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Microplastics in seafood: Implications for food security, safety, and human health

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ABSTRACT

Once critically thought of only as a menace in the marine environment, plastics particulates, especially microplastics (MPs) are gradually gaining access into the human body. However, among diverse sources of exposure examined, seafood might be the most critical, as it is deemed a "necessary evil". Seafood consumption in recent years has experienced geometric increase and so its likelihood to stealthily introduce food-borne to humans. This is because marine organisms have become repositories of MPs and their domiciled microbial community, which are often not beneficial. We ratiocinated that steady human consumption will increase multiple risks presented plastic composites, their leachates and exogenously formed adsorbents (antibiotic resistance bacteria: ARBs, antibiotic resistance genes: ARGs, heavy metals and noxious aromatics) might pose. However, a critical dearth in literature only affords a collaged comprehension of the whole picture regarding this issue, which might impede progress in risk assessment and control measures. In this regard, this study aimed to update knowledge on known trends and delve deeper to suggest unknowns that might be critical for seafood safety and security, and ultimately, human well-being.

1. Introduction

Since 1940s, there have been records of increased use of plastics due to their low cost, wide durability, versatility, and mechanical resistance that help its application in numerous activities of modern life (Plastic Europe, 2019). In packaging, different classes of plastics are used including polypropylene (PP), poly(ethylene terephthalate) (PET); polyethyelene (PE), poly(vinyl chloride) (PVC) and polystyrene (PS) (Andrady, 2011), most of which are indiscriminately disposed after single use. Annually, it is estimated that about 4.6 to 12.7 million tons of plastic are introduced into the ocean (Vital et al., 2021). This constitutes about 80% of marine litter and therefore poses a worldwide environmental challenge. Moreover, plastic particulates are among the contaminants that can be accumulated in seafoods, especially in the edible tissues. Hence, potential health risks that may result from regular human consumption might be inevitable. Plastic particulates may occur as a result of mechanical stress brought by certain environmental factors (in the case of weathering) or may be synthesized on industrial scale to suit certain purposes (Unuofin, 2020). They usually regarded as microplastics (MPs), which are <5 mm in diameter (Wright et al., 2013), but may be extended to include nanoplastics (<100 nm diameter) (Lusher et al., 2017). MPs are known as one of the most ubiquitous constituents of marine debris, having been detected in several environments. So far, they have been discovered within the benthos and throughout the water column (Wright et al., 2013), in outdoor and indoor air, different altitudes, sediments, soil, drinking water, seawater, freshwater, terrestrial and aquatic organism, even human blood (Hu et al., 2022; Leslie et al., 2022). Interestingly, due to their synthetic orientation, loosely bound polymers used during synthesis, which possess high bioaccumulation potentials, may be washed off as leachates, thus presenting severe public and environmental health implications (Unuofin, 2020). Moreover, particulates may act as a vector of heavy metals, microbial pathogens, along with pigments, additives, and dyes present in the plastics that could possibly hamper seafood safety (Daniel et al., 2021). The increasing global concern about MPs has led to an extensive number of studies assessing MPs in water. However, research focused on their food security and human health consequences is gradually being visited. MPs which were previously imagined only as environmental contaminants are critical considered as food contaminant. The knowledge of the impacts of MPs on food safety and human health is vital for risk assessment and a major panacea to this global threat.

Consumption of MPs by marine organisms, such as fish may occur

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through non-selective, incidental ingestion (primary), or ingestion of an MP-fed prey (secondary) (Nelms et al., 2018). In controlled environments, such as the commercial aquaculture farms, seafood may be exposed to MPs through poorly processed fish meals or may be cutaneously embedded during post-harvest processing. In this regard, MPs have been detected in a wide range of commercial animals regarded as seafood, such as fish, oysters, mussels, and brown shrimp (Curren et al., 2020), and may occur in ready-to-eat foods. Such concerns might destabilize the growth of the seafood industry. Furthermore, several laboratory studies have investigated the effects of MPs on a variety of model organisms, including the reports of Aljaibachi and Callaghan (2018) on *Daphnia magna*, Batel et al. (2018) on *Danio rerio*, Bringer et al. (2020) on *Crassostrea gigas*, Horn et al. (2020) on *Emerita analoga*, Li et al. (2020) on *Mytilus edulis*, as well as their fate (biotic and abiotic aging) and interactions with organic, inorganic and other contaminants Rozman and Kalčíková (2022). Despite numerous reviews on the known and known unknowns, regarding microplastic seafood contamination and ultimate environmental and public health consequences, there is a dearth of information on the interactions in microplastics microbiome and how humans can be impacted. In this regard, this study, apart from providing an incisive update on trends in microplastic contamination, will discuss the impact of the microplastic microbiome on the occurrence of foodborne pathogens and antibiotic resistance genes (ARGs).

2. Methodology

Literature search was conducted on published articles written in English language Web of Science (WoS), data base, Google scholar, and Science Direct. A single or combination of keywords were search as the target words including “microplastics”, “seafood”, “seafood security”, “seafood safety”, “food web”, “outbreaks of seafood”, “microplastics as vector for microorganisms”, “microplastics as vector for antibiotic resistant genes”. All these keywords were retrieved in the title, keywords, or in the text of published work. Articles, book chapters and reviews about seafood, microplastics contamination of seafood, incidence in seafood-related disease outbreaks information were selected, including cited references.

2.1. Microplastic environmental pollution

A major leap in curtailing microplastics environmental pollution is having a lucid understanding of the metamorphosis of plastic particulates as well as their respective thresholds. This would be an invaluable tool in risks assessment and further mitigation measures. The earliest contact of plastics with pristine environments is facilitated by anthropogenic activities, which might span across industrial, cosmetical, occupational and recreational leanings. In this regard, plastics might be introduced as whole bulky composites, such as fishing gears, nets, disposable cutlery, cups, toys, buckets. Another gateway could be smaller pieces, such as ornaments (beads or buttons), dice, and other plastic pieces of board games, even body scrubs which are washed down the draining during body care routine (Unuofin, 2020). However, from their initial areas of deposition, plastics may be ferried to other matrices and across boundaries by human (infants and scavengers) and animal agents (pets), and mostly abiotic agents (atmospheric conditions). Alongside this positional reshuffling, larger composites may undergo structural disintegration into finer particulates through a proposed pathway (Fig. 1) (Browne et al., 2007). Although popularly reported pollution sites are major coastlines, rivers and lakes, as well as landfills, it would be interesting to note the emerging sites or sources of MP pollution which could ultimately empty into marine life. Presently, MP adoption and pollution extends from conventional wastes to textile wastes, road dusts from tyre and road frictions, agricultural sludge, polymer-coated fertilizers, counterfeit plastic foods, plumbing, building construction sites, downstream wastewater treatment plants (WWTPs). Essentially, we would refer to phenomena where plastic polymers are being synthesized, fabricated or retrofitted through abrasion, such as in electronics, shoe making, even automobile assemblage inter alia. Since MP released from these sources are mostly diffuse, accurate estimations or fingerprinting of their input into the net atmospheric abundance of these polymeric particulates might not be realizable at present, except advanced, sophisticated sampling and analytics are assumed. Ultimately, since absorption of plastic particulates (mostly nanoplastics) has been observed in tissues of some plant species (Taylor et al., 2020), it is not unthinkable to assume that certain sea weeds and sea plants might serve as agents of MP accumulation in certain seafoods.

