microplastics

Review

The Impact of Microplastics on Global Food Production: A Brief Overview of This Complex Sector

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Abstract: Environmental pollution management combined with food safety represents two of the main challenges of the last decades. Soil and water contamination has historically threatened food safety. As ubiquitous pollutants, microplastics (MPs) have attracted increasing attention over the last few years. These particles can affect the balance of terrestrial, aquatic, and aerial ecosystems. Their negative impacts are intensified when they adsorb and carry toxic chemicals. They can circulate through organisms and accumulate in human beings via food and water. Physiological dysfunctions in all species continue to be reported, both in terrestrial and aquatic ecosystems. This article considers how this might be affecting the global production of food. It reports the adverse effects induced by MPs in soils, their properties and organisms growing within and upon them, including livestock and the pollinating agents necessary for plant growth. A separate section discusses the effects of MPs on aquaculture, mentioning effects on wild species, as well as farmed fish. The growing concern of the food production sector with MPs mimics that of the world with global warming; the danger is real and requires urgent attention.

Keywords: agriculture; pisciculture; ecotoxicology; productivity

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1. Introduction

Plastic production and the resulting increase in solid waste rose in the 1960s, impacting waste management and damaging the environment. The persistent nature of plastics, with their relatively low decomposition rates, results from their chemical nature [1,2]. From the 1970s onwards, opinions regarding this new material began to change, following the alarming reports of its presence in various ecosystems. One of the first was in specific areas of the seas, such as the oceanic gyres [3] and, later, in freshwater bodies worldwide [4].

During its relative persistence in the environment, plastic is transformed into microparticles (microplastics, MPs) by UV radiation and mechanical wear and tear [5]. It is generally accepted that MPs are polymeric particles measuring up to 5 mm [6–8]. They can be classified as primary or secondary. The first case, whereby MPs are produced commercially, includes spherical MPs manufactured for use in personal care products (e.g., toothpastes, shampoos, and shower gels) [9], or as toxin-containing microspheres for the controlled release of antimicrobial substances [10,11]. Secondary microplastics are composed of both particles and fibers, resulting from the breakdown of larger plastic debris and particles [12,13]. Primary and secondary MPs from many sources are found in the marine environment (e.g., [14–17]).

There are serious concerns about the impact of MPs on living beings [18], for example, physical damage, inhibited food assimilation, oxidative stress, physiological alteration and adjustments in energy metabolism [19]. MPs have been demonstrated to concentrate in organs such as the liver, lungs, and gastrointestinal tract, causing, for example, intestinal disorders, gut microflora dysbiosis, metabolic imbalance, oxidative disruptions, and hepatic and renal toxicity in mice [20,21]. In aquatic environments their small particle size, low density, and diverse shapes allow MPs to remain in the water column, available to be assimilated by aquatic organisms [22]. The uptake and subsequent accumulation of MPs have been reported in various marine organisms at different trophic levels [18,23–27]. For instance, zooplankton can feed on phytoplankton and pass MPs upward through the food web. Moreover, MPs play a key role in the ecosystem function, including nutrient and carbon cycling and the production of sinking fecal pellets [28].

Agricultural production is not only essential to supply the world demand for food, but it is also the main source of financial livelihood for a significant part of the population [29]. The amount of food produced has risen dramatically in recent times for two main reasons: the increase in cultivated land and the increase in crop yields with the advent of more modern production techniques (Figure 1) [30,31]. The cultural dissemination of new diets can also be considered an important element in changing agricultural production [32,33]. Initially, cereals, roots, and other staple crops formed the largest fraction of agricultural production [32]. Currently, fruits, vegetables, nuts, seeds, and other foods have conquered more space around the global markets [34]. Agricultural vegetal production not only supplies human food, but is also used as animal feed (Figure 2).

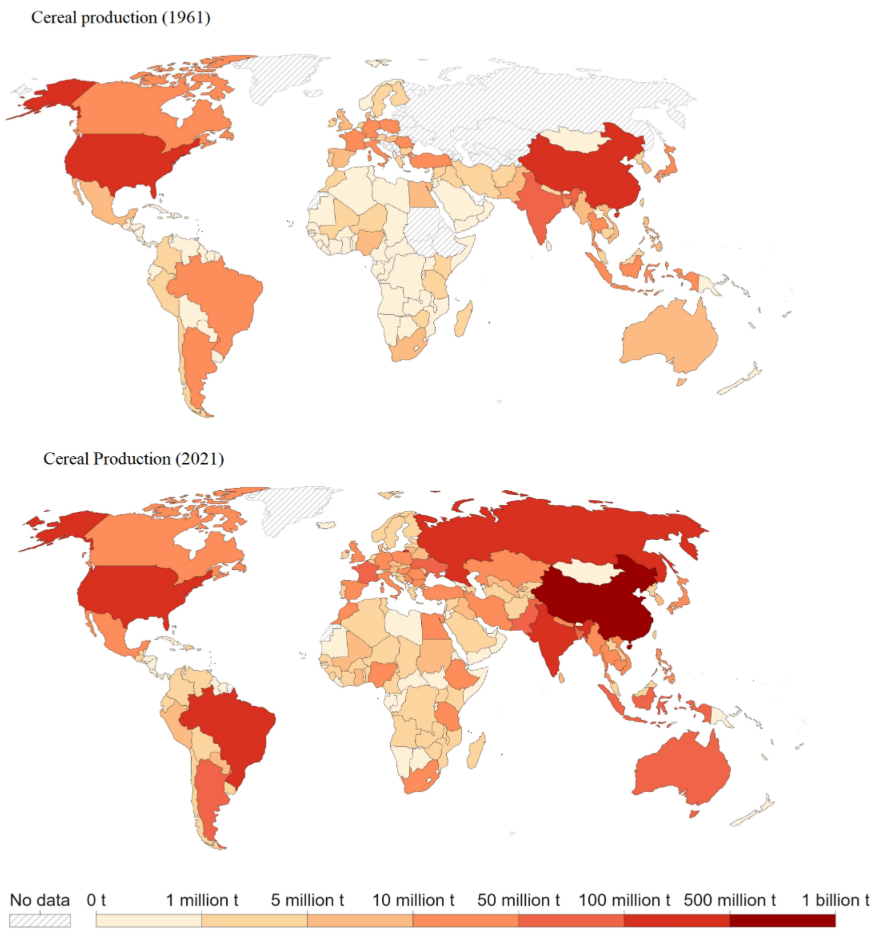

Figure 1. Cereal production measured in tonnes representing the total of all cereal crops, including maize, wheat, rice, barley, rye, millet, and others. (Source: Food and Agriculture Organization of the United Nations OurWorldInData.org/agricultural-production • CC BY) (accessed on 25 January 2023).

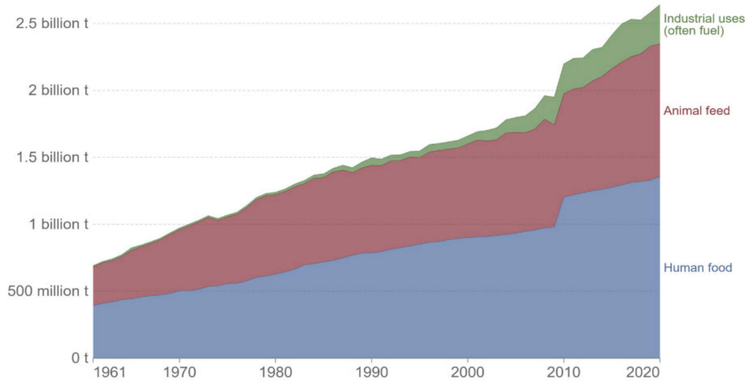

Figure 2. Cereal crops allocated to direct human consumption, used for animal feed and other uses. (Source: Food and Agriculture Organization of the United Nations OurWorldInData.org/agricultural-production • CC BY). (accessed on 25 January 2023).

In addition to agriculture, aquaculture is a fundamental source of food, aiding in reducing the supply-and-demand gap [35]. By 2030, aquatic food production is projected to increase by 15% [36], mainly due to the increase in the aquaculture industry (Figure 3).

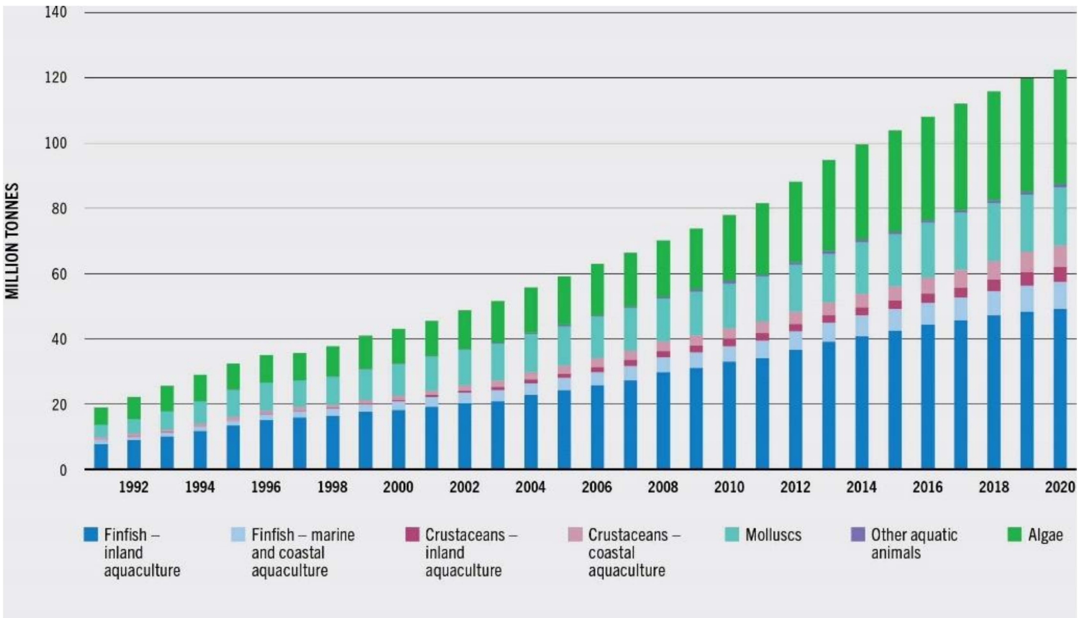

Figure 3. World aquaculture production, 1991–2020.

From the moment that the impact of MPs on plant and animal trophic chains was registered [37], it was realized that this would result in direct and indirect effects on human large-scale food production. The presence and spread of MPs through the air means that these particles are omnipresent in the atmosphere and will affect all open-air industries, such as agriculture. Despite this, studies on the effects of MP pollution on global food production are still scarce and speculative. The impact of MPs on food productivity must be evaluated urgently to ensure health and resources for the next generations. The present article makes a brief assessment of the imbalance of production mechanisms and potential impacts of MPs on the various food production sectors.

2. Potential Impact of Microplastics on Agriculture

Agricultural production has increased by around 260% over the last 60 years [38]. As a result, during the last few years, the impact of MPs on soil compartments has attracted considerable research attention. The persistence of MPs in soils, and the resulting impact of their presence on soil properties, as well as their toxicological effects on the development of soil organisms, have often been reported [39–42]. MPs can alter soil physicochemical characteristics [39], impact enzymatic processes [20], unbalance microbial community structure [39], and ultimately affect organisms at higher trophic levels [37]. Projections suggest that the level of MPs discharged into soils is 4 to 23 times higher than in the oceans [43]. In fact, soils are one of the largest storage reservoirs for MPs [44].

