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*Article*

# The Impact of Microplastics on Global Food Production: A Brief Overview of This Extremely Diverse and Complex Sector

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**Abstract:** Environmental pollution management combined with food safety represent 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

## 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].

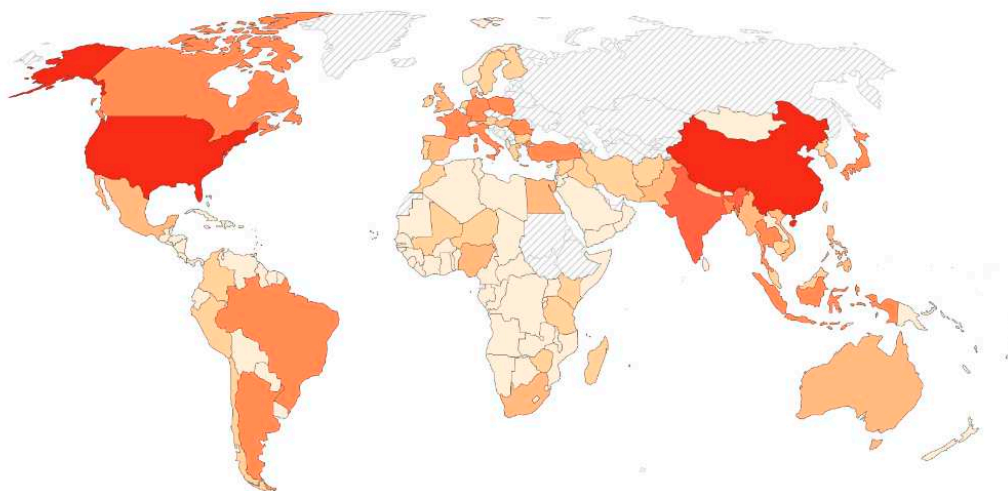
During its relative persistence in the environment, plastic is transformed into microparticles (microplastics, MPs) by UV radiation and mechanical wear and tear [5]. It is generally accepted that MPs are polymeric particles measuring up to 5mm [6, 7, 8]. They can be classified as primary or secondary. The first case, MPs 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 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, 15, 16, 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 liver, lungs,

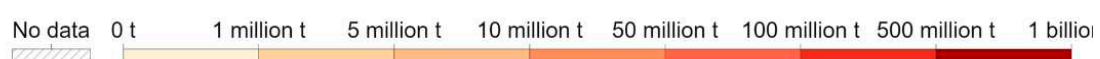
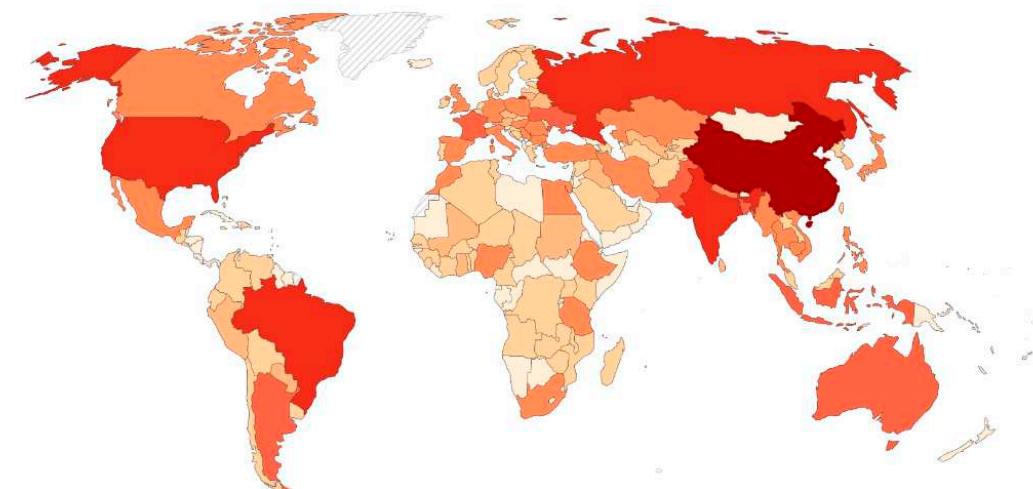
and gastrointestinal tract, causing, for example, intestinal disorders, gut microflora dysbiosis, metabolic imbalance, oxidative disruptions and hepatic and renal toxicity in mice [20, 21]. In aquatic environments their small particle size, low density and diverse shapes allow MPs to remain in the water 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, 24, 25, 26, 27]. For instance, zooplankton can feed on phytoplankton and pass MPs upward through the food web. Moreover, MPs play a key role in 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).