2.2. Microplastics in seafood

Recently, seafood contamination with MPs has been highlighted as an emerging concern for worldwide food security. They have reportedly contaminated all sections of marine ecosystems, including the food web and biota across various trophic levels such as crustaceans (Zhang et al., 2019), bivalves (Zhao et al., 2018), mammals (Nelms et al., 2018) and

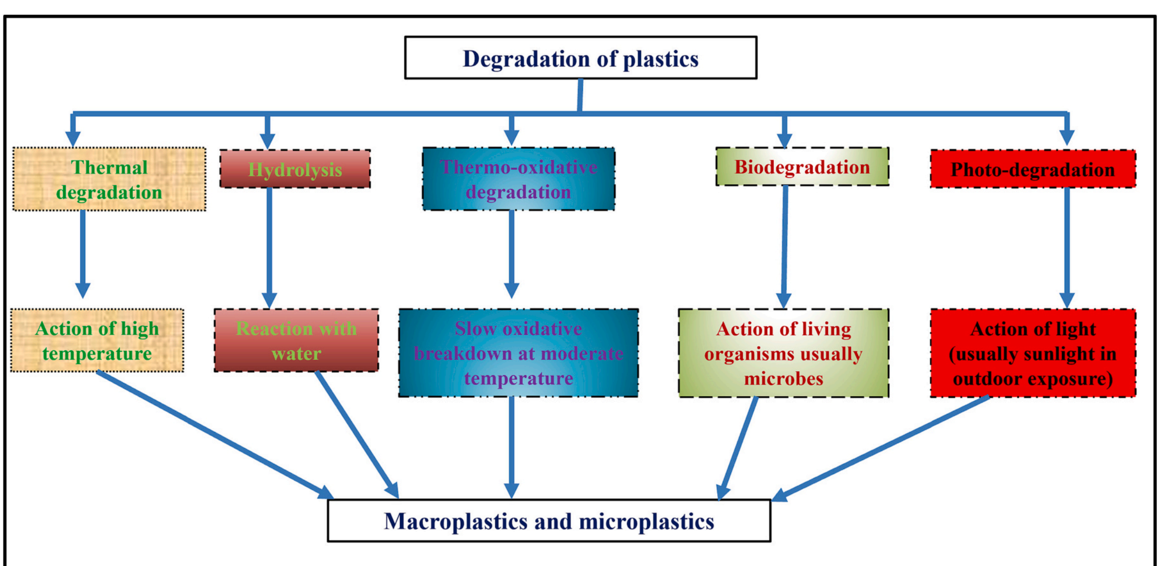

Fig. 1. Environmental degradation of plastics under different conditions.

fish (Yao et al., 2021). Moreover, they have been embedded in different parts of organisms, including the liver (Collard et al., 2017), gills (Jaafar et al., 2021), edible tissues of shellfishes (shrimp, crabs, squid) (Daniel et al., 2021), oyster (*Crassostrea gigas*) (Saelee et al., 2021), in fresh and processed mussels (Nalbone et al., 2021) and in brain and muscle of commercial fish species, such as red mullet and pontic shad (Atamanalp et al., 2021). However, the detection of MPs in the gut of these organisms might not pose a huge health risk as most of them are eviscerated during processing. Nevertheless, some commercial seafoods are usually consumed fresh or whole (bivalves) along with their guts (Dowarah et al., 2020). There is a tremendous increase in reports on MPs detection in seafood and food. However, analytical detection and separation techniques that will facilitate a better understanding of MPs size and distribution in seafood are particularly few. Analytical detection techniques of MPs will necessitate obtaining information on both the morphological structure and chemical composition of the particles (Bogdanović et al., 2022). MPs are known as a pathway of seafood borne threats due to their ability to act as a vector of compounds that could possibly impede seafood safety (Daniel et al., 2021). Hence, their presence in seafood raises concerns on hygiene and safety, as their contamination of seafood as well as its products can probably adversely impact human health. However, to determine whether the uptake of MPs through seafood pose a threat to human health, exposure to MPs must first or foremost be quantified to ascertain whether exposure is high enough to cause harmful effect (Bogdanović et al., 2022). Therefore, regular study should be conducted to detect the presence of MPs in seafood and other food meant for human consumption to help prevent the impeding risk associated with consumption of seafood contaminated with MPs. Likewise, there is also needs to address this emerging threat or risk of MPs contamination of seafood and quickly implement mitigation plans or strategies to help protect the environment and human health against this contaminant.

2.3. Impacts of microplastics on seafood security

By 2050, the world's population is projected to grow to 9.5 billion, and the rise in demand for animal-based protein is expected to double (FAO, 2019; Ong et al., 2021). Globally, seafood is the major source of animal protein and it makes up of over 20% of food intake by weight for over 1.4 billion people (Golden et al., 2016). According to FAO (2017), food security implies when all people regularly have economic and physical access to safe, adequate, and nutritious food that meets their nutritional needs and food preferences for a purposeful life. Currently, some known risks factors that influence food security include eutrophication, pathogens, oxygen depletion, pollution, climate variability due to both climate change and short-term events, conflict, ocean acidification and economic recession. Other risk factors that pose a significant risk to food security includes plastic debris especially MPs in seafood and abandoned fishing gear in the water bodies like ocean (Walkinshaw et al., 2020). MPs or plastic debris ingested by marine organisms may cause intestinal blockage while hard MPs with irregular shapes and sharp edges can pierce the intestinal wall, injure, and damage the digestive system (Ahrendt et al., 2020). All these adverse effects can reduce food intake in these marine organisms, eventually leading to hunger and death (Bucci et al., 2020; Catarino et al., 2021), thereby leading to seafood loss. Moreover, MPs could serve as an adsorbent and vehicle for other contaminants, which could adversely impact seafood, when ingested whole. A regular phenomenon can be observed in the fish, which is demonstrated to manifest different metabolic and physiological disorders (Fig. 2).