There are several potential sources of microplastic in agricultural areas. Among these are included tire fragments [45] and shattered macroplastic released into the atmosphere by littering, resulting in MPs appearing in the agricultural environment. Farmers that apply waste sludge to their crops spread MPs that have accumulated in these biosolids [46], although even the recommended application of biosolids from wastewater treatment can have this result [47]. Other sources include the application of soil corrective dressings, agricultural plastic film, chemical additives and pesticide packaging residues, wastewater watering, surface runoff, and atmospheric deposition [41,48–53].

After arriving in the soil ecosystem, MPs can be transferred either horizontally or vertically, mobilized by abiotic (wind and water fluxes) or biotic (bioturbation) agents. Characteristics of the particle (shape, density, weight, and size) or the environment (substrate porosity, permeability, or grain size) will determine the behavior of the particle [54]. Water fluxes can move MPs through the soil interstitial pores [55]. According to [56], concentrations of MPs accumulated in soils can reach 2.2×10^4–6.9×10^5 particles per kilogram. The same authors suggested that, during percolation, MPs can cause persistent damage in soils, impacting soil physicochemical characteristics, reflecting in nutrient cycling disturbances and pH alterations [57–59]. Agriculture is especially important in China and there have been many articles published on the effects of MP-contaminated soil in this country (for a review, see [60]). However, wheat, rice, maize, and lettuce have been the plants most studied in controlled experiments in this respect [61].

MPs can impact plant development and performance in different ways, through direct toxic effects on plants, alteration of soil characteristics, intoxication of soil, microbial communities, and pollinator agents, and finally toxicity in interstitial organisms, as discussed in the following sections.

2.1. Direct Toxic Effects on Plants

It has been suggested that microplastics, or the smaller-sized nanoplastics, can be assimilated by roots, accumulating in the intertissue spaces, and then being transferred to other parts of the plant body [62–64]. Once inside the plant tissue, MPs can change the biomolecular structure of membranes, resulting in oxidative stress [62,64–67]. There have been several articles evaluating the impacts of MPs and nanoplastics (NPs) on crop species, with results ranging from neutral to significant phytotoxicity [68–71]. For instance, a recent study has suggested that fluorescent polystyrene NPs can accumulate in bean roots and subsequently clog the pores of the cell wall, preventing the absorption of nutrients necessary for plant metabolism [72]. Similarly, rubber ash NPs can accumulate in cucumber roots [73], possibly promoting the same negative effects. A significant decrease (48–63%) in *V. faba* plant biomass was found when it was treated with polystyrene (PS) MPs [72]. The same toxicity was not, however, recorded by Lian et al. [74] with a different plant species assay (*T. aestivum*). Sun et al. [75] and Lian et al. [74] found negative effects resulting from the application of PS NPs on the leaves of *Lactuca sativa* and *Zea mays*.

MPs may also deregulate trace metals that are required for plant enzyme action [74]. Once assimilated, MPs can stimulate a generalized imbalance of the plant physiological and biochemical mechanisms, for example, decreasing seed germination, inhibiting plant growth, changing root/soil exchange capacity, lowering biomass, decreasing fertility and fruit production, deregulating photosynthesis, stimulating oxidative stress, and hence decreasing productivity [22,68,70]. Refs. [67,76] recorded the toxic disturbances of enzyme performance and physiological parameters of plants caused by MPs and NPs. On the other hand, there is little knowledge of the exact effects of plastic particles on the physiological, biochemical, and photosynthetic indexes of plants. This suggests that more studies on the ecotoxicology of these pollutants are fundamental for a more precise understanding of their impact on agroecosystems.

2.2. Alteration of Soil Characteristics

There is a consensus that environmental characteristics control plant development. For instance, plant productivity depends on soil characteristics and soil community biodiversity. MPs may change soil physicochemical properties and microbial populations, which may impact the rhizosphere, as well as the development of and nutrient absorption by plants. For instance, MPs stimulate soil water evaporation, resulting in soil drying [39], which may impact plant performance. MPs may decrease soil richness, resulting in a loss of plant nutrients, and, finally impact fungal symbionts in the rhizosphere, decreasing plant diversity [77].

Once within the soil, MPs tend to associate with soil organic matter and microbial catabolites or exoenzymes and become incorporated into the sedimentary microstructure [78]. This newly deposited and embedded element influences soil physicochemical properties by enhancing porosity, but reducing permeability, resulting in increased water accumulation [79,80]. MPs can also change soil pH. For instance, polyamide (PA) MPs and high-density polyethylene (HDPE) MPs can elevate soil pH [46]. Dong et al. (2021) [81], on the other hand, suggested that PS MPs and polytetrafluoroethylene (PTFE) can decrease pH. The greater issue about the impact of MPs on soil pH is related to plant species. For instance, polychlorofluoride (PCF) MPs in corn cultures considerably raised soil pH [74].

The soil chemical imbalances reported in agriculture are not exclusively related to soil pH. MPs can also modify the biogeochemical cycle of soil nutrients [82]. Liu et al. (2017) [82] reported that high levels of polypropylene (PP) MPs significantly enhanced organic matter accumulation and stimulated the release of some nutrients such as soluble organic C, N, and P.

During polymer matrix processing of plastic production, several toxic chemical compounds (such as plasticizers, flame retardants, and stabilizers) are added to enhance performance and improve versatility. Once released into the environment, these added compounds are gradually made available to the soil, affecting the soil microbiota structure and diversity [2]. In addition, MPs can adsorb environmentally available toxic compounds, such as polyaromatic hydrocarbons, polychlorinated biphenyls, dichlorodiphenyltrichloroethanes, perfluoroalkyl sulfonates, and heavy metals, functioning as contaminant transporters and stimulating the migration of pollutants through the environment. This facilitates dispersion [83] and potentially impacts soil health.

Among the impacts of MP contact is the inhibition of enzyme activities [42,79,80,84–87]. For example, dehydrogenase, alkaline phosphatase, cellobiohydrolase, alkaline phosphatase, and leucine aminopeptidase were decreased in soils treated with PS nanoparticles [85], while PE and polyvinylchloride (PVC) MPs inhibited the hydrolysis of the marker substrate fluorescein diacetate [86]. Using different soil fractions, [87] showed that PE inhibited catalase, phenol oxidase, B-glucosidase, urease, Mn-peroxidase, and laccase, affecting soil nutrient levels. They speculated that soil physicochemical properties were responsible for differing enzyme effects in different fractions. It has been suggested that the reason for reduction in these enzyme activities is the inhibitory action of MPs on the soil microbiota [87]. Soil enzymes are directly related to several biogeochemical processes and represent a fundamental tool regulating soil nutrient recycling [88]. These enzymes can be used as soil fertility monitors [89], permitting the early warning signs of soil ecosystem imbalance.

2.3. Intoxication of Soil and Its Microbial Communities

MPs alter soil microbial community structure, impacting microbial processes [80,82,84,90]. Toxic substances released from MPs cause soil contamination, transforming their properties [91]. MPs thus affect the normal metabolic activities of soil organisms, potentially unbalancing nutrient biogeochemical cycles [92]. For instance, nitrogen represents a fundamental nutrient, providing energy and allowing for biomass production. Throughout its biogeochemical cycle, nitrogen assumes a variety of chemical forms, especially through microbial metabolism. The denitrification pathway plays an essential role, controlling reactive nitrogen concentrations. According to [93], the success of food production directly depends on the bioavailability of reactive nitrogen. Refs. [94,95] found, through laboratory-controlled assays, that PE availability to the microbiota enhances ammonium concentrations, impacting N biocycling, perhaps providing more N for biomass production. Both these research groups reported that nitrogen biogeochemical processes can be significantly influenced by several polymeric substances. According to the authors, MPs may function as organic carbon substrates for microbial colonization, stimulating their community development. Notably, polyurethane (PU) foam or polylactic acid (PLA) can boost nitrification and denitrification mechanisms [95]. On the other hand, both studies suggested that the availability of PE considerably inhibits microbial activities, impacting the nitrification/denitrification reactions. Ref. [96] studied the impact of some MPs on activated sludge; MP availability significantly neutralized the nitrification mechanisms. The presence of MPs throughout the ecosystems impacts microbial ecological equilibrium, leading to a potential imbalance of the biogeochemical cycling of N, and subsequent need for the addition of fertilizers to agricultural soils.

2.4. Intoxication of Pollinating Agents

Pollination plays a fundamental role in the agricultural sector, serving as a key element in agricultural production [97]. Pollinating agents include not only water and wind, but also animals like insects, birds, and bats. Cultivated vegetables are mostly animal-pollinated, with bee-pollinated crops representing one-third of the total human food supply. The pollination process thus has a direct influence on the economic sector [98,99]. Insect pollinators are responsible for 9.5% of the whole economic value of the agricultural industry that supplies human food [100], being particularly important for coffee, cocoa, almond, and soy [101,102]. An estimated USD 11.68 billion was spent on honeybees in 2009 only in the Brazilian Cerrado [103], with similar importance of wild bees and honeybees for agriculturally intensive areas [102] in the USA. In Europe, the European bee species *Apis mellifera* has the same fundamental importance in crop and wild plant pollination [100,101,104,105]. It is worrying that considerable decreases in the population of these insects have been noticed in both Europe and the United States from 2006 until recently [106,107]. Several factors, biotic and abiotic, have been suggested as the causes of this decrease, including parasites, bacterial infections, use of pesticides, decrease in the number of habitats, and improper beekeeping practices [105,108–118]. However, information on how MPs impact honeybee colony health is still scarce. PE, PP, and PA MPs have been found in 12% of the honey, beer, milk, and refreshment samples collected in Ecuador [119]. MPs, mainly particles and fibers, have recently been found in honeybees from 19 apiaries in Copenhagen [120]. Ref. [121], feeding honeybees with sucrose containing PE MP fibers, found that, after one month's feeding, the microfibers became incorporated into the cuticle and digestive tract of adult workers, as well as into the larvae, honey and, mainly, wax. They concluded that the honey remained suitable for human consumption, with MP levels not differing from those found in commercial honey. This fact, in itself, suggests that MPs are already being incorporated into human honey supplies.

As previously mentioned, there are few articles that address the direct effects of MPs on pollinating insects. According to laboratory assays [122], PS MP stress resulted in almost no survival in bees (*Apis mellifera* L.). On the other hand, according to the same authors, PS MP administration decreased community diversity of the bee gut microbiota, causing altered gene expression, potentially resulting in oxidative damage, reduced detoxification capacity, and immunity system imbalance. Experimental evidence showed that a significant mass of PS NPs was assimilated and concentrated within the midgut, increasing the susceptibility of bees to viral infection [123]. According to this study, not only did histological data show that PS MPs altered the midgut tissue and were subsequently transferred through the digestive system, but PCR and transcriptomic data also suggested that the genes involved with membrane lipid metabolism, immune response, detoxification, and the respiratory system were significantly affected. Ref. [124] showed that chronic exposure to irregularly shaped PS MPs had no impact on honeybee survival, but feeding rates and body weight decreased when a concentration of 10 μg PS MP particles per mL was used. Ref. [125] evaluated the impact of PE MPs on the honeybee (*Apis mellifera* L.). They recorded a significant effect on bee mortality for the highest concentrations applied. PE MPs also altered feeding behavior in a dose-dependent way, enhancing food consumption. The most recent findings in the literature thus highlight the risk of MPs on the health of pollinator species. Shah et al. [126] give a review of the effects of MPs and NPs on plant-pollinating species.

