microplastics

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Review

Microplastics in Farmed Animals—A Review

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Abstract: Environmental pollution from plastics has become one of the biggest concerns globally. Microplastics (MPs) are plastic materials less than 5 mm in size. They remain in the environment for hundreds to thousands of years without degrading, only breaking down further to nanoplastics (NPs). Micro- and nanoplastics can be the origin of many diseases and can carry various pathogenic substances on their surface and spread them throughout the biosphere, starting with contained additives and ending with adsorbed toxins from the environment and potentially pathogenic microorganisms. Exposure routes for humans and animals are through air, water and food/feed. Due to the placement of livestock—including ruminants, fish and poultry—and humans at the top of the food web, any pollution in water, air or soil can eventually be transferred to livestock and from livestock to humans. The presence of microplastics in the intestines of aquaculture species, ruminants and poultry, for instance, was found to cause a change in the intestinal microbial population and, as a result, the occurrence of diseases. These particles have also been observed in other organs such as liver, kidneys, lung, spleen, heart, ovaries, and testicles of animals, which causes biochemical changes, structural destruction, and malfunction. While the complete extent of the negative health impacts of microplastics remains still largely unknown, their ubiquitous presence and the transmission of chemicals from microplastics to organisms is a notable issue, underscoring the importance of gaining a more comprehensive understanding of the potential threats posed by microplastics to animal and ultimately human health, coupled with a need for drastic reduction of the plastic freight into the environment. This review article summarizes recent findings on the effect of micro- and nanoplastics on farmed animals and, ultimately, on humans. Action is needed to reduce the number of microplastics to which farmed animals, and thereby humans, are exposed.

Keywords: animals; microplastics; nanoplastics; plasticides; farmed animals; pollution; plasticosis

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1. Introduction

Farmed animals, both terrestrial and aquatic, are immensely important for global food security, providing proteins and other nutrients to humans, with a total global market value of farmed animals ranging between USD 1.61 and 3.3 trillion [1]. Mass and value are dominated by cattle, pigs, sheep, chicken, aquaculture species and others such as goats, camels, and horses, providing mainly meat, fish, milk and eggs. In this paper, we use the term "farmed animals" synonymously with domesticated animals and livestock. "Livestock" traditionally includes cattle, sheep, goats, pigs, and sometimes horses. However, it also extends to other domesticated animals, including poultry (such as chickens, turkeys, ducks, and geese) and, in its broader definitions, can include aquaculture species (e.g., fish and shellfish).

The issue of environmental contamination stemming from plastics has emerged as a prominent issue globally. Microplastics, defined as plastic particles measuring less than 5 mm in size, are generated through various means; less than 10% of all plastics today are recycled, and a large fraction of the over-450 million tons/year of new production is littered.

Improper end of life management, such as disposal of plastic waste in an uncontrolled way e.g., due to a lack of collection infrastructure, leads to materials in various ecosystems that are persisting in the environment for extensive periods of time without undergoing decomposition, a process route that would be the case with natural materials like cellulose (which can undergo biodegradation and then mineralization to CO_2 and H_2O). Some of the biggest "sinks" that are at risk of contamination with microplastics are water bodies, particularly the marine environment, into which rivers carry massive plastic freights. Half of our plastic production is deployed for packaging, mostly in single-use items. Lightweight, low-value items, which easily become "lost" and offer low incentives for reduction, reuse and recycling, are at the core of the problem, but other items were also found to create micro- and nanoplastics (MP, NP) throughout their life cycles. In recent years, the problem of water pollution has attracted the attention of many researchers and environmental activists [2,3], and, meanwhile, the topic has reached the perception of the general public, with, e.g., the Indian video *The plastic cow* [4], news and footage about the "great pacific garbage patch" [5] or pictures of wildlife suffering from plastic pollution, a topic that even made it into children's movies [6,7]. Awareness of littering is important, and can be complimentary to other countermeasures. Farmed animals supply a large quantity of our food, and this review article explores the MP and NP exposure of farmed animals and the implications thereof. Corte Pause et al [8] identified livestock animals as "missing links" in the impact of microplastics on human health, and hence the topic warrants close study.

2. Plastic Products—Trailing Micro- and Nanoplastic Particles

It has been predicted that plastic waste in the world will triple from 2015 to 2060 and reach 270 million tons per year in a "business as usual" scenario [9]. Plastic waste has undoubtedly aggravated environmental pollution [10,11], since plastics are mostly literally "consumed" in short-lived articles in a linear economic model. After entering the environment, plastic waste materials are continuously broken down into small pieces and particles [12], but the shedding of microplastics in fact occurs throughout the entire life cycle of most product; see, e.g., [12]. The existing understanding of the environmental dynamics and ecological impacts associated with small plastic fragments and particles is constrained, thereby complicating the matter of plastic pollution as well as the identification of, and the commitment to, countermeasures. The plastic waste crisis—and the term is more than justified—needs to be tackled at the root. More collection and recycling of fossil, non-degradable materials—even in a perfect world—will not solve the issue entirely. Also, "cleaning up" the waste by "fishing" macro- and microplastics from rivers and oceans—both in the open sea and on shores—can never catch the entire freight, and obviously is a huge exercise with energy expenditure and other undesired side effects. Neither will the large-scale deployment of "plastic-eating" microorganisms [13], even if such "all purpose" ones existed—be without large risks and impacts on the ecosphere. Notably, the extraction of micro- and nano-scale plastics from the environment poses greater challenges, compared to the removal of larger plastic waste.

The externalized costs of fossil plastics are not known, but estimates place them in the region of USD ~15/kg of plastics, which is multiple times the market price of the huge majority of the materials, some of which have a value of only 1/10 thereof. We are only at the very beginning of understanding the true implications of plastic waste—a legacy that started ~7 decades ago and which has increased almost exponentially over recent years—and which will be around for at least hundreds of years. The WWF states that the true costs of plastics are 10 times more than their market price [14]. This translates into approx. USD 750/capita or ~5% of the global average of the gross domestic product, a non-negligible burden that eventually all of us will have to bear, and this estimation is still a conservative one.