In natural environments and commercial fisheries, MPs have the potential to reduce the proliferation of edible marine organisms. The accumulation or increase in occurrence of MPs in the oceans and in other aquatic matrices is certain to create several consequences on the already compromised marine life or health, leading to less energy allocated for growth and reproduction (Choy et al., 2019). MPs can directly affect organisms via leaching of harmful chemical adsorbates, thereby causing trophic transfer of chemical contaminants in marine food webs (Naik et al., 2019). Consequently, numerous adverse effects manifest, such as reduction in fertilization and larval abnormalities (Martínez-Gómez et al., 2017), neurotoxicity (Barboza et al., 2018a), decreased metabolic rate and body mass (Welden and Cowie, 2016), oxidative and intestinal damage (Prokić et al., 2019), decrease in allocation of energy for growth (Farrell and Nelson, 2013), reduction in predatory function (de Sá et al., 2015), reduction in swimming performance, changes in behavioural responses (Barboza et al., 2018b) and death (Yan et al., 2021). Other adverse health effects reported in fishes associated with ingestion of MPs includes reduction in feeding intensity, immune-suppression and improper gill functioning (Mallik et al., 2021). Several marine contaminants or pollutants are well known to biomagnify as well as pose heightened risk to higher trophic organisms. However, very little information depicts this phenomenon with MPs, with current research giving contradictory viewpoints (Hantoro et al., 2019; Walkinshaw et al., 2020). These evidences indicate that the abundance of MPs in any given aquatic environment may adversely affect its biodiversity conservation, environmental health, ecosystem services, and ultimately

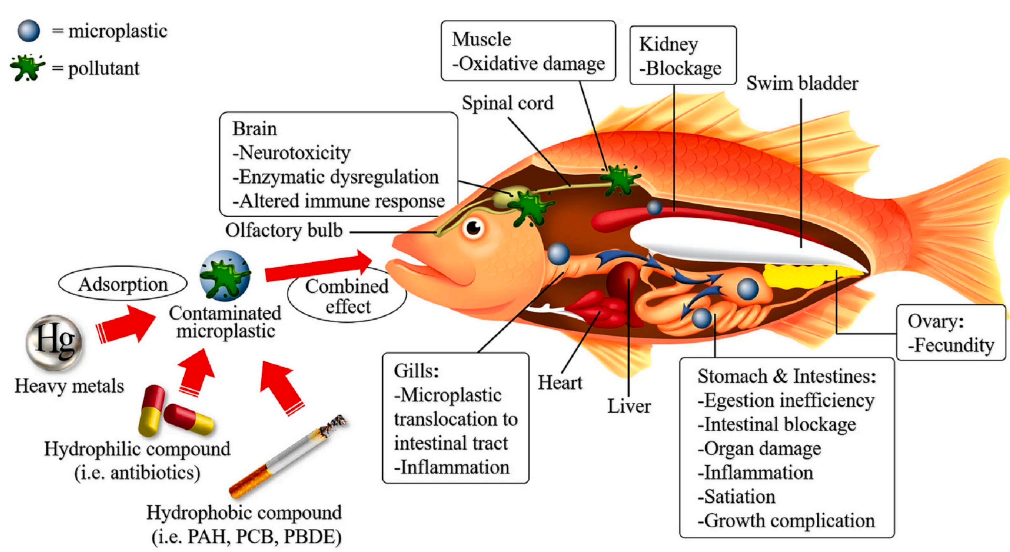

Fig. 2. Illustration of the effects of marine exposure to MPs and their adsorbates, from a fish's perspective. [Adapted from Amelia et al., 2021 (CC BY 4.0)].

food security (Fig. 3). Therefore, to appropriately manage and evaluate the risks, more research or studies on the effects of MPs on marine life should be conducted, especially on the long-term adverse impacts caused by exposure to ecologically applicable concentrations of MPs generally found in the environment. Similarly, research should also focus on the effects of MPs on the health of commercially exploited seafoods or marine organisms as well as its adverse effects on food security to understand the present state of MPs research and assess whether it pose a risk to food security. In addition, more research should be conducted to cover the research gaps to highlight areas where unknown risks may endanger or threaten marine food security.

2.4. Impacts of microplastics on seafood safety

Food safety has attracted much attention due to the rising incidence of food-borne diseases, as well as newly recognized hazards in foods including seafood. Food safety problems generally include food contamination with microbial pathogens, chemicals, toxins, and other environmental hazards (Hu et al., 2014). Seafood safety is primarily a global concern as it is impacted by contamination from land, air as well as inherent water quality issues. Nonetheless, seafood safety is also interwoven with climate change, harmful algal blooms, pathogens, biohazards, and ocean acidification (Bank et al., 2020). Although what was regarded crucial concerning food safety was strictly microbial contamination, the detection of MPs in food are progressively becoming recognized by the public and several regulatory authorities (Liu et al., 2021a). Moreover, the ability of MPs to translocate from the digestive systems into other tissues of marine life or aquatic organisms has raised concerns about the safety of seafood, particularly species meant for human consumption (Karami et al., 2017). Shrimps are one of the commonly consumed seafood and they play a vital role in accumulation and tropic transfer of MPs in the food web. Since they are often consumed whole, they might form a direct route of exposure, and ultimately pose a threat to human health and food safety (Dowarah et al., 2020). Shrimps and other seafood such as decapod crustaceans are majorly impacted by MPs as compared to larger fish, because MPs are small in sizes and shrimps eat everything in their path. As a result of this behavior, shrimps end up incidentally or deliberately ingesting small MPs particles and accumulate it in their intestines (Curren et al., 2020). In this regard, chemical plastic additives as well as other organic pollutants from various sources in the aquatic milieu are adsorbed thereunto (Farady, 2019), thereby presenting a surreptitious threat to animal and human health. Examples of such plastic additives include: nonylphenol, which is an endocrine disrupting chemical (EDC) that is regularly added in polyvinyl-chloride (PVC) and high-density polyethylene (PE) to attain high thermostability of plastics (Wu et al., 2020). Bisphenol A (BPA), a plasticizer in some types of plastics, which has estradiol-like activity characteristic of an EDC, and has been linked to obesogenesis (Talsness et al., 2009). Phthalates or phthalic acid esters (PAEs) mostly used as plasticizers to introduce elasticity and flexibility (Hahladakis et al., 2018). Like BPA and phthalates, brominated flame retardants are also EDCs (Talsness et al., 2009) and they can be found in different items, such as food packaging plastics and personal care products. The potential human health effects of these chemicals are mainly associated with delay in normal reproductive development and function (Garrido Gamarro et al., 2020). According to the report of Seyoum and Pradhan (2019), phthalate was revealed to show a negative impact or effect on lifespan and significantly reduced the lifespan on *Daphnia magna*. This indicates that phthalates could also have harmful or negative effect on aquatic organisms including seafoods. Therefore, MPs may likely serve as a conduit for transporting these harmful chemicals to aquatic organisms or even human via food chain. In addition, metals, marine toxins, hydrophobic chemicals and pathogens (discussed in detail *infra*) have been reported to colonize MPs and have been detected in seafoods (Hou et al., 2021). In this regard, we opine that as much as seafoods are vital sources of nutrition for humans, they might also be crucial to individual and population well-being, as they serve as an avenue for metabolic disorder, foodborne illnesses and even mortality.