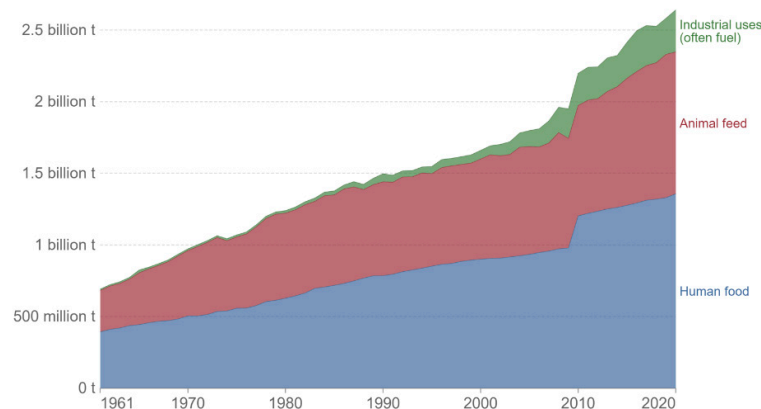
Cereal production (1961)



Cereal Production (2021)

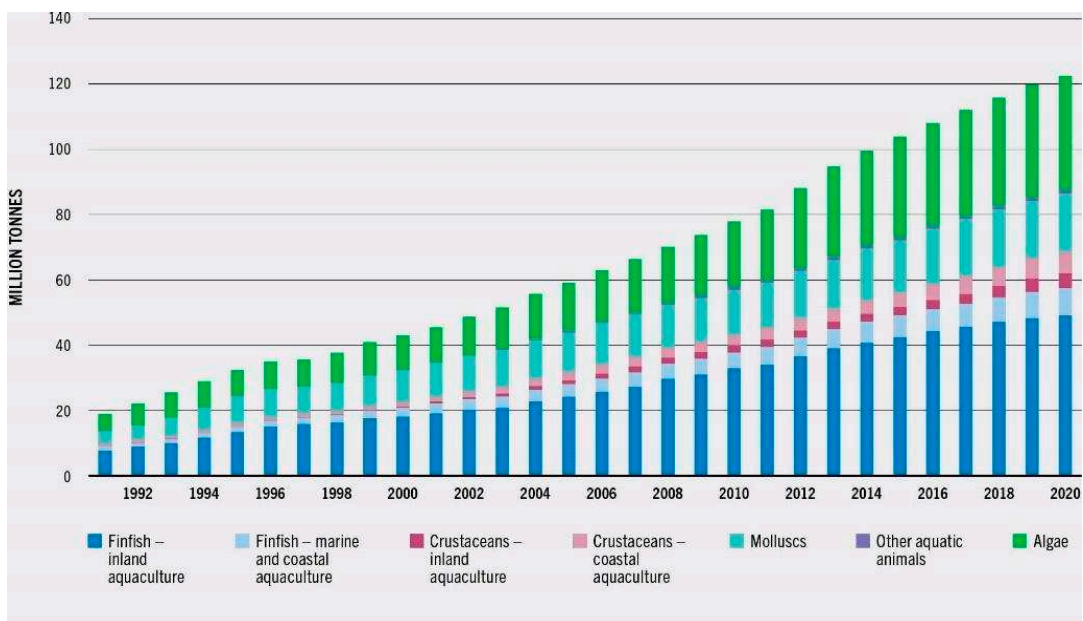


**Figure 1.** Cereal production measured in tonnes representing the total of all cereal crops including maize, wheat, rice, barley, rye, millet and others. (Source: Food and Agriculture Organization of the United Nations OurWorldInData.org/agricultural-production • CC BY).