2.5. Toxicity of Microplastics on Interstitial Organisms

MPs may cause direct and indirect impacts on interstitial fauna, which inhabit the spaces between soil grains. Once present in the soil environment, MPs may become attached to interstitial animal body surfaces and impede their movement [127]. On the other hand, as a result of their small size, MPs are easily ingested by soil organisms, potentially reducing their carbon assimilation and further depleting energy [128]. According to [129], earthworms represent the most studied bioindicator that reflects the toxicity of MPs on interstitial organisms. Ref. [130] recorded that, at low concentrations, MPs have no great effects on the life cycle of earthworms (*Eisenia fetida*) and, indeed, Cui et al. (2022) [131] reported that epigeic earthworms, which live on the soil surface, actually caused an increase in the number of MP particles when used in vermicomposting. Ref. [132], however, studying the earthworm species *Oligochaeta lumbricidae*, found significant growth inhibition rates (>28%).

A wide variety of interstitial organisms other than earthworms are subject to the impacts of microplastics. For instance, MPs may negatively affect the gut microbial community structure, fertility, and survival customs of springtails [127,133]. They can unbalance the energy metabolism of the nematode *Caenorhabditis elegans*, resulting in decreased movement, and finally impacting body development [134]; MPs disturbed the feeding mechanism of snails (*Achatina fulica*), at the same time enhancing oxidative stress [135]. The secondary impacts of MPs (association and carriage of environmentally available pollutants) include increased soil contamination and risk to soil fauna [136,137]. Ref. [138] for instance, posit that MP adsorption enhances zinc bioavailability. The same authors suggested that, once assimilated, zinc carried by MPs can accumulate in the earthworm gut. Ref. [137], on the other hand, suggested that high levels of MPs in soils might decrease the accumulation of PCHs and PCBs, a positive effect. The adsorption and desorption mechanisms of MPs on other environmental contaminants need to be evaluated.

3. Potential Impact of Microplastic on Animal Protein Production

The animal protein industry around the globe has experienced rapid growth over the last few decades, with the total meat production increasing more than threefold between 1980 and 2000 [139]. Livestock production has developed especially in China and India. China, the United States, and India represent the largest producers of milk and eggs [32], while China, the United States and Brazil were the largest average producers of meat in the period of 2007–2011. China's annual chicken production exceeded 13.75 million tons during 2019 and accounted for more than 13% of the world's chicken source, ranking second in the world [140]. At the same time, its total production and consumption have continued to rise due to its rapid growth and low production costs [140,141]. The question is: "How does the introduction of microplastics affect these numbers?".

Ruminants feed on plants, but they do not have the ability themselves to degrade tissue constituents like cellulose. Thus, ruminant species depend on specific microbiota for the assimilation of plant polymers [142]. Assimilated plant fibers pass through a microbial fermentation process, transforming these components into volatile fatty acids, which represent a fundamental energy source for the animal [143]. This complex microbial community is responsible for the production of other vital compounds and bioactive molecules. Microbial digestion supports up to 70% of the total dietary energy [144]. The compounds provided by microbial fermentations are fundamental to other physiological processes, including the development of the rumen epithelium and regulation of the immune system. When the microbial digestion mechanism is unbalanced, acidosis, nitrate toxicity, ammonia intoxication, and other metabolic disorders may manifest themselves, negatively impacting ruminant health [145–148]. Thus, the balance of the intestinal microflora is fundamental for the health of the digestive and other systems in ruminants [149]. MPs in livestock feed and water can result in impacted rumen [150] and decrease in rumen protozoal activity [151], leading to indigestion and even death. Additionally, MPs can be transferred into milk and meat [152]. Natural farming methods, using little artificial feed, can also contribute to the problem. Of the sheep raised on Spanish land on which plastic mulch had been applied, 92% were found to excrete MPs in their feces, thus being responsible for the transfer of contamination to other fields. No adverse effects on the sheep were reported [142].

With their large surface/volume ratio, MPs are effective absorption materials, able to adsorb and take up toxic chemicals [142]. They can adsorb chemical contaminants, such as hydrophilic compounds, which have an affinity for the negatively charged areas of plastics. On the other hand, hydrophobic compounds have an affinity for the neutral areas of plastics [153]. Thus, plastics not only act as sources of toxins that comprise some of their constituents, but also as carriers of the sorbed toxic chemicals [154]. After the aging process of PS and PET MPs via controlled experiments, their adsorptive capacity for environmental copper [Cu (II)] increases, especially after long times at elevated temperatures [155]. This also significantly decreases the volatilization of hydrocarbons, like anthracene and pyrene, altering toxicities to *Phaeodactylum tricornutum* and *Selenastrum capricornutum* [156]. Heavy metal compounds available in the environment may also be adsorbed on the surfaces of MPs [157]. Once ingested by livestock, these MPs potentially affect the immune system, posing significant risks to health.

Although contamination by MPs has resulted in increased studies on the dynamics of diffusion of these contaminants through ecosystems, as well as their impact on wild animals and models, little has been published about their influence on farm animal production.

Many tools used in livestock farming are made of plastic, for example, water hoses, drinking fountains, feed transport pipelines, storage containers, etc. [157]. In contact with environmental factors, these utensils are subject to chemical and mechanical wear, resulting in plastic fragmentation and MP production [59]. Once consumed, the intestine is a pathway for the incorporation and accumulation of microplastics by cattle, pigs and poultry, with the intestinal microbiota being the main target of the negative effects. The intestine is populated by trillions of living organisms [60], including bacteria and fungi. The intestinal microbiota is of fundamental importance in the physiological balance of the host [158], producing, during metabolism, compounds such as antimicrobial peptides, vitamins, short-chain fatty acids, and enzymes [53]. Intestinal functions are fundamental in maintaining intestinal homeostasis. On the other hand, external factors such as diet, antibiotic agents, and toxic agents can impact the microbial cells, affecting their activities [159–162].

Li et al. (2023) [163] explored the effects of MPs on the health of farmed poultry. The MPs negatively impacted the development of the birds. Negative effects were found in the intestine, liver, kidneys, and spleen. In addition, the gut microbiota showed a significant decrease in diversity, as well as significant changes in taxonomic composition. These effects included changes in D-amino acid metabolism, ABC transporters, vitamin digestion and absorption, mineral absorption, and histidine metabolism. These results suggest that microplastic impacts the health of chickens by disturbing intestinal microbial homeostasis and intestinal metabolism.

4. Potential Impact of Microplastics on Aquaculture

Nowadays, aquaculture represents a fundamental food production niche around the globe [164], with over USD 1 billion circulating annually [165,166]. According to the Food and Agriculture Organization [138], around 580 aquatic fauna species are cultivated globally. Aquatic vegetables, such as seaweed, also function as important aquaculture resources, providing nutrition, financial support, and basic chemicals for industry [167].

Many aquatic organisms have been shown to accumulate and assimilate MPs. Of the brown shrimp collected from the English Channel, 63% contained microplastic fibers [168]. Farmed mussels bought in a supermarket were shown, in one study, to contain fewer MPs than wild ones [169]; mussels, being filter feeders, may be expected to take up MPs from contaminated waters. Farmed oysters have also been shown to take up MPs from contaminated seawater; 84% of oysters collected from farms along the China coast were contaminated with MPs, mostly fibers made from PE and PET [170]. Farmed fish, like the mussels mentioned above, have been shown to contain less MP contamination than wild fish; 60% of wild mullets from the east coast of Hong Kong contained MPs, while only 16.7% of farmed mullets were contaminated [171]. As a result of fish exposure to MPs, they may suffer neurotoxicity, reduced physiological development, and behavioral disorders [167]. Such exposure in fish has at least doubled over the last few years [172]. The effects of MPs are proportional to their available levels [173,174] and associated pollutants. For instance, the ingestion of MPs caused metabolic disorders in zebrafish and decreased oyster reproduction [175]; exposure to polystyrene (PS) and polyethylene terephthalate (PET) microplastic pellets provoked genotoxic impacts on wild sea trout larvae *Salmo trutta* [176]. Biomagnification has also been recorded in several fish species and other organisms along the trophic net. For instance, in 2023 Pradit et al. [177] recorded the presence of MPs in the appendages of *O. militaris*. According to some authors, the gastrointestinal tract accumulates microplastics from the small organisms on which this fish feeds [178], although MPs have also been found in organisms from the top trophic level, such as bluefin and albacore tuna, and swordfish [179]. It has been suggested that, as MPs are found mainly in the fish gut, they may be of little importance to the human population, who generally remove fish intestines before eating [167]; however, many small fish are not so treated. Even if ingested MPs do not affect the fish themselves, they will reduce their purchase price to a knowing public.

Over the last few decades, the aquaculture sector has faced great challenges [180]. This may be partially linked to contamination by MPs. Plastic has been detected in aquaculture facilities and aquafeed [181]. Many studies have named potential MP sources in aquaculture; for example, fishing equipment, weathered fish culture tanks and facilities, fish feed, culture water and contaminated salt [181–183]. The picture described represents a real threat to farmed animals and the aquaculture industry. Several and varied lesions, ranging from cellular, subcellular down to molecular, have been attributed to the uptake of MPs in cultured species [184–188].

The negative impacts of MPs are like those seen in farm production; they can be divided into two distinct groups: physical and chemical. Physical impacts are generally related to the size and shape of the plastic microparticle and include obstruction of the digestive system, which may result in mechanical damage such as perforation of the stomach and intestine, and, in more serious cases, the death of the organism [189–192]. Chemical effects, on the other hand, are caused by the polymer composition, the inclusion of chemical additives during plastic matrix production, or the carriage of toxic compounds captured from the surrounding environment [193,194]. The difference between farm production and aquaculture can be attributed to the multiple routes (gut, gills) of plastic uptake in aquatic species and a single route (gastrointestinal) in terrestrial animals. Both types of impacts, mechanical (abrasion) or chemical (inflammation), can occur within various systems of the organism, such as digestive, respiratory, circulatory, neurological, and reproductive, as a result of the ingestion and accumulation of MPs [187,195–203]. Unfortunately, there is still a great lack of information about the response of organisms to MPs in aquaculture systems [201,202], and especially about farmed fish [195].

According to [202], the genetic control of fish production, mainly in farming, has impacted its MP uptake capacity. These authors hypothesized that pisciculture could produce fish that are less selective in food intake compared to the wild individuals, making them more susceptible to MP assimilation. Some farmed fish have been shown to lose the ability to differentiate between edible and inedible particles [204,205], hence making them less able to avoid MP assimilation. However, not all published studies report this difference, as noted previously; farmed fish may contain fewer MPs because of the comparative cleanliness of the water.

5. Conclusions

The global demand for food is expected to increase by at least 50% from 2010 to 2050, mainly as a result of population growth and a shift toward a more 'Westernized' diet in developing regions. Microplastics (MPs), a new class of pollutants, are extremely varied and their effects are particular to each organism, making the qualitative assessment and evaluation of their effects on the global food industry extremely complex. MPs are present in air, earth, and water, and hence can access all sectors of the food production industry. Their adverse effects on the living organisms present in agricultural soils and aquaculture systems include enzyme and whole-system disfunctions, potentially reducing productive yields, and necessitating corrective actions. The rarely reported, but important, contamination of pollinating agents and, in the case of honeybees, of their commercial food products, can cause not only reduced yields of crops, but also polluted human non-protein food. Aquaculture is going to become more important in future years, yet there is little information on the effects of MPs in this industrial sector, in spite of the relatively large research efforts on MPs in fresh, saline, and wastewater. The knowledge gained from MP analyses in the environment is of interest, but not directly relevant, to food industries, and more directed studies are necessary. The impact of MPs is already a reality in production cycles, yet their precise effects and how to reduce them are not clear. The question that arises is: Will we have time to adapt our survival schemes to this new threat? The scenario is chronologically similar to that of global warming, of which the projections are not encouraging. Time is the greatest enemy.

