(Other species)	Microplastics		
	<i>Atactoidea striata</i>		Metabolic effects	[73]
Gastropods	<i>Nassarius pullus</i>	Macroplastics	Behavioral traits	[94]
Crustaceans	<i>Talitrus saltator</i> (Sandhoppers)	Microplastics	Ingestion	[52,54]
	<i>Ocypode quadrata</i> (Ghost crabs)	Beach debris	Homing	[49]
		Microplastics and macroplastics	Ingestion	[56–58]
	<i>Ocypode quadrata</i>	Macroplastics	Behavior traits	[49,53]
		Marine litter		[41,45]
	<i>Atlantorchestoidea brasiliensis</i>	Marine litter	Reduction in abundance	[45]
	<i>Excirrolana brasiliensis</i>			
	<i>Emerita brasiliensis</i>			
	<i>Platorchestia smithi</i>	Microplastics	Behavior traits/shredding	[55,70,115]
	<i>Orchestoidea tuberculata</i>			
<i>Orchestia gammarellus</i>				
<i>Allorchestes compressa</i>	Microplastics	Vehiculation of POPs	[85,86]	
<i>Emerita analoga</i> (Mole Crabs)	Microplastics	Ingestion	[61,71]	
<i>Coenobita perlatus</i> (Strawberry Hermit Crab)	Macroplastics	Entrapment	[92]	
Polychaetes	<i>Saccocirrus papillocercus</i>			
	<i>Saccocirrus pussicus</i>	Microfibers	Ingestion	[59]
	<i>Claudrilus ovarium</i>			
	<i>Meiodrilus gracilis</i>			
(other species)				
Nematodes	<i>Enoplolaimus</i> spp.	Microplastics	Ingestion	[60]
Insects	<i>Isomira</i> sp.	Beach litter	Entrapment	[93]
	<i>Mogulones aubei</i>			
	<i>Ammobius rufus</i>			
	<i>Opatrum obesum</i>			
	(Other species)			
<i>Halobates micans</i>	Plastic pellets	Oviposition	[116]	

Table 1. Cont.

Taxonomic Group	Species Name	Marine Litter Type	Impact Type	Reference
Fish	<i>Chelon rischardsonii</i>	Microplastics	Ingestion	[79,81–83]
	<i>Opisthonema oglinum</i>			
	<i>Bagre marinus</i>			
	<i>Cathorops spixii</i>			
	<i>Sciades herzbergii</i>			
	<i>Chloroscombrus chrysurus</i>			
	<i>Conodon nobilis</i>			
	<i>Haemulopsis corvinaeformis</i>			
	<i>Stellifer brasiliensis</i>			
	<i>Genidens genidens</i>			
Reptiles	Sea turtles	Beach litter	Behavior traits	[96]
	<i>Chelonia mydas</i> (Sea turtles)	Macroplastics	Entanglement	[90]
Beach litter		Behavior traits	[97]	
Marine litter		Entanglement	[91]	
Birds	<i>Trachinotus</i> spp.	Marine litter	Behavior traits	[95]
	<i>Arenaria interpres</i>	Microplastics	Ingestion	[32]
	<i>Calidris alba</i>			
	<i>Calidris alpina</i>			
	<i>Calidris canutus</i>			
<i>Calidris ferruginea</i> (Other species)				
Mammals	<i>Arctocephalus</i> ssp (fur seal)	Marine litter (mainly fishing gear)	Entanglement	[35–38,117–125]
	<i>Arctocephalus forsteri</i>			
	<i>Neophorca cinerea</i>			
	<i>Zalophus californianus</i>			
	<i>Monachus schauinslandi</i>			
	<i>Arctocephalus</i> ssp.			
	<i>Mirounga leonine</i>			
	<i>Callorhinus ursinus</i>			
	<i>Arctocephalus pusillus</i>			
	<i>Arctocephalus gazella</i> <i>Arctocephalus</i> ssp			
<i>Callorhinus ursinus</i>	Fishing gear	Behavioral, energetic and population changes	[38]	

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/microplastics1030039/s1>, Spreadsheet S1: keywords combinations and articles retrieval in Google Scholar; Spreadsheet S2: articles retrieval from citation searching; Spreadsheet S3: dataset used in the meta-analysis; Figure S1: PRISMA flow diagram for systematic review; Doc file S1: Details of the Human Modification Metric (HMc) calculation [29–31]; Doc file S2: PRISMA checklist for systematic reviews [126].

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