**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).

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 (Fig. 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, 40, 41, 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 application of soil corrective dressings, agricultural plastic film, chemical additives and pesticide packaging residues, wastewater watering, surface runoff, and atmospheric deposition [41, 48, 49, 50, 51, 52, 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  $2.2 \times 10^4$ – $6.9 \times 10^5$  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, 58, 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 on 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, 63, 64]. Once inside the plant tissue, MPs can change the biomolecular structure of membranes, resulting in oxidative stress [62, 64, 65, 66, 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, 69, 70, 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 application of PS NPs on 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]. [76] and [77] recorded 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 indices 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 loss of plant nutrients, and, finally, impact fungal symbionts in the rhizosphere, decreasing plant diversity [78].

Once within the soil, MPs tend to associate with soil organic matter and microbial catabolites or exoenzymes and become incorporated into the sedimentary microstructure [79]. This newly deposited and embedded element influences soil physicochemical properties by enhancing porosity but reducing permeability, resulting in increased water accumulation [80, 81] 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) [82], 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 [83]. Liu et al. (2017) [83] 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 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 migration of pollutants through the environment. This facilitates dispersion [84] and potentially impacts soil health.

Among the impacts of MPs contact is the inhibition of enzyme activities [42, 80, 81, 85, 86, 87; 88]. For example, dehydrogenase, alkaline phosphatase, cellobiohydrolase, alkaline phosphatase and leucine aminopeptidase were decreased in soils treated with PS nanoparticles [86], while PE and polyvinylchloride (PVC) MPs inhibited the hydrolysis of the marker substrate fluorescein diacetate [87]. Using different soil fractions, [88] 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 [88]. Soil enzymes are directly related to several biogeochemical processes and represent a fundamental tool regulating soil nutrient recycling [89]. These enzymes can be used as soil fertility monitors [90], permitting 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 [81, 83, 85, 91]. Toxic substances released from MPs cause soil contamination, transforming its properties [92]. MPs thus affect the normal metabolic activities of soil organisms, potentially unbalancing nutrient biogeochemical cycles [93]. For instance, nitrogen represents a fundamental nutrient, providing energy and allowing 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 [94], the success of food production directly depends on the bioavailability of reactive nitrogen. [95] and [96] 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 [96]. On the other hand, both studies suggested that the availability of PE considerably inhibits microbial activities, impacting the nitrification/denitrification reactions. [97] 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 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 [98]. 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 [99, 100]. Insect pollinators are responsible for 9.5% of the whole economic value of the agricultural industry that supplies human food [101], being particularly important for coffee, cocoa, almond, and soy [102, 103]. An estimated USD 11.68 billion was spent on honeybees in 2009, only in the Brazilian Cerrado [104], 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 [101, 102, 105, 106]. 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 [107, 108]. Several factors, biotic and abiotic, have been suggested as causes of this decrease, including parasites, bacterial infections, use of pesticides, decrease in number of habitats and improper beekeeping practices [106, 109, 110 - 119]. 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 [120]. MPs, mainly particles and fibers, have recently been found in honeybees from 19 apiaries in Copenhagen [121]. [122], 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, 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 [123], 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 [124]. 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 also PCR and transcriptomic data suggested that genes involved with membrane lipid metabolism, immune response, detoxification, and the respiratory system were significantly affected. [125] 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. [126] 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. [127] gives 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 [128]. 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 [129]. According to [130], earthworms represent the most studied bioindicator that reflect the toxicity of MPs on interstitial organisms. [131] recorded that, at low concentrations, MPs have no great effects on the life cycle of earthworms (*Eisenia fetida*) and, indeed, Cui et al. (2022) [132] reported that epigeic earthworms, which live on the soil surface, actually caused an increase in the number of MP particles when used in vermicomposting. [133], 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 gut microbial community structure, fertility and survival customs of springtails [128, 134]. They can unbalance the energy metabolism of the nematode *Caenorhabditis elegans*, resulting in decreased movement, and finally impacting body development [135]; MPs disturbed the feeding mechanism of snails (*Achatina fulica*), at the same time enhancing oxidative stress [136]. The secondary impacts of MPs (association and carriage of environmentally available pollutants) include increased soil contamination and risk to soil fauna [137, 138]. [139] 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. [138], 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 total meat production increasing more than threefold between 1980 and 2000 [140]. 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 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 [141]. At the same time, its total production and consumption have continued to rise due to its rapid growth and low production costs [141, 142]. 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 [143]. 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 [144]. 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 [145]. The compounds provided by microbial fermentations are fundamental to other physiological processes, including 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 [146, 147, 148, 149]. Thus, the balance of the intestinal microflora is fundamental for the health of the digestive and other systems in ruminants [150]. MPs in livestock feed and water can result in impacted rumen [151] and decrease in rumen protozoal activity [152], leading to indigestion and even death. Additionally, MPs can be transferred into milk and meat [153]. Natural farming methods, using little artificial feed, can also contribute to the problem. 92% of sheep raised on Spanish land on which plastic mulch had been applied were found to excrete MPs in their faeces, thus being responsible for the transfer of contamination to other fields. No adverse effects on the sheep were reported [143].