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References

1. Crawford, C.B.; Quinn, B. Plastic Production, Waste and Legislation. In *Microplastic Pollutants*; Crawford, C.B., Quinn, B., Eds.; Elsevier Science: Amsterdam, The Netherlands, 2017; Volume 1, pp. 39–56. [CrossRef]
2. Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* **2018**, *344*, 179–199. [CrossRef] [PubMed]

3. Ryan, P.G. A Brief History of Marine Litter Research. In *Marine Anthropogenic Litter*; Bergmann, M., Gutow, L., Klages, M., Eds.; Springer International Publishing: Cham, Switzerland, 2015. [CrossRef]
4. Anderson, J.C.; Park, B.J.; Palace, V.P. Microplastics in aquatic environments: Implications for Canadian ecosystems. *Environ. Pollut.* **2016**, *1*, 269–280. [CrossRef] [PubMed]
5. Hammer, J.; Kraak, M.H.; Parsons, J.R. Plastics in the Marine Environment: The Dark Side of a Modern Gift. In *Reviews of Environmental Contamination and Toxicology*; Springer: New York, NY, USA, 2012; pp. 1–44. [CrossRef]
6. Andrady, A.L. Persistence of Plastic Litter in the Oceans. In *Marine Anthropogenic Litter*; Bergmann, M., Gutow, L., Klages, M., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 57–72.
7. Crawford, C.B.; Quinn, B. *Microplastic Pollutants*; Elsevier: Amsterdam, The Netherlands, 2016.
8. GESAMP. *Sources, Fate and Effects of Microplastics in the Marine Environment: Part Two of a Global Assessment*; International Maritime Organization: London, UK, 2016.
9. Mdlalose, L.; Chimuka, L. Mitigation Approaches to Prevent Microplastics Effects in the Aquatic Environment: Exploration of Microbeads from Personal Care and Cosmetic Products. *Int. J. Environ. Res.* **2022**, *16*, 84. [CrossRef]
10. Bakadia, B.M.; Zhong, A.; Li, X.; Boni, B.O.O.; Ahmed, A.A.Q.; Souho, T.; Zheng, R.; Shi, Z.; Shi, D.; Lamboni, L.; et al. Biodegradable and injectable poly(vinyl alcohol) microspheres in silk sericin-based hydrogel for the controlled release of antimicrobials: Application to deep full-thickness burn wound healing. *Adv. Compos. Hybrid. Mater.* **2022**, *5*, 2847–2872. [CrossRef]
11. Qi, F.; He, L.; Cui, L.; Wang, W.; Siddique, K.H.M.; Li, S. Smart Antibacterial Food Packaging Based on MIL-53 (Fe) Functionalized Polylactic Acid Film for pH-Responsive Controlled Release. *J. Polym. Environ.* **2023**, *31*, 4022–4032. [CrossRef]
12. Gaylarde, C.C.; Baptista Neto, J.A.; Fonseca, E.M. Paint fragments as polluting microplastics: A brief review. *Mar. Pollut. Bull.* **2021**, *162*, 9. [CrossRef]
13. Gaylarde, C.C.; Baptista-Neto, J.A.; da Fonseca, E.M. Plastic microfibre pollution: How important is clothes' laundering? *Heliyon* **2021**, *7*, e07105. [CrossRef]
14. Sundt, P.; Schulze, P.-E.; Syversen, F. *Sources of Microplastic-Pollution to the Marine Environment*; Report No. M-321/2015; Mepex Consult: Asker, Norway, 2014.
15. Essel, R.; Engel, L.; Carus, M.; Ahrens, R. Sources of microplastics relevant to marine protection in Germany. *Texte* **2015**, *64*, 31969.
16. Lassen, C.; Hansen, S.F.; Magnusson, K.; Hartmann, N.B.; Jensen, P.R.; Nielsen, T.G.; Brinch, A. Microplastics: Occurrence, Effects and Sources of Releases to the Environment in Denmark. Danish Environmental Protection Agency, Copenhagen K. 2015. Available online: http://mst.dk/service/publikationer/publikationsarkiv/2015/nov/rapport-om-mikroplast (accessed on 23 January 2023).
17. Magnusson, K.; Noren, F. *Screening of Microplastic Particles in and Downstream a Wastewater Treatment Plant*; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2014.
18. Xu, S.; Ma, J.; Ji, R.; Pan, K.; Miao, A.-J. Microplastics in aquatic environments: Occurrence, accumulation, and biological effects. *Sci. Total Environ.* **2020**, *10*, 134699. [CrossRef]
19. De Ruijter, V.N.; Redondo-Hasselerharm, P.E.; Gouin, T.; Koelmans, A.A. Quality Criteria for Microplastic Effect Studies in the Context of Risk Assessment: A Critical Review. *Environ. Sci. Technol.* **2020**, *54*, 11692–11705. [CrossRef]
20. Lu, L.; Wan, Z.; Luo, T.; Fu, Z.; Jin, Y. Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice. *Sci. Total Environ.* **2018**, *631*, 449–458. [CrossRef] [PubMed]
21. Jin, Y.; Lu, L.; Tu, W.; Luo, T.; Fu, Z. Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. *Sci. Total Environ.* **2018**, *649*, 308–317. [CrossRef] [PubMed]
22. Desforges, J.P.; Galbraith, M.; Ross, P.S. Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean. *Arch. Environ. Contam. Toxicol.* **2015**, *69*, 320–330. [CrossRef] [PubMed]
23. Boerger, C.M.; Lattin, G.L.; Moore, S.L.; Moore, C.J. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. *Mar. Pollut. Bull.* **2010**, *60*, 2275–2278. [CrossRef] [PubMed]
24. Avery-Gomm, S.; O'Hara, P.D.; Kleine, L.; Bowes, V.; Wilson, L.K.; Barry, K.L. Northern fulmars as biological monitors of trends of plastic pollution in the eastern North Pacific. *Mar. Pollut. Bull.* **2012**, *64*, 1776–1781. [CrossRef]
25. Goldstein, M.C.; Titmus, A.J.; Ford, M. Scales of Spatial Heterogeneity of Plastic Marine Debris in the Northeast Pacific Ocean. *PLoS ONE* **2013**, *8*, e80020. [CrossRef] [PubMed]
26. Frias, J.P.G.L.; Otero, V.; Sobral, P. Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. *Mar. Environ. Res.* **2014**, *95*, 89–95. [CrossRef] [PubMed]
27. Kvale, K.; Hunt, C.; James, A.; Koeve, W. Regionally disparate ecological responses to microplastic slowing of faecal pellets yields coherent carbon cycle response. *Front. Mar. Sci.* **2023**, *10*, 1111838. [CrossRef]
28. Botterell, L.R.; Beaumont, N.; Dorrington, T.; Steinke, M.; Thompson, R.C.; Lindeque, P.K.L. Bioavailability and effects of microplastics on marine zooplankton: A review. *Environ. Pollut.* **2019**, *245*, 98–110. [CrossRef]
29. Fanzo, J.; Bellows, A.L.; Spiker, M.L.; Thorne-Lyman, A.L.; Bloem, M.W. The importance of food systems and the environment for nutrition. *Am. J. Clin. Nutr.* **2021**, *113*, 7–16. [CrossRef]
30. Eberhardt, M.; Vollrath, D. The Effect of Agricultural Technology on the Speed of Development. *World Dev.* **2018**, *109*, 483–496. [CrossRef]

31. Sharma, P.; Singh, S.P.; Iqbal, H.M.N.; Parra-Saldivar, R.; Varjani, S.; Tong, Y.W. Genetic modifications associated with sustainability aspects for sustainable developments. *Bioengineered* **2022**, *13*, 9508–9520. [CrossRef] [PubMed]
32. Msangi, S.; Enahoro, D.; Herrero, M.; Magnan, N.; Havlik, P.; Notenbaert, A.; Nelgen, S. Integrating livestock feeds and production systems into agricultural multi-market models: The example of IMPACT. *Food Policy* **2014**, *49*, 365–377. [CrossRef]
33. Dwivedi, S.L.; Lammerts van Bueren, E.T.; Ceccarelli, S.; Grando, S.; Upadhyaya, H.D.; Ortiz, R. Diversifying Food Systems in the Pursuit of Sustainable Food Production and Healthy Diets. *Trends Plant Sci.* **2017**, *22*, 842–856. [CrossRef] [PubMed]
34. Ritchie, H.; Rosado, P.; Roser, M. Agricultural Production. 2023. Available online: https://ourworldindata.org/agricultural-production (accessed on 25 January 2023).
35. Pradeepkiran, J.A. Aquaculture role in global food security with nutritional value: A review. *Transl. Anim. Sci.* **2019**, *3*, 903–910. [CrossRef] [PubMed]
36. OECD/FAO. *OECD-FAO Agricultural Outlook 2021–2030*; OECD Publishing: Paris, France, 2021. [CrossRef]
37. Neves, C.V.; Gaylarde, C.C.; Baptista Neto, J.A.; Vieira, K.S.; Pierri, B.; Waite, C.C.C.; Scott, D.C.; da Fonseca, E.M. The transfer and resulting negative effects of nano- and micro-plastics through the aquatic trophic web—A discreet threat to human health. *Water Biol. Secur.* **2022**, *1*, 100080. [CrossRef]
38. FAO. *FAOSTAT Online Database*; FAO: Rome, Italy, 2020.
39. Wang, F.; Wang, Q.; Adams, C.A.; Sun, Y.; Zhang, S. Effects of microplastics on soil properties: Current knowledge and future perspectives. *J. Hazard. Mater.* **2021**, *424*, 127531. [CrossRef]
40. Hartmann, G.F.; Ricachenevsky, F.K.; Silveira, N.M.; Pita-Barbosa, A. Phytotoxic effects of plastic pollution in crops: What is the size of the problem? *Environ. Pollut.* **2021**, *292*, 118420. [CrossRef]
41. Okeke, E.S.; Okoye, C.O.; Atakpa, E.O.; Ita, R.E.; Nyaruaba, R.; Mgbechidinma, C.L.; Akan, O.D. Microplastics in agroecosystems-impacts on ecosystem functions and food chain. *Resour. Conserv. Recycl.* **2022**, *177*, 105961. [CrossRef]
42. Ren, X.; Yin, S.; Wang, L.; Tang, J. Microplastics in plant-microbes-soil system: A review on recent studies. *Sci. Total Environ.* **2022**, *816*, 151523. [CrossRef]
43. Horton, A.A.; Walton, A.; Spurgeon, D.J.; Lahive, E.; Svendsen, C. Microplastics in Freshwater and Terrestrial Environments: Evaluating the Current Understanding to Identify the Knowledge Gaps and Future Research Priorities. *Sci. Total Environ.* **2017**, *586*, 127–141. [CrossRef] [PubMed]
44. Pinto, A.P.; Ferreira, T.; Dordio, A.V.; Carvalho, A.J.P.; Faria, J.M. What Do We Know About the Effects of Microplastics on Soil? *Microplast. Ecosphere Air Water Soil Food.* **2023**, *1*, 271–304. [CrossRef]
45. Neto, J.A.B.; Gaylarde, C.C.; de Carvalho, D.G.; Lourenço, M.F.; da Fonseca, E.M. Occurrence of microplastics derived from tyres in bottom sediments of Guanabara Bay, Brazil: A form of pollution that is neglected or difficult to detect? *Water Emerg. Contam. Nanoplast.* **2023**, *2*, 10. [CrossRef]
46. Yang, L.; Zhang, Y.; Kang, S.; Wang, Z.; Wu, C. Microplastics in soil: A review on methods, occurrence, sources, and potential risk. *Sci. Total Environ.* **2021**, *780*, 146546. [CrossRef] [PubMed]
47. Radford, F.; Horton, A.; Hudson, M.; Shaw, P.; Williams, I. Agricultural soils and microplastics: Are biosolids the problem? *Front. Soil Sci.* **2023**, *2*, 941837. [CrossRef]
48. Horton, A.A.; Svendsen, C.; Williams, R.J.; Spurgeon, D.J.; Lahive, E. Large microplastic particles in sediments of tributaries of the River Thames, UK—Abundance, sources and methods for effective quantification. *Mar. Pollut. Bull.* **2017**, *114*, 218–226. [CrossRef]
49. Chae, Y.; An, Y.-J. Current Research Trends on Plastic Pollution and Ecological Impacts on the Soil Ecosystem: A Review. *Environ. Pollut.* **2018**, *240*, 387–395. [CrossRef]
50. He, P.; Chen, L.; Shao, L.; Zhang, H.; Lü, F. Municipal Solid Waste (MSW) Landfill: A Source of Microplastics? -Evidence of Microplastics in Landfill Leachate. *Water Res.* **2019**, *159*, 38–45. [CrossRef]
51. Lu, X.; Vogt, R.D.; Li, H.; Han, S.; Mo, X.; Zhang, Y.; Ullah, S.; Chen, C.; Han, X.; Li, H.; et al. China's Ineffective Plastic Solution to Haze. *Science* **2019**, *364*, 1145. [CrossRef]
52. Zhou, B.; Wang, J.; Zhang, H.; Shi, H.; Fei, Y.; Huang, S.; Tong, Y.; Wen, D.; Luo, Y.; Barceló, D. Microplastics in Agricultural Soils on the Coastal plain of Hangzhou Bay, east China: Multiple Sources Other Than Plastic Mulching Film. *J. Hazard. Mater.* **2020**, *388*, 121814. [CrossRef]
53. Han, L.H.; Xu, L.; Li, Q.L.; Lu, A.X.; Yin, J.W.; Tian, J.Y. Levels, Characteristics, and Potential Source of Micro(meso)plastic Pollution of Soil in Liaohe River basin. *Environ. Sci.* **2021**, *42*, 1781–1790. [CrossRef]
54. Almeida, M.P.d.; Gaylarde, C.C.; Pompermayer, F.C.; Lima, L.d.S.; Delgado, J.d.F.; Scott, D.; Neves, C.V.; Vieira, K.S.; Baptista Neto, J.A.; Fonseca, E.M. The Complex Dynamics of Microplastic Migration through Different Aquatic Environments: Subsidies for a Better Understanding of Its Environmental Dispersion. *Microplastics* **2023**, *2*, 62–77. [CrossRef]
55. O'Connor, D.; Pan, S.; Shen, Z.; Song, Y.; Jin, Y.; Wu, W.-M.; Hou, D. Microplastics Undergo Accelerated Vertical Migration in Sand Soil Due to Small Size and Wet-Dry Cycles. *Environ. Pollut.* **2019**, *249*, 527–534. [CrossRef] [PubMed]
56. Liu, K.; Wang, X.; Wei, N.; Song, Z.; Li, D. Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health. *Environ. Intern.* **2019**, *132*, 105127. [CrossRef] [PubMed]
57. Zang, H.; Zhou, J.; Marshall, M.R.; Chadwick, D.R.; Wen, Y.; Jones, D.L. Microplastics in the Agroecosystem: Are They an Emerging Threat to the Plant-Soil System? *Soil Biol. Biochem.* **2020**, *148*, 107926. [CrossRef]