2.5. Transport of microplastics in the food web

As of 2015, global seafood consumption was 6.7% for all protein consumed, while 17% was total animal protein consumed. This not only represents a phenomenal increase in seafood consumption, but it also signifies an increased likelihood of major exposure pathway to MPs through seafood (Usman et al., 2020). Aside from MPs contamination of seafood, studies have reported presence of MPs in other edibles, such as fruit, salt, sugar, chicken, and honey. However, there has been particular focus regarding the investigation of MPs in sea products and drinking water. The high number of studies conducted on water might be because of the easy transport of MPs from a contaminated water environment to associated food products. Marine organisms regarded as seafood play a key role in the transport of MPs to human as diverse marine organisms at different stages of life have been reported to consume or ingest plastics particles from the environment (Fig. 4). However, exposure routes of

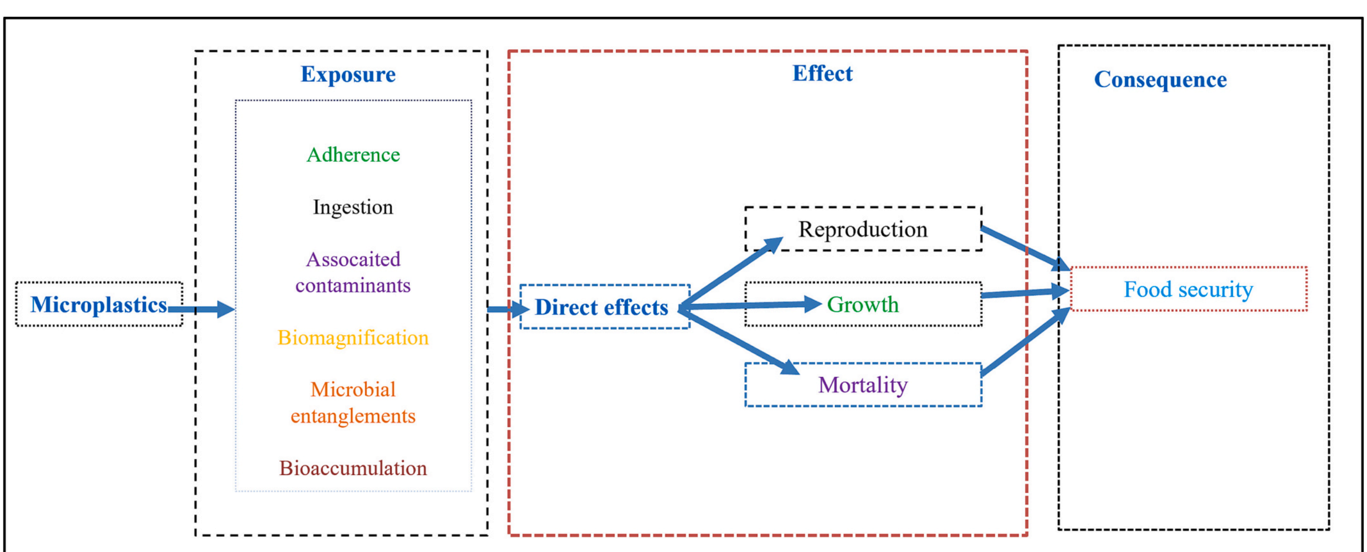

Fig. 3. Perceived impact and routes of microplastics on food security.

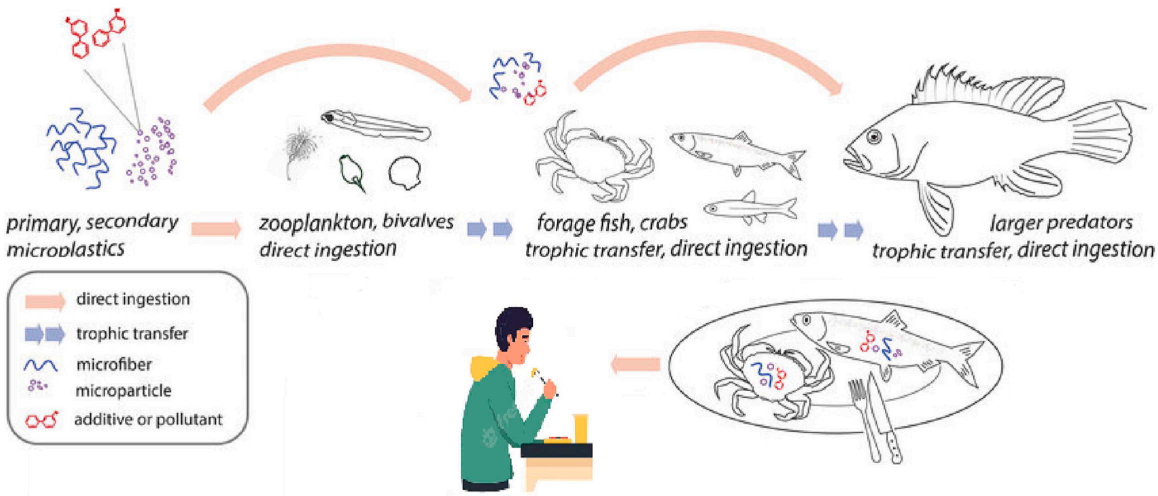

Fig. 4. Illustration of MPs contamination of the food web, and potential human exposure. [Adapted, with slight modifications, from Baechler et al., 2019 (CC BY 4.0)].