Recently, the possible threats of microplastics to human health have attracted broad attention, and, due to the widespread presence of microplastics in food used by humans, such as fish [15], honey [16], milk [17], salt [18,19], beer [20], drinking water [21] and also air [22] have captured the interest of many researchers. Consumption of some food products such as seafood, honey and others can be minimized or avoided, but exposure to salt, drinking water and air contaminated with micro- and nanoplastics is unavoidable [23]. Although the daily intake of salt is relatively low in comparison to other sources of exposure, certain regions experience notable levels of microplastic pollution in salt, for instance, where the microplastics not only stem from the plastic grinder used in salt dispensers, but also from the sources of the salt. Microplastics present in salt intended for consumption and drinking water have the potential to be ingested by humans through the digestive system, while those found in the air may come into contact with both the digestive and respiratory systems of individuals. Just as suspended microplastics can be inhaled and deposited in the lung, microplastics might also be swallowed through hand-to-mouth contact, especially for children [22,24], and by the entire population when contained in food. A recent study by Zhao and You [25] estimated the microplastic exposure per country, where it was found that in the most affected country, Indonesia, the average per capita intake of MPs is 15 g/month, chiefly via seafood.

The understanding of potential human health risks associated with microplastics is still in its early stages, primarily due to a lack of comprehensive data regarding how individuals are exposed to these particles, their interactions within biological systems, and the resulting health impacts.

It goes without saying that non-degradable particles deposited in the lung, for instance, cannot be beneficial for one's health, even if the freight of adsorbed toxins and contained additives were at a low level. MPs in the lung have been proven to cause chronic inflammation [26,27].

Microplastics are suspected to cause cancer in humans. For instance, Park et al. [28] found that PP microplastics promote metastatic features in human breast cancer, and Li et al. [29] associated colorectal cancer in the under-50-year-olds with microplastics. For two recent MP-related reviews, see e.g., Baj et al. [30] and Domenech et al. [31].

2.1. Plastics

While polymers are made from monomers, plastics consist of at least one polymer (resin) and various additives (compare Driver, 1979 [32]). Classic fossil plastics are synthetic organic polymers that are usually light, cheap, durable and resistant to corrosion [33,34]. The majority of plastics are made from monomers that have been sourced from fossil resources, predominantly crude oil. In order to increase the performance and appearance when turning the resin into a product, a wide range of additives (such as fillers, plasticizers, flame retardants, heat, oxygen and UV stabilizers, antimicrobial agents and coloring) are added. It is estimated that more than 16,000 different chemicals can be found in plastic articles and hence in plastic waste [35]. At least 4200 thereof are toxic. Mechanical recycling through recompounding will introduce additional, often unknown compounds, like oxygenated species from the polymers, which can be an add-on risk, which is hard to predict. Andrady and Neal [36] classified plastic residues in different ways, including shape, color, size, type of polymer and its uses (e.g., packaging) [37,38]. These plastics are often made of commodities such as PVC, PP or PE, and are a significant part of the waste that goes to landfills, incineration and into the environment [39]. Disposable plastic items (single use), as well as fishing gear (ropes and nets) are found in abundance in the marine environment [40], but micro- and nanoplastics can be detected in virtually every, even the remotest, ecosystems, such as Antarctica [41].

2.2. Global Production of Plastics

The versatility of plastic materials has led to a significant increase in their use worldwide, from 5 million tons in the 1950s to more than 450 million tons until today (compare [36,42]. The majority of plastics are thermoplastics, with lesser quantities being produced of elastomers and thermosets. These latter two cannot be remolded, which makes recycling even more difficult and less common than with thermoplastics, where mechanical recycling is the dominant route that the industry promotes as desired end-of-life management. Products made from different materials and not intrinsically "safe and sustainable by design" (SSbD) limit the end-of-life options. The seminal article by Geyer et al. [24], "Production, use, and fate of all plastics ever made" gives a good overview of what happened to all plastics—6.3 billion tons of plastic waste till 2015. Today, only 9 years later, in 2024, we are already talking about an additional ~350 million tons of plastic waste per year, out of ~450 million tons of production– and still about the same rate of only 9% recycling and approx. 0.5% or 10 million tons/year ending up in the oceans. Figure 1 shows an example of where plastics spread in the environment.

Figure 1. Gannets (*Morus bassanus*) on the island of Helgoland, August 2022: they use plastic waste—obviously from fishing gear—for their nests. The strings pose a risk of entanglement to the chicks, too.

Artificial polymers can not only be found in plastic articles, but also in paints and coatings, as well as in many other, high-volume products. Cigarette butts, for instance, contain filters made from cellulose acetate, which is not biodegradable. Each of them is made from ~15,000 microplastic fibers [43]. Globally, it is estimated that 4.5 trillion cigarette butts weighing 766,000 tons per year litter the environment. Interestingly, some birds were found to use them to protect their nests from ectoparasites [44]. Cigarettes and chewing gums are just two examples of plastic products that are carelessly tossed into the environment. Responsible end-of-life treatment cannot solely be attributed to consumer responsibility; producers need to foresee, through proper material selection, that littered products cannot cause disproportionate harm. SSbD principles need to be included in product development. Apart from a strict legal framework, manufacturers have a decisive role to play. It is estimated that more than 90% of all plastics can be replaced by bio-based and biodegradable alternatives and substitutes, yet only 2% of all plastics today are such bio-based and biodegradable materials, as the market still heavily relies on and favors fossil plastics. The success and proliferation of plastics a result of their set of properties, but is mainly driven by their low costs; plastics are not only cheap on a per-kg basis—and they are lightweight—but they can also be shaped very cost-effectively, e.g., by injection molding, joined simply, e.g., by snap-fit mechanisms, avoiding screws, bolts and adhesives, and be directly colored and tailored for targeted applications through compounding. The increasing versatility of composites is in stark contrast to (mechanical) recycling initiatives.

3. Different Forms of Microplastic Materials in the Environment

Plastics in the environment are usually classified in terms of size, into three categories: macroplastics (>20 mm in diameter), mesoplastics (5–20 mm) and microplastics (<5 mm)

Thompson [34]. Nanoplastics with a size of less than one micrometer are added to this classification as the fourth category. Macroplastics are materials larger than 20 mm, and the term mesoplastics refers to materials smaller than 20 mm and larger than 5 mm.

3.1. Microplastics

Microplastics is used as a collective term for the heterogeneous range of small plastics with a length of particles and fibers < 5 mm. Microplastics can be divided into primary and secondary, based on their origin [34,38]. The term "primary microplastics" refers to plastics intentionally manufactured in small dimensions that are directly introduced into the environment, such as microbeads found in cosmetic items, industrial abrasives, or fibers released from textiles (a major source), or as intermediate products such as powder coating or selective laser sintering (SLS) for additive manufacturing, while "secondary microplastics" are generated through the breakdown of larger plastic materials in the environment due to various chemical and physical processes, such as the disintegration of polymer fragments [45]. Examples are floating polyolefin articles that have become brittle by UV light; see also the discussion below.