58. Qi, R.; Jones, D.L.; Li, Z.; Liu, Q.; Yan, C. Behavior of Microplastics and Plastic Film Residues in the Soil Environment: A Critical Review. *Sci. Total Environ.* **2020**, *703*, 134722. [CrossRef]
59. Wang, X.; Zhang, R.; Li, Z.; Yan, B. Adsorption properties and influencing factors of Cu(II) on polystyrene and polyethylene terephthalate microplastics in seawater. *Sci. Total Environ.* **2022**, *812*, 152573. [CrossRef]
60. Tang, K.H.D. Microplastics in agricultural soils in China: Sources, impacts and solutions. *Environ. Pollut.* **2023**, *322*, 121235. [CrossRef]
61. Lima, J.Z.; Cassaro, R.; Ogura, A.P.; Vianna, M.M.G.R. A systematic review of the effects of microplastics and nanoplastics on the soil-plant system. *Sustain. Prod. Consum.* **2023**, *38*, 266–282. [CrossRef]
62. Liu, H.; Wang, X.; Shi, Q.; Liu, Y.; Lei, H.; Chen, Y. Microplastics in arid soils: Impact of different cropping systems (Altay, Xinjiang). *Environ. Pollut.* **2022**, *303*, 119162. [CrossRef]
63. Li, H.; Lu, X.; Wang, S.; Zheng, B.; Xu, Y. Vertical migration of microplastics along soil profile under different crop root systems. *Environ. Pollut.* **2021**, *278*, 116833. [CrossRef] [PubMed]
64. Li, Z.; Li, Q.; Li, R.; Zhao, Y.; Geng, J.; Wang, G. Physiological responses of lettuce (*Lactuca sativa* L.) to microplastic pollution. *Environ. Sci. Pollut. Res.* **2020**, *27*, 30306–30314. [CrossRef] [PubMed]
65. Giorgetti, L.; Spanò, C.; Muccifora, S.; Bottega, S.; Barbieri, F.; Bellani, L.; Castiglione, M.R. Exploring the Interaction between Polystyrene Nanoplastics and Allium cepa during Germination: Internalization in Root Cells, Induction of Toxicity and Oxidative Stress. *Plant Physiol. Biochem.* **2020**, *149*, 170–177. [CrossRef] [PubMed]
66. Gong, W.; Zhang, W.; Jiang, M.; Li, S.; Liang, G.; Bu, Q.; Xu, L.; Zhu, H.; Lu, A. Species-dependent Response of Food Crops to Polystyrene Nanoplastics and Microplastics. *Sci. Total Environ.* **2021**, *796*, 148750. [CrossRef] [PubMed]
67. Yin, L.; Wen, X.; Huang, D.; Du, C.; Deng, R.; Zhou, Z.; Tao, J.; Li, R.; Zhou, W.; Wang, Z.; et al. Interactions between Microplastics/nanoplastics and Vascular Plants. *Environ. Pollut.* **2021**, *290*, 117999. [CrossRef] [PubMed]
68. Bosker, T.; Bouwman, L.J.; Brun, N.R.; Behrens, P.; Vijver, M.G. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant Lepidium sativum. *Chemosphere* **2019**, *226*, 774–781. [CrossRef]
69. Kováčik, J.; Babula, P.; Hedbavny, J.; Švec, P. Manganese-induced oxidative stress in two ontogenetic stages of chamomile and amelioration by nitric oxide. *Plant Sci.* **2014**, *215–216*, 1–10. [CrossRef]
70. Qi, Y.; Yang, X.; Pelaez, A.M.; Lwanga, E.H.; Beriot, N.; Gertsen, H.; Garbeva, P.; Geissen, V. Macro- and micro-plastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth. *Sci. Total Environ.* **2018**, *645*, 1048–1056. [CrossRef]
71. Van Weert, S.; Redondo-Hasselerharm, P.E.; Diepens, N.J.; Koelmans, A.A. Effects of nanoplastics and microplastics on the growth of sediment-rooted macrophytes. *Sci. Total Environ.* **2019**, *654*, 1040–1047. [CrossRef]
72. Jiang, X.; Chen, H.; Liao, Y.; Ye, Z.; Li, M.; Klobučar, G. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. *Environ. Pollut.* **2019**, *250*, 831–838. [CrossRef]
73. Moghaddasi, S.; Khoshgoftarmanesh, A.H.; Karimzadeh, F.; Chaney, R. Fate and effect of tire rubber ash nano-particles (RANPs) in cucumber. *Ecotoxicol. Environ. Saf.* **2015**, *115*, 137–143. [CrossRef] [PubMed]
74. Lian, J.; Liu, W.; Meng, L.; Wu, J.; Chao, L.; Zeb, A.; Sun, Y. Foliar-applied polystyrene nanoplastics (PSNPs) reduce the growth and nutritional quality of lettuce (*Lactuca sativa* L.). *Environ. Poll.* **2021**, *280*, 116978. [CrossRef] [PubMed]
75. Sun, H.; Lei, C.; Xu, J.; Li, R. Foliar uptake and leaf-to-root translocation of nanoplastics with different coating charge in maize plants. *J. Hazard. Mater.* **2021**, *416*, 125854. [CrossRef] [PubMed]
76. Azeem, I.; Adeel, M.; Ahmad, M.A.; Shakoor, N.; Jiangcuo, G.D.; Azeem, K.; Ishfaq, M.; Shakoor, A.; Ayaz, M.; Xu, M.; et al. Uptake and Accumulation of Nano/Microplastics in Plants: A Critical Review. *Nanomaterials* **2021**, *11*, 2935. [CrossRef]
77. Van der Heijden, M.G.A.; de Bruin, S.; Luckerhoff, L.; van Logtestijn, R.S.P.; Schlaeppi, K. A widespread plant-fungal-bacterial symbiosis promotes plant biodiversity, plant nutrition and seedling recruitment. *ISME J.* **2016**, *10*, 389–399. [CrossRef] [PubMed]
78. Rillig, M.C.; Ingraffia, R.; de Souza Machado, A.A. Microplastic Incorporation into Soil in Agroecosystems. *Front. Plant Sci.* **2017**, *8*, 1805. [CrossRef]
79. De Souza Machado, A.A.; Lau, C.W.; Till, J.; Kloas, W.; Lehmann, A.; Becker, R.; Rillig, M.C. Impacts of Microplastics on the Soil Biophysical Environment. *Environ. Sci. Technol.* **2018**, *52*, 9656–9665. [CrossRef] [PubMed]
80. De Souza Machado, A.A.; Lau, C.W.; Kloas, W.; Bergmann, J.; Bachelier, J.B.; Faltin, E.; Becker, R.; Görlich, A.S.; Rillig, M.C. Microplastics Can Change Soil Properties and Affect Plant Performance. *Environ. Sci. Technol.* **2019**, *53*, 6044–6052. [CrossRef]
81. Dong, Y.; Gao, M.; Qiu, W.; Song, Z. Effect of microplastics and arsenic on nutrients and microorganisms in rice rhizosphere soil. *Ecotoxicol. Environ. Saf.* **2021**, *211*, 111899. [CrossRef]
82. Liu, H.; Yang, X.; Liu, G.; Liang, C.; Xue, S.; Chen, H.; Ritsema, C.J.; Geissen, V. Response of Soil Dissolved Organic Matter to Microplastic Addition in Chinese Loess Soil. *Chemosphere* **2017**, *185*, 907–917. [CrossRef]
83. Hartmann, N.B.; Rist, S.; Bodin, J.; Jensen, L.H.; Schmidt, S.N.; Mayer, P.; Meibom, A.; Baun, A. Microplastics as Vectors for Environmental Contaminants: Exploring Sorption, Desorption, and Transfer to Biota. *Integr. Environ. Assess. Manag.* **2017**, *13*, 488–493. [CrossRef] [PubMed]
84. Awet, T.T.; Kohl, Y.; Meier, F.; Straskraba, S.; Grün, A.-L.; Ruf, T.; Jost, C.; Drexel, R.; Tunc, E.; Emmerling, C. Effects of Polystyrene Nanoparticles on the Microbiota and Functional Diversity of Enzymes in Soil. *Environ. Sci. Eur.* **2018**, *30*, 11. [CrossRef] [PubMed]