MPs to humans cannot be delimited to seafood alone; there are diverse exposure routes to human. Moreover, since MPs are diffuse and diverse in nature, they can be transported across various environmental routes in the food web, relatively undergoing exchanges between different terrestrial florae and faunae (as well as their products), and ultimately being domiciled in human body. However, from a wholistic view, it is safe to assume that the transport of MPs in any food web begins and ends with humans, since they are the major role players in birthing MPs environmental contamination. Conversely, determining MPs exposure levels is essential in creating or formulating their risk assessment framework (Bucci et al., 2020). Hence, appropriate measure should be taken by policy makers, government agents and constituted authority to mitigate and prevent the possible health risk associated to consumption of contaminated seafood.

2.6. Potential impact of microplastics on human health

Pigmented microplastics ranging from 5 to 10 μM, have been detected in the human placenta (Ragusa et al., 2021). This means the foetus might most likely be fed with MPs alongside essential nutrients. Meanwhile, about 1.6 μg/mL concentrations were recently found in human blood (Leslie et al., 2022). Despite this, the potential impact of MPs on human health has only emerged as a concern recently, following overwhelming evidence revealing the intake and adverse effects of MPs on marine organisms. In many animal species, accumulation of MPs or plastic debris from diverse environments has been inferred both in vivo and in vitro ecotoxicological studies. This has demonstrated the potential of MPs to induce oxidative stress, modification of gene expression, endocrine disruption, immunological responses, genotoxicity, transgenerational effects, neurotoxicity, reproductive abnormalities, and behavioural abnormalities (Alimba and Faggio, 2019). In contrast, several aspects connected to the fate, behavior, and effects of MPs in human including accumulation, adsorption across membranes, elimination, translocation to secondary organs and tissues, acute and long-term effects, or impacts remain largely unknown (SAPEA, 2019). However, Schwabl et al. (2019) detected MPs in human stool samples, which indicates the presence of MPs in human body; Shi et al. (2021) has also detected MPs in human tissues including lungs. Moreover, from scantily available information, it is assumed that MPs entering the human body via inhalation or ingestion can be taken up in different organs and affect human health by inducing immune and inflammatory reactions or damage cells (Vethaak and Legler, 2021; Walker, 2021). Ingestion of MPs via food might lead to plastic bezoar, a rare cause of gastrointestinal blockade or obstruction that occur mainly in individuals with psychiatric ailments (Lehner et al., 2019). In another submission, the failure of the immune system to get rid of or remove synthetic particles or MPs might lead to increased risk of neoplasia and chronic inflammation (Prata et al., 2020). According to Cox et al. (2019), human exposure to MPs may induce chemical and physical toxic effect. Also, the type of MPs particles and individual susceptibility may facilitate the occurrences of cell damage, enhanced oxidative stress, inflammatory response, and size-related toxicity. MPs may leach out various kinds of chemicals including additi es, or adsorbed environmental contaminants, such as toxic metals, PAHs, and polychlorinated biphenyls (PCBs). Among these plastic leachates, BPA and phthalates can induce neurotoxic and carcinogenic effects on humans and animals (Santonicola et al., 2019). A few brominated flame retardants, BPA and phthalates are known as endocrine disruptors that can negatively affect human health upon exposure through inhalation and ingestion (Galloway, 2015). Critically, continuous or long-time exposure to high concentrations of airborne MPs can lead or result to interstitial lung disease as well as possibly lead to the development of malignant lesions (Prata et al., 2021). According to the report of Mahler et al. (2012), serious oral exposure to positively charged polystyrene nanoparticles can upset or disrupt intestinal cellular uptake and iron transport. The likelihood of MPs to induce toxic effects in humans has been mainly highlighted by some members of the academic society; in consequence, both policy-makers and citizens are demanding scientific answers with respect to the risk posed by these pollutant (Catarino et al., 2021). Nevertheless, scientific assessment of the risks of MPs is not an easy work. MPs are extremely complex contaminant owing to the different kind of shapes, polymers, and particles sizes, making it hard to assess the potential hazardous effects on biota (Catarino et al., 2021).

The lack of standardized procedures for the evaluation of the effects of MPs together, with the regular use of high exposure concentrations in laboratory experimental settings, has added a measure of indecision on the dependability and explanation of ecotoxicological data required for risk assessments (Wardman et al., 2020). Aside from human exposure to MPs via seafood consumption, it is worth noting that they are vulnerable to other exposures route. Furthermore, the knowledge of the risks posed to human due to ingestion of MPs is still in infancy; thus, a proper risk analysis is not yet feasible. Therefore, implementing food safety risk assessment frameworks to estimate hazards and risks pose by MPs contaminated seafood to consumers is of ultimate necessity (Barboza et al., 2018b). In this regard, analysis of the possible health risk of MPs to humans should include foods exposure of various type and the knowledge of various parameters including particle shape, size, density, polymeric composition, surface area, persistence, additive chemicals, and toxicological significances are prerequisite for proper risk analysis (Barboza et al., 2018a). In general, the paucity of information concerning the potential human health risks associated with exposure to MPs is currently a limitation to create or establish whether general regulatory actions are required or needed for global protection of public health and wellbeing of people in synergy with ecosystem integrity and food safety. The adverse effects of MPs on human health are still under examination and research from toxicological studies have shown that MPs effects will be dose dependent. Food safety is controlled or managed in terms of hazards and risk assessment. According to the ability or potential to cause adverse health effects, hazards are categorized into three categories including chemical, physical and biological. MPs health impacts that are presently of concern consist of all these three categories. MPs contain different chemicals with varying concentration and its effects or impacts can either come from the plastics' primary components (polymer), additives (plasticizers), the chemical adsorbates while in the environment (Hartmann et al., 2017) or the microbes that colonize their surfaces. To better understand the impacts of MPs on seafood and human health, more study/research is required to further advise or inform on the risk assessment of human pose by ingestion of MPs contaminated seafood.