The majority of microplastic research has focused around the oceans; however, there is growing evidence that microplastic pollution is also prevalent in virtually all freshwater systems [46–51].

After mechanical disintegration, photodegradation is the first mechanism of degradation of plastics in the oceans, during which polymers such as low-density poly(ethylene) (LDPE), high-density poly(ethylene) (HDPE) and poly(propylene) (PP), which are lighter than water and are hence floating, are broken down by the sun's ultraviolet rays. This initial breaking in the presence of oxygen leads to further degradation of the plastic debris through thermal and oxidative attack [52]. It is believed that biological degradation, if degradation occurs, is much slower than optical degradation [53]. It is known that biofilms form quickly on microscopic debris and change the physicochemical properties of plastics, causing their dispersion into the water column. Hydrolysis in seawater, like biological degradation, is not considered a significant mechanism for the degradation of conventional plastics.

3.2. Sources of Microplastics

When we consider the global plastic industry output, most of it becomes waste within less than a year; also, a considerable fraction thereof is introduced into the environment, partly on purpose or due to lack of reclaimability (e.g., plastic seed coatings, wet wipes) but mostly due to ignorance, "ease", and negligence (classic littering, where consumers and other stakeholders dump plastic items in the environment). This littering not only occurs in humanitarian crises such as a pandemic or a war, but also when proper disposal would be feasible, but there is little or no incentive, as plastics are cheap.

The degradation of these littered materials can take several centuries to complete. Nanoparticles and microplastics are generated as byproducts of the breakdown of larger plastic items into smaller fragments. Microplastics are typically classified into primary and secondary categories, based on their origin and characteristics [54].

Primary: The primary type of these materials can be seen in products such as personal care articles (e.g., in skincare as peelings), plastic pellets used in the plastic industry as intermediate products, or in tire attrition. While tire attrition is a huge problem, the tires themselves are also an unresolved issue globally. The sheer number of waste tires per year—over 2 billion units as a conservative estimation—is a problem, and end-o- life options [55] are limited. Tire devulcanization could keep the bulk of materials in the loop, but the technology is not mature see [56]. A possible solution for tire attrition could be the swapping of raw materials from vulcanized, natural and synthetic rubber for medium-chain-length poly(hydroxyalkanoates) (mcl-PHA). Neupert et al. [57] suggested ways to reduce the discharge of tire attrition waste into the environment.

Primary microplastics enter the environment directly, through various ways. For example, microplastics in personal care come into the biosphere as a result of washing and through water and sewage channels, and sewage treatment plants cannot fully precipitate them. Also, by creating scratches or wear during the washing of clothes with synthetic fibers, mostly made from polyesters, microplastics are released [58]. These can be considered "primary", as they enter the environment in that small size, or "secondary", since they are set free from larger plastic items (see also below), depending on the perspective.

Secondary: The secondary type of these materials is created from the decomposition of larger plastics into smaller ones. This event usually occurs when larger plastics are exposed to conditions such as ultraviolet rays from the sun, wind abrasion, etc. In general, among the main sources of production of these materials, the following ones can be mentioned: residues of the agricultural industry (e.g., mulching film, silage film), aquaculture, fishing and the shipping industry (ropes, nets), waste management (landfill effluent), and municipal wastewater [58,59].

We have long grossly underestimated the prevalence of microplastics. Sobhani et al. [60] found that plastic packaging basically always releases microplastics when being opened, and, depending on the material and the method, between 0.46 and 250 microplastic particles/cm. The plastic cutting board in the kitchen, the pepper and salt grinders made from plastic (e.g., POM, poly(oxomethylene)), and microplastics in the air, water and food; the estimations of how much microplastic we ingest vary, and have been summarized by [61]. The range goes from an equivalent mass of up to 50 plastic bags per year [62] [250 g/year], the "famous" one credit card per week ([63], corresponding to 5 g per week) [250 g/year], to a median value of 4.1 μg/week for adults [64] [<0.25 g/year]; see also the work by Zhao and You [25]. The huge spread in reported numbers by several orders of magnitude highlights two aspects: there are no standardized protocols for MP and NP measurements in place, yet there are a lack of large, representative studies, and there are huge individual exposure differences depending on lifestyle, diet, geography, etc. Also, early studies have not included small particles, e.g., below 20 μm, thereby underestimating the total load [65].

3.3. Chemical Effects of Plastics on Organisms

Some additives that are added during the production process of plastics, including bisphenol A (BPA, e.g., as comonomer in poly(carbonates)), phthalates (as plasticizers), and flame retardants, which are known hormone disruptors [66,67]. Studies have shown that exposure to BPA can be associated with the onset of obesity and leads to cardiovascular diseases and disruption of hormone secretion.

BPA is a so-called xenoestrogen, which shows hormone-like properties, mimicking the effects of estrogen. Cancer and changes in behavioral development are other effects of additives in plastics [68]. Toxic heavy metals in dyes and stabilizers, e.g., cadmium, chromium, lead and mercury, are other harmful additives in several plastic items [69], see also Table 1.

3.4. Dangers and Diseases Caused by Microplastics

The impact of microplastic particles on organisms is primarily determined by the physical and chemical characteristics of these particles. The chemical attributes of microplastics are dictated by the polymer type and additives utilized. The types of additives that are added to improve the properties of polymer materials include plasticizers, antioxidants, stabilizers against ultraviolet rays, processing aids, colorants, mineral fillers and flame retardants. The physical properties of microplastics are determined by the shape and size of the particles, their polymers with associated mechanical properties, and their surface charge [70,71], which depends on their size (Zeta potential). Nanoplastics were found to typically be negatively charged and highly oxidized [72].

There are indications that microplastics can have detrimental impacts on various aspects of ecosystems, including plants, microbes, soil structure and function, and ultimately the well-being of both animals and humans. For example, the presence of microplastics in the soil has shown inhibition of growth, destruction of the digestive system, weight loss, increased mortality, reduced immune response, reduced reproduction and changes in bacterial activity in earthworms [73–76].

Microplastics have the ability to transport various pollutants, including heavy metals, pharmaceuticals, chemicals contained in personal care products, hydrophobic organic pollutants including persistent organic pollutants (POP), and pathogens. The release of zinc and copper metals from microplastics such as poly(styrene) and poly(vinyl chloride) in sea water has been reported [77,78].