85. Fei, Y.; Huang, S.; Zhang, H.; Tong, Y.; Wen, D.; Xia, X.; Wang, H.; Luo, Y.; Barcel, D. Response of Soil Enzyme Activities and Bacterial Communities to the Accumulation of Microplastics in an Acid Cropped Soil. *Sci. Total Environ.* **2020**, *707*, 135634. [CrossRef] [PubMed]
86. Yu, H.; Fan, P.; Hou, J.; Dang, Q.; Cui, D.; Xi, B.; Tan, W. Inhibitory Effect of Microplastics on Soil Extracellular Enzymatic Activities by Changing Soil Properties and Direct Adsorption: An Investigation at the Aggregate-Fraction Level. *Environ. Pollut.* **2020**, *267*, 115544. [CrossRef] [PubMed]
87. Guo, Q.Q.; Xiao, M.R.; Ma, Y.; Niu, H.; Zhang, G.S. Polyester Microfiber and Natural Organic Matter Impact Microbial Communities, Carbon-Degraded Enzymes, and Carbon Accumulation in a Clayey Soil. *J. Hazard. Mater.* **2021**, *405*, 124701. [CrossRef]
88. Burns, R.G.; De Forest, J.L.; Marxsen, J.; Sinsabaugh, R.L.; Stromberger, M.E.; Wallenstein, M.D.; Weintraub, M.N.; Zoppini, A. Soil Enzymes in a Changing Environment: Current Knowledge and Future Directions. *Soil Biol. Biochem.* **2013**, *58*, 216–234. [CrossRef]
89. Bandick, A.K.; Dick, R.P. Field Management Effects on Soil Enzyme Activities. *Soil Biol. Biochem.* **1999**, *31*, 1471–1479. [CrossRef]
90. Hou, J.; Xu, X.; Yu, H.; Xi, B.; Tan, W. Comparing the Long-Term Responses of Soil Microbial Structures and Diversities to Polyethylene Microplastics in Different Aggregate Fractions. *Environ. Int.* **2021**, *149*, 106398. [CrossRef]
91. Zhang, Z.; Peng, W.; Duan, C.; Zhu, X.; Wu, H.; Zhang, X.; Fang, L. Microplastics Pollution from Different Plastic Mulching Years Accentuate Soil Microbial Nutrient Limitations. *Gondwana Res.* **2021**, *108*, 91–101. [CrossRef]
92. De Almeida, M.P.; Gaylarde, C.C.; Baptista Neto, J.A.; Delgado, J.F.; Lima, L.S.; Neves, C.V.; Pompermayer, L.L.O.; Vieira, K.; da Fonseca, E.M. The prevalence of microplastics on the earth and resulting increased imbalances in biogeochemical cycling. *Water Emerg. Contam. Nanoplast.* **2023**, *2*, 7. [CrossRef]
93. Chang, J.; Havlík, P.; Leclère, D.; de Vries, W.; Valin, H.; Deppermann, A.; Hasegawa, T.; Obersteiner, M. Reconciling regional nitrogen boundaries with global food security. *Nat. Food.* **2021**, *2*, 700–711. [CrossRef] [PubMed]
94. Cluzard, M.; Kazmiruk, T.; Kazmiruk, V.; Bendell, L. Intertidal Concentrations of Microplastics and Their Influence on Ammonium Cycling as Related to the Shellfish Industry. *Arch. Environ. Contam. Toxicol.* **2015**, *69*, 310–319. [CrossRef] [PubMed]
95. Seeley, M.E.; Song, B.; Passie, R.; Hale, R.C. Microplastics affect sedimentary microbial communities and nitrogen cycling. *Nat. Commun.* **2020**, *11*, 2372. [CrossRef] [PubMed]
96. Li, X.; Chen, L.; Mei, Q.; Dong, B.; Dai, X.; Ding, G.; Zeng, E.Y. Microplastics in sewage sludge from the wastewater treatment plants in China. *Water Res.* **2018**, *142*, 75–85. [CrossRef] [PubMed]
97. Khalifa, S.A.M.; Elshafiey, E.H.; Shetaia, A.A.; El-Wahed, A.A.A.; Algethami, A.F.; Musharraf, S.G.; AlAjmi, M.F.; Zhao, C.; Masry, S.H.D.; Abdel-Daim, M.M.; et al. Overview of Bee Pollination and Its Economic Value for Crop Production. *Insects* **2021**, *12*, 688. [CrossRef]
98. Gill, R.J.; Baldock, K.C.; Brown, M.J.; Cresswell, J.E.; Dicks, L.V.; Fountain, M.T.; Garratt, M.P.; Gough, L.A.; Heard, M.S.; Holland, J.M.; et al. Protecting an Ecosystem Service: Approaches to Understanding and Mitigating Threats to Wild Insect Pollinators. *Adv. Ecol. Res.* **2016**, *54*, 135–206. [CrossRef]
99. Hristov, P.; Neov, B.; Shumkova, R.; Palova, N. Significance of apoidea as main pollinators. Ecological and economic impact and implications for human nutrition. *Diversity* **2020**, *12*, 280. [CrossRef]
100. Gallai, N.; Salles, J.-M.; Settele, J.; Vaissière, B.E. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol. Econ.* **2009**, *68*, 810–821. [CrossRef]
101. Geeraert, L.; Aerts, R.; Berecha, G.; Daba, G.; De Fruyt, N.; D'Hollander, J.; Helsen, K.; Stynen, H.; Honnay, O. Effects of landscape composition on bee communities and coffee pollination in Coffea arabica production forests in southwestern Ethiopia. *Agric. Ecosyst. Environ.* **2020**, *288*, 106706–106717. [CrossRef]
102. Luo, D.; Silva, D.P.; De Marco Júnior, P.; Pimenta, M.; Caldas, M.M. Model approaches to estimate spatial distribution of bee species richness and soybean production in the Brazilian Cerrado during 2000 to 2015. *Sci. Total Environ.* **2020**, *737*, 139674. [CrossRef]
103. Calderone, N.W. Insect pollinated crops, insect pollinators and US agriculture: Trend analysis of aggregate data for the period 1992–2009. *PLoS ONE* **2012**, *7*, 37235. [CrossRef]
104. Moritz, R.F.A.; de Miranda, J.; Fries, I.; Le Conte, Y.; Neumann, P.; Paxton, R.J. Research strategies to improve honeybee health in Europe. *Apidologie* **2010**, *41*, 227–242. [CrossRef]
105. Al Naggar, Y.; Codling, G.; Giesy, J.P.; Safer, A. Beekeeping and the Need for Pollination from an Agricultural Perspective in Egypt. *Bee World.* **2018**, *95*, 107–112. [CrossRef]
106. Le Conte, Y.; Ellis, M.; Ritter, W. Varroa mites and honeybee health: Can Varroa explain part of the colony losses? *Apidologie* **2010**, *41*, 353–363. [CrossRef]
107. Staveley, J.P.; Law, S.A.; Fairbrother, A.; Menzie, C.A. A Causal Analysis of Observed Declines in Managed Honey Bees (Apis mellifera). *Hum. Ecol. Risk Assess* **2014**, *20*, 566–591. [CrossRef] [PubMed]
108. Jacques, A.; Laurent, M.; Ribière-Chabert, M.; Saussac, M.; Bougeard, S.; Budge, G.E.; Hendrikx, P.; Chauzat, M.-P. A pan-European epidemiological study reveals honey bee colony survival depends on beekeeper education and disease control. *PLoS ONE* **2017**, *12*, e0172591. [CrossRef] [PubMed]
109. Kulhanek, K.; Steinhauer, N.; Rennich, K.; Caron, D.M.; Sagili, R.R.; Pettis, J.S.; Ellis, J.D.; Wilson, M.E.; Wilkes, J.T.; Tarpy, D.R.; et al. A national survey of managed honeybee 2015–2016 annual colony losses in the USA. *J. Apic. Res.* **2017**, *56*, 328–340. [CrossRef]

110. Al Naggar, Y.; Baer, B. Consequences of a short time exposure to a sublethal dose of Flupyradifurone (Sivanto) pesticide early in life on survival and immunity in the honeybee (Apis mellifera). *Sci. Rep.* **2019**, *9*, 19753. [CrossRef]
111. Al Naggar, Y.; Paxton, R.J. Mode of transmission determines the virulence of black queen cell virus in adult honeybees, posing a future threat to bees and apiculture. *Viruses* **2020**, *12*, 535. [CrossRef]
112. Gray, A.; Brodschneider, R.; Adjlane, N.; Ballis, A.; Brusbardis, V.; Charrière, J.-D.; Chlebo, R.F.; Coffey, M.; Cornelissen, B.; Amaro da Costa, C.; et al. Loss rates of honeybee colonies during winter 2017/18 in 36 countries participating in the COLOSS survey, including effects of forage sources. *J. Apic. Res.* **2019**, *58*, 479–485. [CrossRef]
113. Neov, B.; Georgieva, A.; Shumkova, R.; Radoslavov, G.; Hristov, P. Biotic and Abiotic Factors Associated with Colonies Mortalities of Managed Honey Bee (Apis mellifera). *Diversity* **2019**, *11*, 237. [CrossRef]
114. Nechaume Moncharmont, F.-X.; Decourtye, A.; Hennequet-Hantier, C.; Pons, O.; Pham-Delègue, M.-H. Statistical analysis of honeybee survival after chronic exposure to insecticides. *Environ. Toxicol. Chem.* **2003**, *22*, 3088. [CrossRef] [PubMed]
115. Gill, R.J.; Ramos-Rodriguez, O.; Raine, N.E. Combined pesticide exposure severely affects individual- and colony-level traits in bees. *Nature* **2012**, *491*, 105–108. [CrossRef] [PubMed]
116. Potts, S.G.; Biesmeijer, J.C.; Kremen, C.; Neumann, P.; Schweiger, O.; Kunin, W.E. Global pollinator declines: Trends, impacts and drivers. *Trends Ecol. Evol.* **2010**, *25*, 345–353. [CrossRef]
117. Goulson, D.; Nicholls, E.; Botias, C.; Rotheray, E.L. Bee declines are driven by combined stress from parasites, pesticides, and lack of flowers. *Science* **2015**, *347*, 1255957. [CrossRef]
118. Manley, R.; Boots, M.; Wilfert, L. Review: Emerging viral disease risk to pollinating insects: Ecological, evolutionary and anthropogenic factors. *J. Appl. Ecol.* **2015**, *52*, 331–340. [CrossRef]
119. Diaz-Basantes, M.F.; Conesa, J.A.; Fullana, A. Microplastics in Honey, Beer, Milk and Refreshments in Ecuador as Emerging Contaminants. *Sustainability* **2020**, *12*, 5514. [CrossRef]
120. Edo, C.; Fernández-Alba, A.R.; Vejsnæs, F.; van der Steen, J.J.M.; Fernández-Piñas, F.; Rosal, R. Honeybees as active samplers for microplastics. *Sci. Total Environ.* **2021**, *767*, 144481. [CrossRef]
121. Alma, A.M.; de Groot, G.S.; Buteler, M. Microplastics incorporated by honeybees from food are transferred to honey, wax and larvae. *Environ. Pollut.* **2023**, *320*, 121078. [CrossRef]
122. Wang, K.; Chen, H.; Lin, Z.-G.; Niu, Q.-S.; Wang, Z.; Gao, F.-C.; Ji, T. Carbendazim exposure during the larval stage suppresses major royal jelly protein expression in nurse bees (Apis mellifera). *Chemosphere* **2021**, *266*, 129011. [CrossRef]
123. Deng, Y.; Jiang, X.; Zhao, H.; Yang, S.; Gao, J.; Wu, Y.; Diao, Q.; Hou, C. Microplastic Polystyrene Ingestion Promotes the Susceptibility of Honeybee to Viral Infection. *Env. Sci. Technol.* **2021**, *55*, 11680–11692. [CrossRef]
124. Al Naggar, Y.; Sayes, C.M.; Collom, C.; Ayorinde, T.; Qi, S.; El-Seedi, H.R.; Paxton, R.J.; Wang, K. Chronic Exposure to Polystyrene Microplastic Fragments Has No Effect on Honeybee Survival, but Reduces Feeding Rate and Body Weight. *Toxics* **2023**, *11*, 100. [CrossRef]
125. Balzani, P.; Galeotti, G.; Scheggi, S.; Masoni, A.; Santini, G.; Baracchi, D. Acute and chronic ingestion of polyethylene (PE) microplastics has mild effects on honeybee health and cognition. *Environ. Pollut.* **2022**, *305*, 119318. [CrossRef] [PubMed]
126. Shah, S.; Ilyas, M.; Li, R.; Yang, J.; Yang, F.L. Microplastics and Nanoplastics Effects on Plant–Pollinator Interaction and Pollination Biology. *Environ. Sci. Tech.* **2023**, *57*, 6415–6424. [CrossRef] [PubMed]
127. Kim, S.W.; An, Y.J. Soil microplastics inhibit the movement of springtail species. *Environ. Int.* **2019**, *126*, 699–706. [CrossRef] [PubMed]
128. Cole, M.; Lindeque, P.; Fileman, E.; Halsband, C.; Goodhead, R.; Moger, J.; Galloway, T.S. Microplastic ingestion by zooplankton. *Environ. Sci. Technol.* **2013**, *47*, 6646–6655. [CrossRef]
129. Wu, M.; Yang, C.; Du, C.; Liu, H. Microplastics in waters and soils: Occurrence, analytical methods and ecotoxicological effects. *Ecotoxicol. Environ. Saf.* **2020**, *202*, 110910. [CrossRef]
130. Wang, J.; Coffin, S.; Sun, C.; Schlenk, D.; Gan, J. Negligible effects of micro- plastics on animal fitness and HOC bioaccumulation in earthworm Eisenia fetida in soil. *Environ. Pollut.* **2019**, *249*, 776–784. [CrossRef]
131. Cui, G.; Lü, F.; Hu, T.; Zhang, H.; Shao, L.; He, P. Vermicomposting leads to more abundant microplastics in the municipal excess sludge. *Chemosphere* **2022**, *307*, 136042. [CrossRef]
132. Huerta Lwanga, E.; Gertsen, H.; Gooren, H.; Peters, P.; Salanki, T.; van der Ploeg, M.; Besseling, E.; Koelmans, A.A.; Geissen, V. Microplastics in the terrestrial ecosystem: Implications for lumbricus terrestris (Oligochaeta, lumbricidae). *Sci. Total Environ.* **2016**, *50*, 2685–2691. [CrossRef]
133. Ju, H.; Zhu, D.; Qiao, M. Effects of polyethylene microplastics on the gut microbial community, reproduction and avoidance behaviors of the soil springtail, Folsomia candida. *Environ. Pollut.* **2019**, *247*, 890–897. [CrossRef] [PubMed]
134. Lei, L.; Liu, M.; Song, Y.; Lu, S.; Hu, J.; Cao, C.; Xie, B.; Shi, H.; He, D. Polystyrene (nano)microplastics cause size-dependent neurotoxicity, oxidative damage and other adverse effects in Caenorhabditis elegans. *Environ. Sci. J. Integr. Environ. Res. Nano.* **2018**, *5*, 2009–2020. [CrossRef]
135. Song, Y.; Cao, C.; Qiu, R.; Hu, J.; Liu, M.; Lu, S.; Shi, H.; Raley-Susman, K.M.; He, D. Uptake and adverse effects of polyethylene terephthalate microplastics fibers on terrestrial snails (Achatina fulica) after soil exposure. *Environ. Pollut.* **2019**, *250*, 447–455. [CrossRef] [PubMed]
136. Hüffer, T.; Metzelder, F.; Sigmund, G.; Slawek, S.; Schmidt, T.C.; Hofmann, T. Polyethylene microplastics influence the transport of organic contaminants in soil. *Sci. Total Environ.* **2019**, *657*, 242–247. [CrossRef]