2.7. Microplastics as niche for pathogenic microorganisms/biofilm formation

Plastic debris or MPs represents a new type of pelagic substrate for microbial attachment, colonization, and transportation (Jiang et al., 2018). Due to their hydrophobic surface, plastics can provide attachment points in a relatively stable or steady habitats for the microorganisms, encourage and promote micro-organisms enrichment, accelerate, or speed up biofilm's formation and become a vector for harmful microorganisms (Zhang et al., 2020a). Conversely, we presume that compared to plastic materials larger in size, MPs will present a better niche, as their surface structure is less attenuated by friction from ocean currents or air friction. Instead, due to their persistence and light weight, they can only be ferried alongside their adsorbed microbial community by winds and water currents, consequently transferring both pathogenic and non-pathogenic organisms to non-native habitats. The formation of microbial communities on MPs in natural water bodies might not be cumbersome, since biofilms have been readily formed on wood and rock surfaces as well as extracellular and cellular polymers (Flemming et al., 2016). Biofilm formation in bacterial colonies is initiated through the secretion of diverse species of exopolymeric substances (mostly polysaccharides) that enable them to attach to each other as well as nonliving or living surfaces; polymers secreted also creates a protective and nutritive niche that allows these microbes to endure hostile environments (Fig. 5) (Katyal et al., 2020).

Usually, formation and growth of biofilms are generally impacted by environmental conditions, including the properties and types of solid surfaces, which are directly linked with early biofilm formation (Miao et al., 2019). However, it should be noted that as would be expected of resources-delimited niches, MPs are subjected to intense competition by their indwelling microbial community, which might exclusively comprise environmental-hardy and some virulent species. This might also hold true for all MPs, regardless of the matrices they are domiciled (Fig. 6a). For example, notorious fish pathogens, such as *Vibrio alginolyticus* and *Vibrio campbelli*, exhibiting metal resistance and environmental adaption, were observed as the most dominant members of *Vibronaceae* in polystyrene polymer MP (Bhagwat et al., 2021). Several studies have detected gut-associated pathogens and pathogenic microorganisms usually found in sewage colonizing the surface of MPs, and such pathogen-laden particulates have been observed across different oceanic zones (Rodrigues et al., 2019). According to the report of Zhang et al. (2020b), the total culturable bacteria on MPs (1.44–2.80 $\times 10^8$ CFU/g) were higher than the total culturable bacteria of water samples (0.29–3.0 $\times 10^6$ CFU/mL) and this report support that plastic particles or MPs are good attachment base for biofilm formation and transport of pathogens. However, animal host infection and subsequent transfer to human host might depend on several factors, most notably the substrate colonization time and the MP ingestion time (Fig. 6b). The influence of microplastic on the human gut microbiome is a new area of research; however, some studies have already suggested the influence of

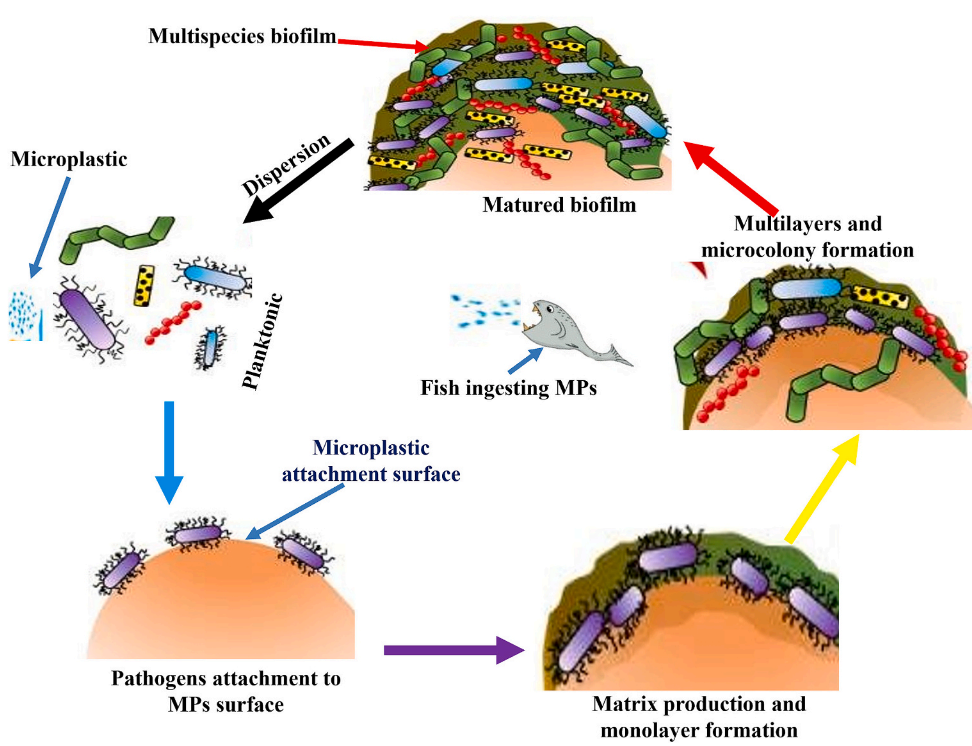

Fig. 5. MPs colonized by a wide range of microorganisms in forming multi-species biofilms.