Various hydrophobic organic pollutants (HOCs), including hexachlorocyclohexane, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated biphenyl ethers, have been identified in conjunction with microplastics in the environment, typically through association with poly(ethylene)-based microplastics. Medical drugs, as well as their degradation compounds, and ingredients from personal care products such as carbamazepine and 4-methylbenzylidene, have a strong tendency to bond with the poly(ethylene) microplastic particles. Pathogenic agents can be attached by forming colonies on the surface of microplastics, and among them there are genetic cases resistant to 18 antibiotics, which leads to the proliferation of super microbes [79,80], also known as multiresistant bacteria. Increasing antibiotic resistance in animals and humans is a growing concern, which might lead, e.g., to more nosocomial infections, and microplastics as vectors (or as "Trojan horses", as [81], put it), which can aggravate the development of antibiotic resistance.

The very important issue with respect to microplastics is that these materials can transfer pollution to remote areas such as high mountain areas, oceans, deserts and polar regions, areas that were previously considered healthy [82]. Humans are exposed to microplastics in two ways, directly, such as through direct ingestion, breathing, or skin contact with microplastics in the soil, water and air, and indirectly, by transfer through the food chain and thereby through farmed animals. Figure 2 shows the routes of transferring microplastics to the human body [83].

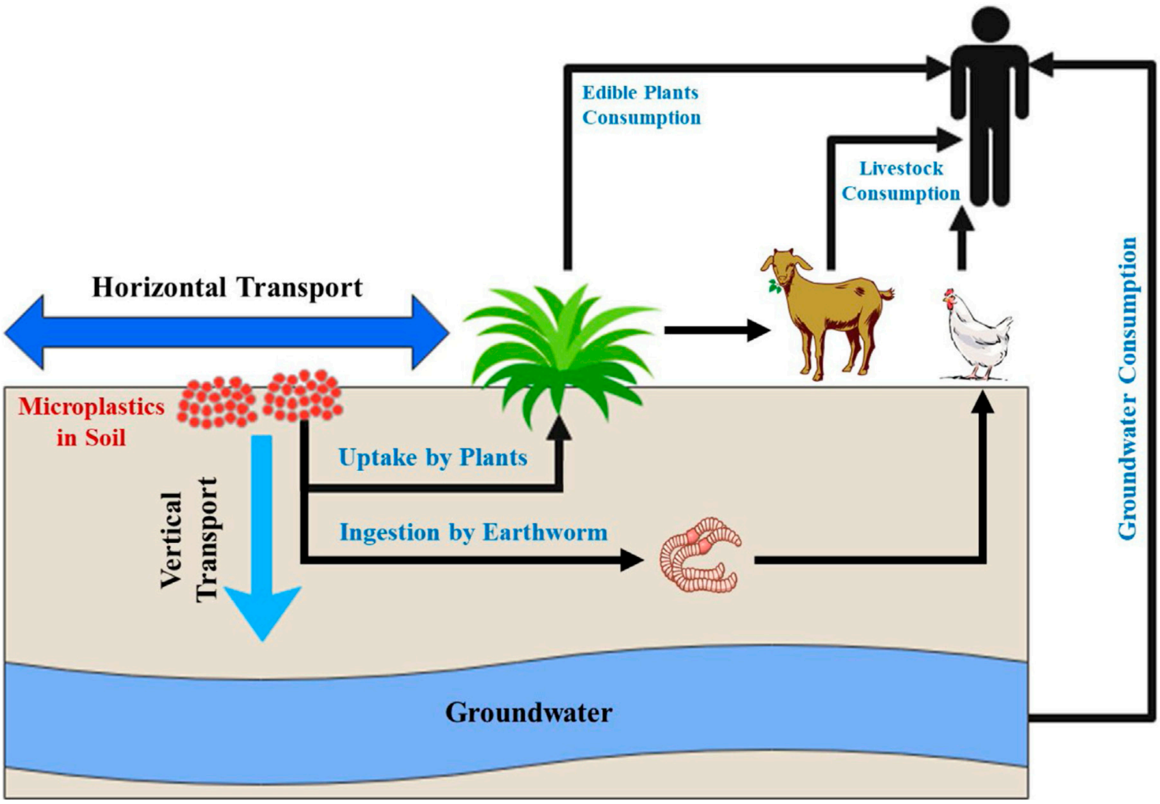

Figure 2. Pathways for transferring microplastics to animals and humans [83]. Farmed animals can ingest microplastics and pass them on to humans.

A large number of cosmetic products bear microbeads, although many such items, fortunately, have been phased out or modified to contain degradable microparticles. For instance, toothpaste, exfoliators, etc., can contain a considerable number of microplastics that come into direct contact with the skin, but in order to pass through the epidermis layer of the skin they must be less than 100 nanometers in size, and the skin acts as a barrier to prevent the passage of many microplastic particles. Microplastics are also present in the air, both indoors and outdoors, and can be absorbed by the respiratory system of humans or animals. Studies have shown that small microplastic particles can even pass through the epithelial tissue of the lung [84]. Also, evidence could be established that a person with low physical activity typically breathes in 272 microplastic particles per day [85]. Food, and then digestion, is the main way in which microplastics enter the body. Microplastics are present both in drinking water and in all types of food. The digestive tract is in direct contact with microplastics, and, through this, microplastics can enter the blood circulation system [86], reach different tissues and affect them, or accumulate in the intestines [87]. There, they interact with the microorganisms in the intestine [73,88,89] studied the interaction of microorganisms with microplastics in the environment.

Recently, a rising number of cases of microplastics in human food such as honey, milk, beverages, seafood, table salt and drinking water have been reported [58]. The industrial production of milk has undergone the development of new technologies to increase human health, which has an effect on the composition of milk. The possibility of contamination of milk with microplastics can be due to the use of poor equipment in the washing operation, the environment around water sources and improper storage of milk. A study has been conducted on 23 milk samples in Mexico, in which the presence of microplastics has been observed in all of them. A total of 150 different microplastic types have been detected in milk, and there is an average of 6500 microplastic particles per cubic meter. The interesting thing to note is that most contamination of milk with microplastics has been observed with thermoplastic polymers from the sulfone family, which are specially used in the preparation of membranes used in milk ultrafiltration and microfiltration technologies [90]. High pressure and continuous chemical action cause the destruction of the membrane, separating the particles from the filters and allowing them to contaminate the product. These cases can cause serious concerns, especially when milk is used to prepare baby food products [90]. The potential risks associated with microplastics for human health encompass oxidative stress, inflammation induced by particle toxicity resulting in conditions such as cancer, impairment of the immune system, interference with metabolic processes, inhibition of fat digestion, and generation of neurotoxins with adverse cognitive effects. Mathematical models predict that human internal organs are exposed to microplastics in the amount of 10^5–10^7 particles per year (compare the estimated masses mentioned earlier), which is an average number, and certain groups of people, such as consumers who drink tea daily or infants who are fed formula, are at risk of digesting significantly higher loads of microplastics [91].