137. Wang, J.D.; Peng, J.P.; Tan, Z.; Gao, Y.F.; Zhan, Z.W.; Chen, Q.Q.; Cai, L.Q. Microplastics in the surface sediments from the Beijiang River littoral zone: Composition, abundance, surface textures and interaction with heavy metals. *Chemosphere* **2017**, *171*, 248–258. [CrossRef]
138. Hodson, M.E.; Duffus-Hodson, C.A.; Clark, A.; Prendergast-Miller, M.T.; Thorpe, K.L. Plastic bag derived-microplastics as a vector for metal exposure in terrestrial invertebrates. *Environ. Sci. Technol.* **2017**, *51*, 4714–4721. [CrossRef]
139. FAO. *The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2018.
140. Li, L.; Abouelezz, K.; Gou, Z.; Lin, X.; Wang, Y.; Fan, Q.; Cheng, Z.; Ding, F.; Jiang, S.; Jiang, Z. Optimization of dietary zinc requirement for broiler breeder hens of Chinese yellow-feathered chicken. *Animals* **2019**, *9*, 472. [CrossRef]
141. Chen, F.; Jiang, Z.; Jiang, S.; Li, L.; Lin, X.; Gou, Z.; Fan, Q. Dietary vitamin a supplementation improved reproductive performance by regulating ovarian expression of hormone receptors, caspase-3 and fas in broiler breeders. *Poult. Sci.* **2016**, *95*, 30–40. [CrossRef]
142. Beriot, N.; Peek, J.; Zornoza, R.; Geissen, V.; Lwanga, E.H. Low density-microplastics detected in sheep faeces and soil: A case study from the intensive vegetable farming in Southeast Spain. *Sci. Total Environ.* **2021**, *755*, 142653. [CrossRef]
143. Cammack, K.M.; Austin, K.J.; Lamberson, W.R.; Conant, G.C.; Cunningham, H.C. Tiny but mighty: The role of the rumen microbes in livestock production. *J. Anim. Sci.* **2018**, *6*, 752–770. [CrossRef]
144. Jami, E.; Israel, A.; Kotser, A.; Mizrahi, I. Exploring the bovine rumen bacterial community from birth to adulthood. *ISME J.* **2013**, *7*, 1069–1079. [CrossRef] [PubMed]
145. Flint, H.J.; Bayer, E.A. Plant cell wall breakdown by anaerobic microorganisms from the mammalian digestive tract. *Ann. N. Y. Acad. Sci.* **2008**, *1125*, 280–288. [CrossRef]
146. Baldwin, R.L. Digestion and metabolism of ruminants. *BioScience* **1984**, *34*, 244–249. [CrossRef]
147. Church, D.C. *The Ruminant Animal: Digestive Physiology and Nutrition*; Prentice-Hall, Inc: Englewood Cliffs, NJ, USA, 1988.
148. Russell, J.B.; Rychlik, J.L. Factors that alter rumen microbial ecology. *Science* **2001**, *292*, 1119–1122. [CrossRef] [PubMed]
149. Millen, D.D.; Arrigoni, M.D.B.; Lauritano Pacheco, R.D. (Eds.) *Rumenology*; Springer International Publishing: Cham, Switzerland, 2016. [CrossRef]
150. Ross, E.M.; Moate, P.J.; Bath, C.R.; Davidson, S.E.; Sawbridge, T.I.; Guthridge, K.M.; Cocks, B.G.; Hayes, B.J. High throughput whole rumen metagenome profiling using untargeted massively parallel sequencing. *BMC Genet.* **2012**, *13*, 53. [CrossRef]
151. Priyanka, M.; Dey, S. Ruminal impaction due to plastic materials-an increasing threat to ruminants and its impact on human health in developing countries. *Vet. World.* **2018**, *11*, 1307. [CrossRef]
152. Mahadappa, P.; Krishnaswamy, N.; Karunanidhi, M.; Bhanuprakash, A.G.; Bindhuja, B.V.; Dey, S. Effect of plastic foreign body impaction on rumen function and heavy metal concentrations in various body fluids and tissues of buffaloes. *Ecotoxicol. Environ. Saf.* **2020**, *189*, 109972. [CrossRef]
153. Tourinho, P.S.; Kočí, V.; Loureiro, S.; van Gestel, C.A.M. Partitioning of chemical contaminants to microplastics: Sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation. *Environ. Pollut.* **2019**, *252*, 1246–1256. [CrossRef]
154. Jaskulak, M.; Zorena, K. Migration of Microplastic-Bound Contaminants to Soil and Their Effects. In *Microplastics in the Ecosphere*; Vithanage, M., Prasad, M.N.V., Eds.; Wiley: Hoboken, NJ, USA, 2023. [CrossRef]
155. Wang, X.F.; Xu, Y.; Qin, M.Y.; Zhao, Z.; Fan, X.F.; Li, Q.B. Insight into the effects of Cu^{2+} ions and CuO species in Cu-SSZ-13 catalysts for selective catalytic reduction of NO by NH_3. *J. Colloid. Interface Sci.* **2022**, *622*, 1–10. [CrossRef]
156. Huang, J.; Duan, P.; Tong, L.; Zhang, W. Influence of polystyrene microplastics on the volatilization, photodegradation and photoinduced toxicity of anthracene and pyrene in freshwater and artificial seawater. *Sci. Total Environ.* **2022**, *819*, 152049. [CrossRef]
157. Gao, X.; Hassan, I.; Peng, Y.T.; Huo, S.L.; Ling, L. Behaviors and influencing factors of the heavy metal's adsorption onto microplastics: A review. *J. Clean. Prod.* **2021**, *319*, 128777. [CrossRef]
158. Lavers, J.L. A review of concurrent threats to Flesh-footed Shearwaters (Puffinus carneipes): Words of warning from a top marine predator in decline. *ICES J. Mar. Sci.* **2014**, *72*, 316–327. [CrossRef]
159. Lavers, J.L.; Hutton, I.; Bond, A.L. Clinical pathology of plastic ingestion in marine birds and relationships with blood chemistry. *Environ. Sci. Tech.* **2019**, *53*, 9224–9231. [CrossRef] [PubMed]
160. Patangia, D.V.; Anthony Ryan, C.; Dempsey, E.; Paul Ross, R.; Stanton, C. Impact of antibiotics on the human microbiome and consequences for host health. *Microbiologyopen* **2022**, *11*, 1260. [CrossRef]
161. Jandhyala, S.M.; Talukdar, R.; Subramanyam, C.; Vuyyuru, H.; Sasikala, M.; Nageshwar Reddy, D. Role of the normal gut microbiota. *World J. Gastroenterol.* **2015**, *21*, 8787–8803. [CrossRef]
162. Kong, A.; Zhang, C.; Cao, Y.; Cao, Q.; Liu, F.; Yang, Y.; Tong, Z.; Rehman, M.U.; Wang, X.; Huang, S. The fungicide thiram perturbs gut microbiota community and causes lipid metabolism disorder in chickens. *Ecotoxicol. Environ. Saf.* **2020**, *206*, 111400. [CrossRef]
163. Li, A.; Wang, Y.; Fakhar-e-Alam Kulyar, M.; Iqbal, M.; Lai, R.; Zhu, H.; Li, K. Environmental microplastics exposure decreases antioxidant ability, perturbs gut microbial homeostasis and metabolism in chicken. *Sci. Total Environ.* **2023**, *856*, 159089. [CrossRef]
164. Tidwell, J.H.; Bright, L.A. Freshwater aquaculture. In *Encyclopedia of Ecology*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2019; Volume 1, pp. 91–96. [CrossRef]