With their large surface/volume ratio, MPs are effective absorption materials, able to adsorb and take up toxic chemicals [154]. 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 [155]. Thus, plastics not only act as sources of toxins that comprise some of their constituents, but also as carriers of sorbed toxic chemicals [156]. After the aging process of PS and PET MPs by controlled experiments, their adsorptive capacity for environmental copper [Cu (II)] increases, especially after long times at elevated temperatures [157]. This also significantly decreases the volatilization of hydrocarbons, like anthracene and pyrene, altering toxicities to *Phaeodactylum tricornutum* and *Selenastrum capricornutum* [158]. Heavy metal compounds available in the environment may also be adsorbed on the surfaces of MPs [159]. 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 [159]. 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 [160], 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 [161, 162, 163, 164].

Li et al. (2023) [165] 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 [166], with over US\$ 1 billion circulating annually [167, 168]. According to the Food and Agriculture Organization [139], 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 [169].

Many aquatic organisms have been shown to accumulate and assimilate MPs. 63% of brown shrimp collected from the English Channel contained microplastic fibers [170]. Farmed mussels bought in a supermarket were shown, in one study, to contain fewer MPs than wild ones [171]; 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 [172]. Farmed fish, like the mussels mentioned above, have been shown to contain less MP contamination than wild; 60% of wild mullets from the east coast of Hong Kong contained MPs, while only 16.7% of farmed mullets were thus contaminated [173]. As a result of fish exposure to MPs, they may suffer neurotoxicity, reduced physiological development and behavioral disorders [169]. Such fish exposure has at least doubled over the last few years [174]. The effects of MPs are proportional to their available levels [175, 176] and associated pollutants. For instance, the ingestion of MPs caused metabolic disorders in zebrafish and decreased oyster reproduction [177]; exposure to polystyrene (PS) and polyethylene terephthalate (PET) microplastic pellets provoked genotoxic impacts on wild sea trout larvae *Salmo trutta* [178]. Biomagnification has also been recorded in several fish species and other organisms along the trophic net. For instance, Pradit et al., 2023 [179] 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 [180], although MPs have also been found in organisms from the top trophic level, such as bluefin and albacore tuna and swordfish [181]. 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 [169]; 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 [182]. This may be partially linked to contamination by MPs. Plastic has been detected in aquaculture facilities and aquafeed [183]. 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 [183, 184, 185]. 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 [186, 187, 188, 189, 190].

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 [191, 192, 193, 194]. 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 [195, 196]. 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 impact, mechanical (abrasion) or chemical (inflammation), can occur in the various systems of the organism, such as digestive, respiratory, circulatory, neurological and reproductive, as a result of the ingestion and accumulation of MPs [189, 197, 198, 200, 201, 202, 203, 204, 205]. Unfortunately, there is still a great lack of information about the response of organisms to MPs in aquaculture systems [203, 204], and especially about farmed fish [197].

According to [204], 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 [206, 207], 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

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 towards a more 'westernized' diet in developing regions. Microplastics (MPs), a new class of pollutant, are extremely varied and their effects 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 waste water. 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, whose projections are not encouraging. Time is the greatest enemy.

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