Formerly, of course, it was known that humans eat microplastic particles, e.g., from plastic cutting boards in the kitchen, but it was naively believed that, due to the high molecular mass of the polymers, they cannot be dissolved, and would leave the body like non-digestible fibers contained in fruits and vegetables. People believed that only small quantities of "food grade" products with only safe additives like food packaging from plastics would come into internal contact with the human body—in retrospect, it is hardly possible to image how the risks of plastics and their additives were so invisible. The shedding of microplastics from everyday plastic items is astonishing. For instance, today, it is known that a tea bag creates more than 11 million microplastic particles and more than 3 million nanoplastic particles in a single cup when brewed at a temperature of 95 °C [92]. Also, for babies, the consumption of PET microplastics is estimated to be around 83 micrograms per kilogram of weight per day [93]. PET bottles are used in tremendous numbers, globally. Yes, they do save weight, compared to glass bottles, and the industry does recycle them—an estimated one-third on a global level, by mechanical recycling, with ideas to increase this rate by chemical recycling—but they set free microplastics and nanoplastic particles, making PET bottles intrinsically unsustainable; recycled PET bottles release more microplastics than virgin ones [65]. Poly(ethylene) films used in agriculture (mulching, silaging), which are now widely used for various crops, due to their low thickness and UV exposure, are easily converted into microplastics, contaminating our agricultural soils for centuries. The more they are used in agriculture, the more microplastics are created in arable land. These microplastics can absorb pesticides that are in the soil or sprayed on the fields, such as carbendazim [94] and the organophosphates dipterex (O,O-dimethyl-2,2,2-trichloro-1-hydroxyethyl phosphonate), and malathion. When formed from conventional plastics, these MPs and NPs are non-degradable, and will accumulate in the soil. For a recent risk report on microplastics in agricultural soil, see [95].

Microbes are highly prevalent in natural environments, with potentially hundreds of millions of bacteria present per kg of soil. The significant abundance of microorganisms plays a crucial role in ecosystem functions, such as facilitating metabolic processes, supporting agricultural production, and contributing to the food chain cycle. The complex environment around us includes microbes with special structures and diverse categories in which the microbial population is dynamically connected. Microbial populations can respond to changes in their surrounding environment or quickly adapt to it. These changes can include tensions caused by humans or climate changes. Microplastics have the ability to alter the composition of microbial communities within arid ecosystems based on soil physical characteristics. Specifically, the presence of poly(ethylene) in soil has been associated with an increase in bacteria belonging to the *Proteobacteria*, *Bacteroidetes* and *Gammatomonadites* families [96]. This phenomenon may be attributed to variations in soil organic-matter content, bulk density, and moisture levels. In water environments such as oceans, lakes and rivers, plastic materials are prone to the colonization by microbial populations on their surface, most of which are pathogenic bacteria. The invasion of pathogenic bacteria can disrupt the normal activity of the intestinal bacterial population and reduce the defense capacity of living organisms [97].

A report published in 2019 showed that more than half of the 20 types of microbes that accumulate on the surface of poly(ethylene) microplastics (which float due to their low density) are pathogenic, and it was found that plastics can act as a transfer agent for harmful microorganisms and are considered a potential risk to animal and human health [98].

3.5. Animal Health Affected by Microplastics

From the perspective of the animal ecosystem, the food chain serves as a crucial mechanism for the provision and retention of nutrients. The food cycle plays a role in the transportation of plastics and associated materials within the ecosystem.

According to the available studies, the number of microplastic particles in marine mollusks is between 0 and 10.5; among crustaceans it is 0.1–8.6 and among fish it is 0–2.9 pieces per gram of living weight [99], depending on the location. This information shows that the number of microplastics entering the human body in one year reaches huge numbers when seafood is consumed. A study by Cox et al. [100] found that Americans consume between 39,000 and 52,000 plastic particles per year, and, including inhalation, are exposed to between 74,000 and 121,000 microplastic particles, with a rising tendency [25]. Again, the wide spread of numbers amongst this and previously cited works shows that common standards for MP and NP measurements in different matrices need to be developed, to elucidate the influence of the key driving forces.

In the food chain of terrestrial animals, it has been proven that through the accumulation of microplastics from the soil to the body of earthworms and from earthworms to the body of birds, finally, the presence of microplastics can be detected in poultry droppings [101].

While research has extensively examined the transfer of microplastics within the food web of marine and land-based organisms, recent focus has predominantly centered on marine species. Limited investigations have been carried out on terrestrial animals, highlighting the need for further research in this area, particularly farmed animals, since they are a direct source of food. Digestion of microplastics by animals can have destructive effects for them. As a specific pollutant, microplastic particles can cause various types of physiological damage to animals; see Table 1, Cverenkárová et al. [102], and Wang et al. [103].

Table 1. The role of microplastics in causing various diseases in several samples of living organisms. MPs = microplastics; NPs = nanoplastics; SOD = Superoxide dismutase; MDA = Malondialdehyde; BPA = bisphenol A; PS = poly(styrene); PE = poly(ethylene); PA = poly(amide); PP = poly(propylene); PVC = poly(vinylchloride); PET = poly(ethylene terephthalate).