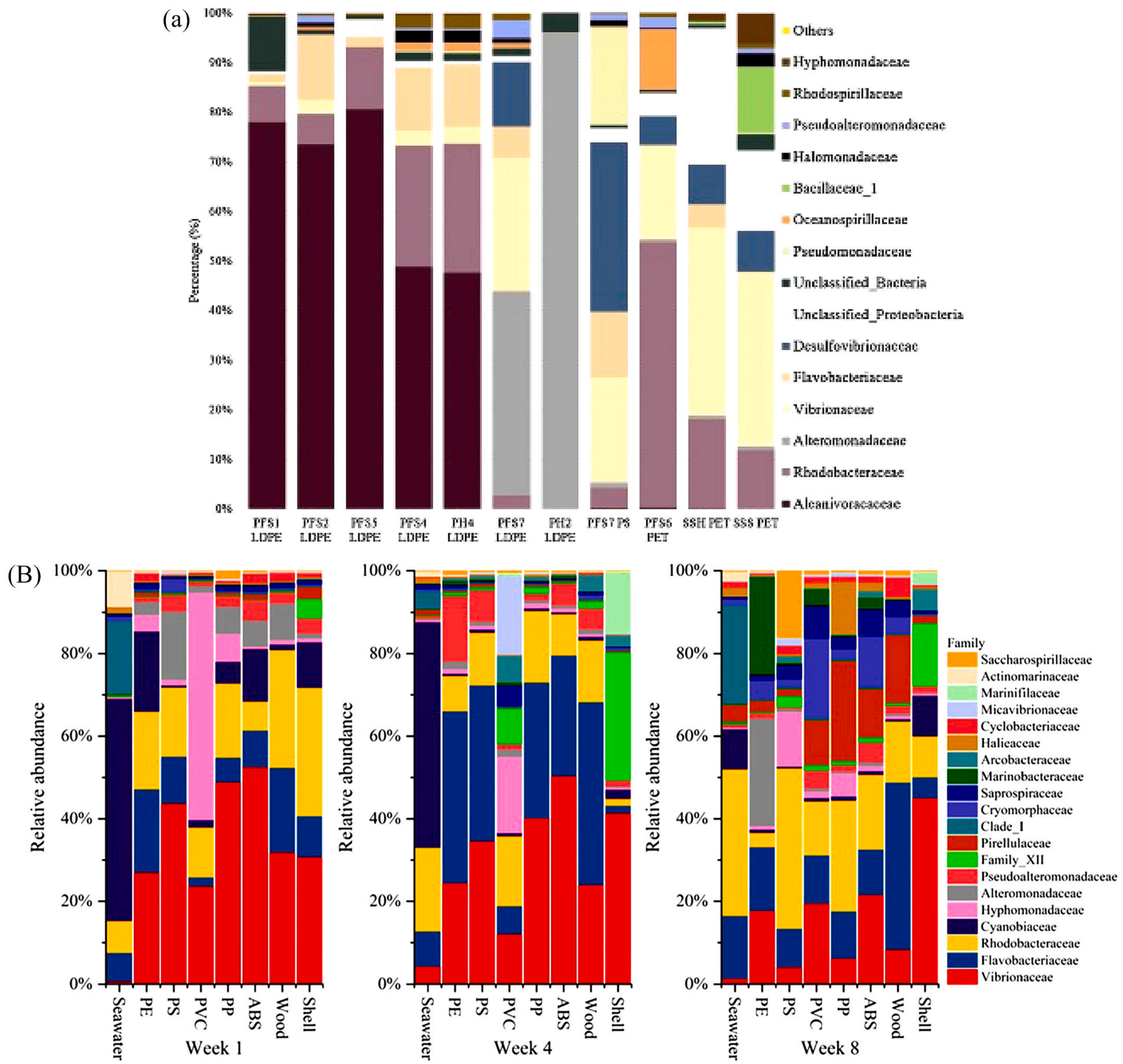

Fig. 6. a: Abundance of bacterial families present in biofilms on Low Density PolyEthylene (LDPE), PolyEthylene Terephthalate (PET) and PolyStyrene (PS) [Adapted from Delacuvellerie et al., 2019] Here, it was observed that the abundance of environmental-hardy and virulent communities, especially *Vibrionaceae* are well represented in the resources constrained plastic particulates. This observation was corroborated by Wright et al. (2021).
b: Relative abundance of taxonomic families of bacteria in biofilm communities formed on different marine model samples after periodic exposure to seawater [adapted from Zhang et al., 2022]. Samples comprised polymer microbeads (PE: polyethylene; PP: polypropylene; PVC: polyvinyl chloride; PS: polystyrene and ABS: acrylonitrile butadiene styrene), wood shell and seawater. Here, we infer that early ingestion of certain microplastic species by edible marine animals might facilitate the spread certain food-borne pathogens.

microplastics on the human gut microbiome (Gruber et al., 2022; Tamargo et al., 2022). While Gruber et al. (2022) and references therein suggested their intestinal absorption alongside carcinogenic leachates, thereby spearheading carcinogensis, hormonal imbalance, nutrient unavailability and alteration in microbiota. The latter group of investigators discussed the resultant reduction in healthy essential species diversity and the proliferation of pathogenic or non-beneficial species of bacteria. Although there is no preceding information regarding the potentials of biofilm-laden MPs to cause bacteremia or septicemia, we believe it should be looked into. This is because, since not all microplastics have glabrous edges, certain particulates might be capable of causing internal abrasions and lesions through which their biofilm community as well as opportunistic pathogens might seep into the blood stream.

2.8. Microplastics as vector for antibiotic resistance genes

In scenarios where there is overuse of antimicrobial compounds, such as biocides and heavy metals, and their subsequent release into the aquatic milieu untreated, selection pressure might occur in these perturbed natural environments leading to the development of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs)

(Francino, 2016). Interestingly, the expression of ARG or toxin production might occur right from the inception of MP colonization, where virulence genes involved in iron acquisition regulation, toxins and immune evasion could be up-regulated (Radisic and Marathe, 2021). Similarly, antibiotics, heavy metals, and biocides and other and other antimicrobial compounds can promote not only the development of AR but also stimulate horizontal gene transfer (HGT) of ARGs (Marathe and Bank, 2022). HGT is influential in driving bacterial evolution as well as contributes to the spread of ARGs in both environmentally and clinically important bacteria. Antibiotics can be adsorbed to plastic debris through biofilms, hence aiding the spread of ARB and/or ARGs and in making waterbodies natural reservoirs of AR (Caruso, 2019). Moreover, reports have showed that MPs can act as a reservoir or vector for the transfer and transport of pollutants, such as plastic additives, ARGs and other pollutants absorbed from the aquatic environment, and likewise influence the transport of these pollutants, therefore posing potential risks to marine life (Ma et al., 2020). MPs exhibit hydrophobicity, with high specific surface area and are favourable for the accumulation of pollutants and colonization of ARG host (Liu et al., 2021b). It was also reported that the number of ARB on MPs was 100–5000 times more or higher than those ARB detected in the surrounding water body (Zhang et al., 2020b). The presence of the adsorbed ARB or antibiotics on MPs can directly influence the vertical and HGT of ARGs in bacterial groups or communities (Li et al., 2019). HGT mediates the movement or flow of ARGs between environmental bacteria and the microorganisms in biofilm through mobile genetic elements (MGEs) including plasmids, integrons, bacteriophages, transposons, and insertion sequences (Stokes and Gillings, 2011). In addition, it has been observed that HGT of ARGs between microorganisms on MPs is much quicker than HGT of ARGs between free-living microbes; thus, causing a potential risk or threat of multidrug resistance via consumption of MPs contaminated seafood (Imran et al., 2019). Organic pollutants such as PAHs and inorganic pollutants including heavy metals can exert selection pressure on ARG transfer through cross-selection or co-selection (Imran et al., 2019). Conversely, high bacteria density, including ARB could form a denser biofilm structure on MPs which might facilitate their enhanced environmental persistence and increase their respective contact time for transfer of genetic material (Ma et al., 2020). Humans are majorly exposed to ARGs and their host via consumption of contaminated food, milk, and water (Igwaran and Okoh, 2019). Therefore, the understanding of potential risks of human exposure, transfer, and transport of ARGs is important. Biofilms formation on MPs also serves as reservoirs for pathogenic bacteria as well as microenvironments for HGT (Wu et al., 2019). ARB accumulation on MPs and the transmission of their associated ARGs via consumption of contaminated food or seafood have caused serious concerns on the treatment of persistent infections (Dadgostar, 2019). Infections cause by pathogens harbouring ARGs make them hard to treat with antibiotics and this poses a potential global risk to human health (Wu et al., 2019). Globally, it has been projected that approximately 10 million persons could die, and about $300 billion to $1 trillion hospital expenses could be paid yearly by 2050 if no successful or effective measure is taken against infections caused by ARB (Chokshi et al., 2019). It is noteworthy that MPs can change the structural composition of ARGs and in turn, MGEs promote or encourage the movements of ARGs. MGEs such as plasmid may influence the incidence and evolution of ARGs in water via the mechanism of lateral gene transfer (Dong et al., 2021). So far, over 200 ARG subtypes have been detected using high-throughput PCR or metagenome (Liu et al., 2021b). Several researcher including the studies of Nawaz et al. (2012) and Done and Halden (2015), have reported the presence of ARB and low level of drug residues or deposits in retail seafood products. Regrettably, the dynamics of ARBs and ARBGs with regard to MP colonization and ultimately, human systemic invasion is a repetitive trend (Fig. 7). Therefore, model studies should be conducted on how certain safe, ingestible formulations that encourage beneficial microbial-substrate(nutrient) interactions (synbiotics) can intervene. Specifically, gut-healthy polymers or substrates which can outcompete the influence of microplastics in the gut or serve as mops for these particulates should be looked into.