165. Iheanacho, S.C.; Ikwo, T.N.; Igweze, N.; Chukwuidha, C.; Ogueji, E.O.; Onyeneke, R. Effect of different dietary inclusion levels of melon seed (Citrullus lanatus) peel on growth, hematology and histology of Oroechromis niloticus juvenile. *Turk. J. Fish. Aquat. Sci.* **2018**, *18*, 377–384. [CrossRef]
166. Ogunji, O.; Iheanacho, S.C.; Mgbabu, C.C.; Amaechi, N.C.; Evulobi, O.C. Housefly maggot meal as a potent bioresource for fish feed to facilitate early gonadal development in Clarias gariepinus (Burchell, 1822). *Sustainability* **2021**, *13*, 921. [CrossRef]
167. Lusher, A.; Welden, N.; Sobral, P.; Cole, M. Sampling, isolating and identifying microplastics ingested by fish and invertebrates. *Anal. Methods* **2017**, *9*, 1346–1360. [CrossRef]
168. Devriese, L.I.; Van der Meulen, M.D.; Maes, T.; Bekaert, K.; Paul-Pont, I.; Frère, L.; Robbens, J.; Vethaak, A.D. Microplastic contamination in brown shrimp (Crangon crangon, Linnaeus 1758) from coastal waters of the Southern North Sea and Channel area. *Mar. Poll. Bull.* **2015**, *98*, 179–187. [CrossRef] [PubMed]
169. Van Cauwenberghe, L.; Claessens, M.; Vandegehuchte, M.B.; Janssen, C.R. Microplastics are taken up by mussels (Mytilus edulis) and lugworms (Arenicola marina) living in natural habitats. *Environ. Poll.* **2015**, *199*, 10–17. [CrossRef] [PubMed]
170. Teng, J.; Wang, Q.; Ran, W.; Wu, D.; Liu, Y.; Sun, S.; Liu, H.; Cao, R.; Zhao, J. Microplastic in cultured oysters from different coastal areas of China. *Sci. Tot. Environ.* **2019**, *653*, 1282–1292. [CrossRef] [PubMed]
171. Cheung, L.T.O.; Lui, C.Y.; Fok, L. Microplastic Contamination of Wild and Captive Flathead Grey Mullet (*Mugil cephalus*). *Inter. J. Environ. Res. Public Health* **2018**, *15*, 597. [CrossRef]
172. Savoca, M.S.; McInturf, A.G.; Hazen, E.L. Plastic ingestion by marine fish is widespread and increasing. *Glob. Change Biol.* **2021**, *27*, 2188–2199. [CrossRef]
173. Bhuyan, M.S. Effects of microplastics on fish and in human health. *Front. Environ. Sci.* **2022**, *10*, 250. [CrossRef]
174. Siddiquia, S.A.; Khanc, S.; Tariqd, T.; Sameend, A.; Nawaze, A.; Walayath, N.; Oboturovai, N.P.; Ambartsumovi, T.G.; Nagdaliani, A.A. Potential risk assessment and toxicological impacts of nano/micro-plastics on human health through food products. *Nano/Micro-Plast. Toxic. Food Qual. Food Saf.* **2023**, *103*, 361. [CrossRef]
175. Marco, D.G.; Conti, G.O.; Giannetto, A.; Cappello, T.; Galati, M.; Iaria, C.; Pulvirenti, E.; Capparucci, F.; Mauceri, A.; Ferrante, M.; et al. Embryotoxicity of polystyrene microplastics in zebrafish Daniorerio. *Environ. Res.* **2022**, *208*, 112552. [CrossRef]
176. Jakubowska, M.; Białowąs, M.; Stankevičiūtė, M.; Chomiczewska, A.; Pažusienė, J.; Jonko-Sobuś, K.; Hallmann, A.; Urban-Malinga, B. Effects of chronic exposure to microplastics of different polymer types on early life stages of sea trout Salmo trutta. *Sci. Total Environ.* **2020**, *740*, 139922. [CrossRef]
177. Pradit, S.; Noppradit, P.; Jitkaew, P.; Sengloyluan, K.; Yucharoen, M.; Suwanno, P.; Tanrattanakul, V.; Sornplang, K.; Nitiratsuwan, T. Microplastic Accumulation in Catfish and Its Effects on Fish Eggs from Songkhla Lagoon, Thailand. *J. Mar. Sci. Eng.* **2023**, *11*, 723. [CrossRef]
178. Angsupanich, S.; Somsak, S.; Phrommoon, J. Stomach Contents of the Catfishes Osteogeneiosus Militaris (Linnaeus, 1758) and Arius Maculatus (Thunberg, 1792) in the Songkhla Lake. Warasan Songkhla Nakharin (Sakha Witthayasat lae Technology). 2005. Available online: https://agris.fao.org/agris-search/search.do?recordID=TH2008001875 (accessed on 25 February 2023).
179. Romeo, T.; Pietro, B.; Pedà, C.; Consoli, P.; Andaloro, F.; Fossi, M.C. First Evidence of Presence of Plastic Debris in Stomach of Large Pelagic Fish in the Mediterranean Sea. *Mar. Pollut. Bull.* **2015**, *95*, 358–361. [CrossRef] [PubMed]
180. Kaleem, O.; Sabi, S. Overview of aquaculture systems in Egypt and Nigeria, prospects, potentials, and constraints. *Aquac. Fish.* **2020**, *6*, 535–547. [CrossRef]
181. Hanachi, P.; Karbalaei, S.; Walker, T.R.; Cole, M.; Hosseini, S.V. Abundance and properties of microplastics found in commercial fish meal and cultured common carp (Cyprinus carpio). *Environ. Sci. Pollut. Res.* **2019**, *26*, 23777–23787. [CrossRef] [PubMed]
182. Cole, M.; Lindeque, P.; Halsband, C.; Galloway, T.S. Microplastics as contaminants in the marine environment: A review. *Mar. Pollut. Bull.* **2011**, *62*, 2588–2597. [CrossRef] [PubMed]
183. Pironti, C.; Ricciardi, M.; Motta, O.; Miele, Y.; Proto, A.; Montano, L. Microplastics in the Environment: Intake through the Food Web, Human Exposure and Toxicological Effects. *Toxics* **2021**, *9*, 224. [CrossRef] [PubMed]
184. Barnes, D.K.; Galgani, F.; Thompson, R.C.; Barlaz, M. Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. B* **2009**, *364*, 1985–1998. [CrossRef] [PubMed]
185. Rochman, C.M.; Lewison, R.L.; Eriksen, M.; Allen, H.; Cook, A.M. Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats. *Sci. Total Environ.* **2014**, *476*, 622–633. [CrossRef]
186. Yu, J.; Tian, J.Y.; Xu, R.; Zhang, Z.Y.; Yang, G.P.; Wang, X.D.; Chen, R. Effects of microplastics exposure on ingestion, fecundity, development, and dimethylsulfide production in Tigriopus japonicus (Harpacticoida, copepod). *Environ. Pollut.* **2020**, *267*, 115429. [CrossRef]
187. Iheanacho, S.C.; Odo, G.E. Dietary exposure to polyvinyl chloride microparticles induced oxidative stress and hepatic damage in Clarias gariepinus (Burchell, 1822). *Environ. Sci. Pollut. Res.* **2020**, *27*, 21159–21173. [CrossRef]
188. Parker, B.; Andreou, D.; Green, I.D.; Britton, J.R. Microplastics in freshwater fishes: Occurrence, impacts and future perspectives. *Fish Fish.* **2021**, *22*, 467–488. [CrossRef]
189. Farrell, P.; Nelson, K. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). *Environ. Pollut.* **2013**, *177*, 1–3. [CrossRef] [PubMed]
190. Kühn, E.L.; Bravo, J.A.; Franeker, V. *Deleterious Effects of Litter on Marine Life, Marine Anthropogenic Litter*; Springer International Publishing: Cham, Switzerland, 2015. [CrossRef]

191. Seltenrich, N. New link in the food chain? Marine plastic pollution and seafood safety. *Environ. Health Perspect.* **2015**, *123*, 34–41. [CrossRef] [PubMed]
192. Sharma, S.; Chatterjee, S. Microplastic pollution, a threat to marine ecosystem and human health: A short review. *ESPR* **2017**, *24*, 21530. [CrossRef] [PubMed]
193. Ferrando, J.S. *The Effect of Microplastics on Commercially Value Aquaculture Species: A review*; Universitat Politécnica de Valencia: Valencia, Spain, 2021; Volume 48. Available online: http://hdl.handle.net/10251/174972 (accessed on 23 January 2023).
194. GESAMP. *Sources, Fate and Effects of Microplastics in the Marine Environment: A global Assessment*; International Maritime Organization: London, UK, 2015.
195. Savoca, S.; Matanović, K.; D'Angelo, G.; Vetri, V.; Anselmo, S.; Bottari, T.; Mancuso, M.; Kužir, S.; Spanò, N.; Capillo, G.; et al. Ingestion of plastic and non-plastic microfibers by farmed gilthead sea bream (Sparus aurata) and common carp (Cyprinus carpio) at different life stages. *Sci. Total Environ.* **2021**, *782*, 146851. [CrossRef]
196. Talvitie, J.; Heinonen, M.; Paakkonen, J.P.; Vahtera, E.; Mikola, A.; Setala, O.; Vahala, R. Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, baltic sea. *Water Sci. Tech.* **2015**, *72*, 1495–1505. [CrossRef]
197. Wright, S.L.; Rowe, D.; Thompson, R.C.; Galloway, T.S. Microplastic ingestion decreases energy reserves in marine worms. *Curr. Biol.* **2013**, *23*, 1031–1033. [CrossRef]
198. Jovanovic, B.; Gokdag, K.; Guven, O.; Emre, Y.; Whitely, E.M.; Kideys, A.E. Virgin microplastics are not causing imminent harm to fish after dietary exposure. *Mar. Pollut. Bull.* **2018**, *130*, 123–131. [CrossRef]
199. Kim, J.; Poirier, D.G.; Helm, P.A.; Bayoumi, M.; Rochman, C.M. No evidence of spherical microplastics (10–300 μm) translocation in adult rainbow trout (Oncorhynchus mykiss) after a two-week dietary exposure. *PLoS ONE* **2020**, *15*, e0239128. [CrossRef]
200. Hamed, M.; Soliman, H.A.M.; Badrey, A.E.A.; Osman, A.G.M. Microplastics induced histopathological lesions in some tissues of tilapia (Oreochromis niloticus) early juveniles. *Tissue Cell* **2021**, *71*, 101512. [CrossRef]
201. Halsband, C.; Galloway, T.S. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod Calanus helgolandicus. *Environ. Sci. Tech.* **2015**, *49*, 1130–1137.
202. Lyu, W.; Chen, Q.; Cheng, L.; Zhou, W. *Microplastics in Aquaculture Systems and Their Transfer in the Food Chain. Microplastics in Terrestrial Environments. The Handbook of Environmental Chemistry*; Springer International Publishing: Cham, Switzerland, 2020; Volume 95. [CrossRef]
203. Thodesen, J.; Grisdale-Helland, B.; Helland, S.J.; Gjerde, B. Feed intake, growth and feed utilization of offspring from wild and selected Atlantic salmon Salmo salar. *Aquaculture* **1999**, *180*, 237–246. [CrossRef]
204. Rikardsen, A.; Sandring, S. Diet and size-selective feeding by escaped hatchery rainbow trout Oncorhynchus mykiss (Walbaum). *J. Mar. Sci.* **2006**, *63*, 460–465. [CrossRef]
205. Skilbrei, O.T. The importance of escaped farmed rainbow trout (Oncorhynchus mykiss) as a vector for the salmon louse (Lepeophtheirus salmonis) depends on the hydrological conditions in the fjord. *Hydrobiologia* **2012**, *686*, 287–297. [CrossRef]