Microplastic Type	Animal	Physiological Damage	Source
PS	Nematode (*Caenorhabditis elegans*)	Intestinal injury, oxidative stress	[104]
PA, PE, PP, PVC	Zebra fish (*Dania rerio*)	Intestinal damage	[105]
PS	*Ascidian ciona Intestinalis*	Decreased growth and food uptake	[106]
PET, PA	*Sardinella gibbose* (Fish)	Feeding habit, decreased body weight	[107]
PE	*Emys orbicularis* (Pond turtle)	Liver and kidney disease	[108]
PS	*Crepidula onyx* (Mollusca)	Decrease growth	[48]
PS	*Rattus* (Rat)	Alteration of the serum triglyceride and cholesterol concentrations	[109]
MP	*Mus musculus* (Mouse)	Increase in SOD (superoxide dismutase) and MDA (malondialdehyde) contents	[110]
MPs and NPs	Poultry	NPs could be transported into the embryo and accumulate in the yolk sac, leading to alterations in nutrient absorption	[111]
BPA	Female mouse	Impaired cytoskeletal dynamics in the oocyte, induction of oxidative stress, increased DNA damage and epigenetic alterations in oocytes	[112]
BPA	Cattle	Increased apoptotic gene expression in bovine oocytes	[113]
BPA	Cattle	Decreased likelihood of mature oocytes	[114]
BPA	Chickens	Increased embryo mortality and the malformation of reproductive organs	[115]
monoethylhexyl phthalate	Cattle	Inhibits the meiotic maturation of oocytes	[116]
BPA	Mice, pigs, cattle	Abnormalities in meiosis, spindle fibers and congenital defects in mice, pigs, cattle and humans	[117,118]

3.6. Consumption of Microplastics by Marine Organisms

Due to their small size, microplastics can, directly or through the food chain [49,119,120], enter the bodies of various organisms, and they are passed on through the food web; planktonic organisms are eaten by a wide range of aquatic species, up to larger marine organisms [121,122]. Various factors such as dimension, form, compactness, prevalence, and hue can contribute to the heightened availability of microplastics. Aquatic organisms may consume microplastics either through their regular feeding activities, when they are already contained in their prey, or by confusing them with natural food sources (e.g., a turtle mistaking a plastic bag for a jelly fish, or a bird eating floating plastic debris). Many organisms have a limited choice between consuming microplastics and catching anything that has the right size [122], often excreting comminuted particles in significantly larger numbers [123]. The presence of microplastics in a wide range of marine taxa at different trophic levels, including commensals [124], zooplankton [125,126], echinoderms [120,127] annelids, decapoda [128,129], cnidaria, amphipoda [120,130], clams [131,132], cephalopod [133], barnacles [134], birds [53], sea turtles [135] and marine mammals [121,136], has been shown. Microplastics are also reported to have been found in the digestive tract [137–143], muscle [144] and liver [145] of many marine fish species.

Vianello et al. [146] investigated for the first time the contamination with microplastics in the sediments of the lagoon of Venice, Italy. They stated that there is a wide distribution of microplastics throughout the lagoon, and their total abundance was 672–2175 pieces per kilogram of dry sediments. The authors found 10 types of polymers and identified the most abundant ones as poly(propylene) and poly(ethylene), which constituted more than 82% of the total microplastics. This might be explained by the use of these commodity plastics for packaging items and the mismanagement thereof. The most common size (93% of observed microplastics) in the study by Vianello et al. [146] was in the range of 30–500 µm. For a discussion on sinking speed of microplastics, see Kowalski et al. [147].

The digestive tract of 64 pieces of Japanese anchovy fish (*Engraulis japonicus*) was examined by Tanaka and Takada [148] in terms of microplastic contamination in Tokyo Bay. Microplastics were found in 77% of the fish, with an average of 2.3 and a maximum of 15 pieces per fish. The consumption of microplastics by herring (*Mullus surmuletus*) and its oxidative stress potential (biological attacks on the body organs of this fish) were studied by Alomara et al. [149]. Microplastic particles were detected in the gastrointestinal tract of approximately 30.27% of fish in a study involving a total of 417 individuals. On average, each fish contained 0.04 ± 0.42 pieces of microplastics, with 97% of these particles being of the string type. Notably, despite the presence of microplastics, there was no evidence of oxidative stress or cellular damage in the livers of the affected fish. In a study conducted by Vendel et al. [150], focusing on the consumption of microplastics by 69 species of fish in Brazilian tropical estuaries, it was found that out of 2223 fish examined, 9% (comprising 24 species) had microplastics present in their digestive tract contents.

Brett studied the microplastic content of fish meal, which ranged from 0 to 526.7 ng/kg. The highest levels of microplastic contamination were found in fishmeal from China (337.5 ± 34.5 ng/kg) and Morocco (253.3 ± 43.4 ng/kg), while (still) no plastic was detected in krill meal from Antarctica. Fish meal is an important feed for aquaculture as well as chicken, with an annual production of the order of 5 million tons [151].

3.7. The Effect of Microplastics on Marine Organisms

The effect of large pieces of plastic on marine life has been widely investigated [33] Studies have shown that 267 species around the world are affected by plastic pollution [152]. For example, there is clear evidence that plastics cause serious physical harm to marine organisms through direct contact, and, due to the strength and complex structures of plastics (mesoplastics), many marine species can become trapped in plastic debris, e.g., fishing gear "ghost nets" and six-pack rings. Birds who eat plastic particles can die from starvation, as their stomach becomes clogged up with these materials, which is a huge problem also for other for marine species [153]. The term "plasticosis" was coined by these authors, describing the sub-lethal effects of plastic-induced fibrotic disease (in seabirds, but the term can be used more broadly).

Meanwhile, the full effects of microplastics on marine organisms have been less studied. The presence of microplastics has been reported in 94% of seabirds [154] and 35% of plankton-eating fish [155], which indicates the interaction between microplastics and marine species. Consumption of microplastics may cause side effects on animal species. The risks associated with plastic particles include the physical effects of the material [10,156], chemical compounds of plastics [10,157] and chemicals absorbed from the environment [10,157].

The effect of consuming microplastics on the growth and survival of the glass fish (*Ambassis dussumier*) was investigated by Naidoo and Glassom [158]. In this laboratory study, two types of microplastics (raw and collected from a city port for 95 days) were included in the diet of juvenile fish. Standard length, the body depth and mass of the fish were recorded every 20 days and the survival of the fish was recorded every day for the different categories of study fish. Generally, the fish that included microplastics in their diet had less body length and thickness than the control fish. Also, the mass of fish in the treatments with raw plastic was less than in the control group. This was while the mass growth of these fish was lower than that of the fish which did not use the diet containing microplastics collected from the port. The probability of fish survival in both treatments fed with plastic was lower than in the control group. It is estimated that today, the ratio of fish:plastics in the oceans is 5:1 by mass, and this ratio might become less than 1:1 by 2050 [159]. The ratio of fish from aquacultures to fish from wild catch is continuously increasing, and these farmed fish are at high risk of accumulating large amounts of microplastics, given the proximity of aquaculture farms to the shore (mariculture) where rivers transport plastic pollution into the sea, for instance. Microplastics were also found in other farmed aquatic species, e.g., mussels [160].