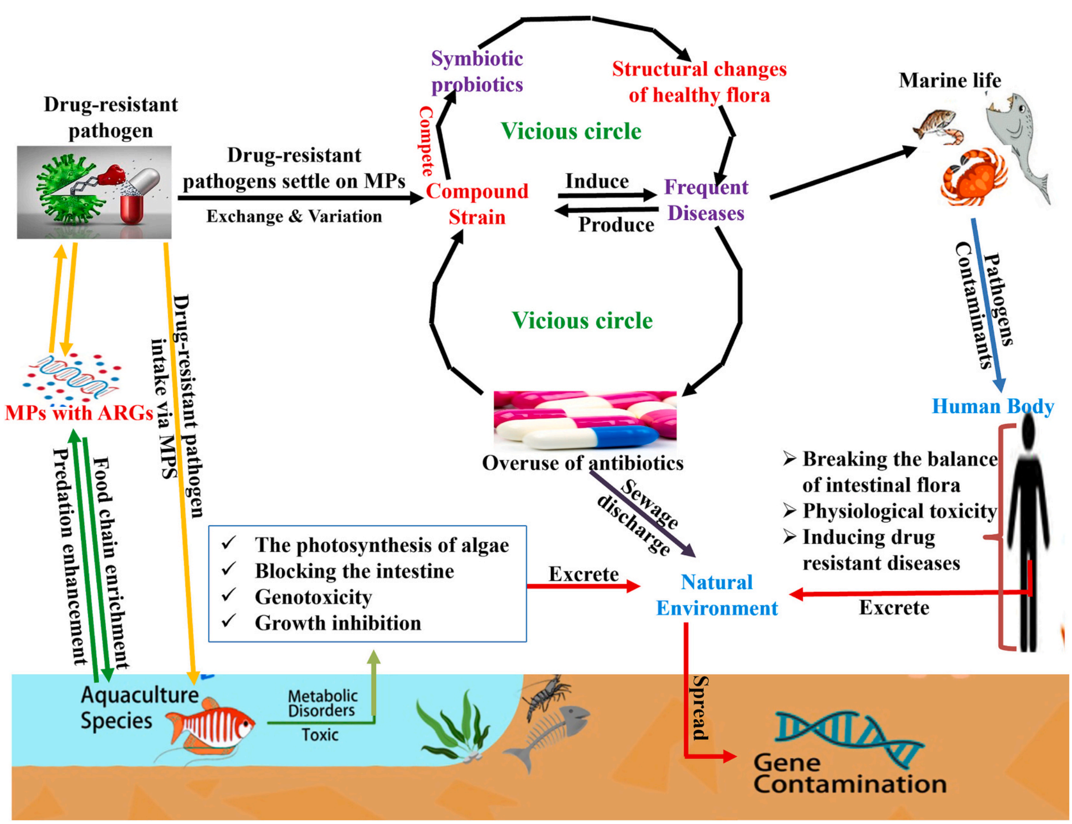

Fig. 7. The interactions and relationships between MPs, ARGs, marine life and human beings.

3. Conclusion

This review provides a comprehensive information on MPs seafood contamination and the potential human health risks from microplastics ingestion. We discussed the possible health risks of consumption of MPs contaminated seafood, impacts on food safety, food security, seafood infection outbreaks, biofilm formation, transport of pathogens and antibiotic resistance genes. It is well known that majority of the seafood are eaten whole including bivalves, and this could contribute to the amounts of ingested MPs when humans consume this seafood. Indeed, there is overwhelming evidence regarding the ubiquity of MPs in seafoods and potential threats human exposure and ingestion could engender. However, the required quality control data to carry out maximum safety risk assessment analysis is lacking. In view of the impacts of MPs to human as well as to the marine environment or marine organisms, the presence or existence of MPs in seafood must be monitored. Hence, future research work is needed to assess the exact dietary or nutritional exposure of MPs via seafood and the health risks associated with them. In addition, thorough research is also needed to understand the impacts of MPs in metabolic disorders, oxidative stress mechanisms and inflammatory reaction and explore the potential toxicological mechanisms of plastic particles such as MPs on humans and animals. Although there is no preceding information regarding certain MPs species to instigate bacteremia and septicemia, model studies should be trialed to ascertain this hypothesis. Since seafood bacterial infection stemming from MPs-domiciled ARBs and ARGs have more immediate adverse impacts than would the MPs themselves, research should not only focus on the long-term MPs degradation, but also on ways they can been immediately cleaned up through gut-healthy polymer formulations (synbiotics).

Author contribution

The authors had equal contribution to this manuscript. JOU and AI wrote the first draft, reviewed, and approved the final version of the manuscript.

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Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

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