Barboza et al. [139] investigated the contamination of microplastics and the effect of biomarkers in three species of commercially important fish in the Northeast Atlantic Ocean. Among the 150 species that were analyzed, microplastics were present in 49% of them. The microplastics were detected in various parts of the fish, including the digestive system, gills, and dorsal muscles across all three species studied. Fish that harbored microplastics exhibited notably higher levels of lipid peroxidation in the brain, gills, and dorsal muscle, with a statistically significant difference ($p \geq 0.05$). Moreover, the activity of brain acetylcholinesterase was observed to increase in fish with microplastics in comparison to those without. These findings indicate the occurrence of lipid oxidative damage in the gills and muscle, as well as neurotoxic effects resulting from lipid oxidative damage and the stimulation of acetylcholinesterase in connection to either "pure" microplastics or microplastics exposed to chemicals.

de Vriesa et al. [161] studied the frequency of consumption of microplastics in the digestive tract and their relationship with the length, weight, fullness of the digestive tract and condition index [162] of two commercial fish species of Iceland, *Gadus morhua* and *Pollachius virens*. Microplastics were found in 20.5% of *Gadus morhua* fish and 4.17% of *Pollachius virens* fish. There was no significant relationship between the fullness of the digestive tract and the condition index with microplastics found, which indicates that microplastics are not preserved to a large extent, especially in large samples, and if so, it is likely that the condition factor is not affected. In spite of this, there was a significant difference between fish containing microplastics and fish without them in terms of length, which is a clear indication of the direct detrimental effect of microplastics on fish.

3.8. Physical Effects

The direct effects of consuming microplastics include blockage of the digestive tract and internal damage, reduced food consumption, reduced nutrition, and, ultimately, starvation and death [163]. For example, microplastics stuck in the gills may reduce the respiration rate [125]. Laboratory studies on zooplankton show that consumption of microplastics may cause blockage of the digestive system and accumulation of particles [120]. The main concern of the presence of microplastics in the digestive tract is that with the increase in their residence time, the organisms feel falsely full, and hence their feeding rate decreases [164]. In addition, microplastic particles can be transferred from the intestine to other internal organs of organisms. For example, Browne et al. [165] found that microplastics can be transferred from the intestine of blue mussels (*Mytilus edulis*) to the circulatory system and remain there for up to 48 days, although they do not have a significant biological effect on them. Recently, some studies have reported that microplastics may lead to disruption of fish reproduction through the downregulation of gonadotropin-releasing hormone (GnRH), choriogenin (Chg H) and vitellogenin (Vtg I) [143,166,167] Nevertheless, there is a lack of information regarding the presence of microplastics in the reproductive organs of fish.

3.9. Chemical Effects

Recently, due to the increase in the use of additives in commercial plastics, a new classification has appeared called plasticides [168,169]. Numerous organic compounds are employed as additives in plastics to modify specific attributes of plastic goods, including color, heat and aging resistance, flexibility, and overall performance. For example, polybrominated diphenyl is used for heat resistance, nonylphenol prevents degradation by oxidation, and triclosan hinders microbial degradation [34,170]. In some cases, additives make up more than 50% of the mass of plastic products [143]. Phthalate esters, bisphenol A (BPA), and brominated flame retardants (BFRs) are among many plastic additives known as toxic compounds for organisms when released into the environment [157]. While plastics are primarily composed of inert polymers, they commonly contain additives, typically of small molecular weight, which are not chemically bonded to the matrix and can migrate and be dissolved. Additionally, the polymerization processes involved in plastics manufacturing are often not fully completed, leading to the presence of residual monomers, solvents, catalyst residues (containing metals) and additives that may potentially leach out of the synthetic structure. Therefore, they are able to migrate out of plastic materials [171]. The majority of these additives are lipophilic in nature and possess the ability to effectively permeate cell membranes. As a result, they participate in biochemical reactions and, in addition to severe behavioral effects, they also have a negative effect on the reproduction of organisms [122]. For example, polybrominated diphenylates and phthalates are known as endocrine-disrupting chemicals, as they can interfere with the synthesis of endogenous hormones [172]. Phthalates cause effects such as genotoxic damage in aquatic organisms and fish, inhibiting the transport of substances in aquatic organisms, and creating a hermaphrodite state in fish [173].

Research results have shown that polymers such as poly(vinyl chloride) (PVC), poly(styrene) (PS) and poly(carbonate) (PC) release toxic monomers that are related to the development of reproductive abnormalities and cancer, both in rodents and humans [174]. It has also been proven that additives used in making plastics are separated from them and are taken up by marine species.

Moreover, research has demonstrated that plastics found in water environments can also harbor various contaminants, such as organic chemicals that have been assimilated from the nearby surroundings. Among such organic pollutants are persistent organic pollutants (POPs), which include polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides (for example, dichlorodiphenyltrichloroethane or DDT), which are of major concern, due to their high persistence in the environment [52]. Regarding micron- and below-sized particles, these bear additional risks because of their high surface-to-volume ratio. For example, some POPs, such as polybrominated diphenyl ethers (PBDEs), as well as some pesticides, can cause reproductive disorders by mimicking hormones. Studies on the liver [163,171,175] show that when fish are exposed to pure poly(ethylene) and poly(ethylene) with chemical pollutants absorbed from the marine environment, they experience toxicity effects and liver damage, including a decrease in glycogen, formation of fat cavities, and necrosis (death) of individual cells. Also, these particles bring about eosinophilic concentration caused by cell changes (tumor precursor) and the creation of a hepatocellular gland (liver cell cancer gland) in fish [176]. In addition, nanoplastics (NPs) can cross the blood–brain barrier and accumulate in the brain tissue of fish, leading to behavioral disorders in them [177].

Furthermore, heavy metals and metalloids such as antimony, arsenic and selenium, where both concentration and speciation play an important role, are among the additional pollutants that can be absorbed onto the surface of microplastics. This phenomenon increases the potential risks and hazards associated with the dispersion of MPs and NPs in the environment.

Microplastics can have a synergistic effect with other toxins; see, e.g., Tunali et al. [178] for heavy metals and Prata et al. [179] for pharmaceuticals, an area that has hardly been studied.

3.10. Effects of Microplastics on Farmed Animals—Poultry and Ruminants

Table 2 summarizes the effects of microplastics on farmed animals, where the body of knowledge is still far from approaching completeness.

Table 2. Potential effects of micro- or macro-plastics in ruminants and other farmed animals.

Animal	Plastics	Organ	Effect	Source
Chicken	PS	Kidney	Induced damage to kidney tissue, Mitochondria impairment, disturbance or disorderly arrangement of the blood–urinary barrier.	[180]
Chicken	PS	Heart	No notable impact on body weight or myocardial weight in chicken was observed; caused oxidative stress and inflammation in the chicken myocardium, mitochondrial impairment, and weakened or dysfunctional energy metabolism.	[93]
Chicken	PS	Testicular tissue and blood samples	The effect on the exposed chickens were impaired testicular tissue, inflammatory infiltration in the testicular tissue, and affected BTB-related proteins.	[181]
Chicken	PS	Heart	Caused "myocardial dysplasia" and myocardial endoplasmic reticulum (ER) stress in the exposed chickens.	[93]
Chicken	PE	Blood, intestine, liver, kidney, and spleen	Loss of body weight, significant levels of ALT and AST, induced liver inflammation, and renal glomerular hypoplasia, disruption of the intestinal villi, decline in gut microbiota composition and richness.	[29]
Chicken	PS	Leg and breast muscles, liver, intestine	Increase in breast and leg muscles of chickens, disruption of physiological function of chicken liver and skeletal muscle was observed; PS exposure affected chicken meat quality.	[182]
Camels	PE, PP	Intestines	Intestinal tract damage, pathogenic (bacterial) infection, organ failure.	[183]
Buffaloes	MP	Body fluids and tissues	Ruminal impaction, higher concentration of heavy metals in rumen, blood, liver, muscles and kidney.	[184]
Chicken	PE	Gizzards	Increased volume of gizzards, lowered feeding volume and fitness.	[185]
Aquatic birds	MP, PE	Stomach, adipose tissue	Biomagnification of toxic chemical.	[186]
Aquatic birds	PE	Stomachs and GI tracts	Decreased feeding capacity, lowered reproductive capacity, mortality.	[187]
Wild and indoor hares	PU, PA, PET, PS, PE, PP	Intestines	Intestinal inflammation, changes to intestinal mucosa.	[188]
Terrestrial birds	Microplastics (polyester)	Stomachs and GI tracts	Inflammation, GI blockage, cellular necrosis.	[189]

GI = gastrointestinal; BTB = Blood–Testis Barrier; ALT = Alanine Aminotransferase; AST = Aspartate Aminotransferase.

As Table 2 highlights, several adverse effects were found. The key points are as follows:

Chickens: Exposure to poly(styrene) (PS) microplastics has been linked to kidney tissue damage, mitochondrial impairment, and disruption of the blood–urinary barrier. Heart tissue exposure caused oxidative stress, inflammation, myocardial dysplasia, and mitochondrial impairment. Testicular tissue exposure resulted in inflammation and affected BTB-related proteins. Moreover, exposure to poly(ethylene) (PE) microplastics caused loss of body weight, liver inflammation, renal glomerular hypoplasia, intestinal villi disruption, and a decline in gut microbiota diversity. There was also a noted impact on meat quality, with disruptions in liver and muscle physiological functions.

Camels and Buffaloes: Intestinal tract damage, pathogenic infections, and organ failure were observed in camels exposed to PE and poly(propylene) (PP) microplastics. Buffaloes showed ruminal impaction and higher concentrations of heavy metals in various tissues.

Aquatic and Terrestrial Birds: Aquatic birds exhibited biomagnification of toxic chemicals in their stomach and adipose tissue, leading to decreased feeding and reproductive capacities, and increased mortality. Terrestrial birds experienced gastrointestinal blockage, inflammation, and cellular necrosis due to microplastics.

Wild and Indoor Hares: Exposure to various microplastics led to intestinal inflammation and changes in the intestinal mucosa.

Bahrani et al. [190] found 0.14 and 0.13 MP per g of edible tissues of cows and sheep, mainly consisting of poly(amide). MPs were also detected in pigs [191], goats [192] and horses.

A species that must not be neglected here are bees. While they are farmed for honey production, they also act as pollinators, and an estimated 75% of all food crops, by number, depend on pollinators [193]. Al Naggar et al. [194] studied the effect of MPs on honey bees and found that more research is needed, while Wang et al. [103] did find altered microbiota and stronger toxicity of antibiotics in the presence of PS microplastic particles in bees.

3.11. Transmission of Microplastics to Humans and Their Possible Effects

Fish is one of the healthiest and most important diets for humans, providing protein and other nutrients, from wild-catch and, more and more, aquaculture operations. Despite this, consumption of fish containing microplastics, especially in polluted areas where fish consumption is high, may pose serious risks for human health [23]. Some recent studies have indicated that microplastics have the potential to infiltrate the human body via the consumption of fish [138,139], which increases the importance of studying edible fish tissues for microplastics. In addition to fish, humans eat other seafood items contaminated with microplastics such as oysters [143,195]. Also, salt, sugar and honey [19,196] may introduce this pollution into human bodies. In addition, the presence of microplastics in the Earth's atmosphere may cause these particles to settle on the skin and be inhaled, also eventually causing skin diseases, respiratory and lung diseases, and possibly inflicting also other side effects with still unknown consequences for human health [197,198]. Therefore, the transfer of microplastics to humans may occur through several routes (i.e., consumption, absorption through the skin, or inhalation), and the transfer through these routes is likely to be significantly higher than the transfer through fish consumption [100] and the diet of other farmed animals.

The presence of microplastics in human feces was reported for the first time in 2018 [199], which shows that humans digest and eliminate these particles, at least in part. It is estimated that more than 90% of micro- and nanoplastics consumed by humans are eliminated through the body's excretory system. Several factors, including size, shape, type of polymer, surface chemistry, or other chemicals absorbed from the environment, probably affect the retention or elimination of microplastics in the human body [200]. After microplastics have been ingested, absorption may occur. It is assumed that only microplastics smaller than 150 μm can be absorbed by the human body [201]. Cellular absorption of microplastics and nanoplastics may be strongly influenced by their interactions with surrounding biological compounds such as proteins, phospholipids or carbohydrates [202].

A human-feces test report in 2019 showed that there are about 20 microplastic particles in every 10 g of human feces, of which poly(propylene) and poly(ethylene terephthalate) were the most common ones [1], possibly stemming from flexible and rigid packaging, to a large extent. Also, research conducted in 2021 showed that there is a direct relationship between the presence of microplastics in human feces and digestive diseases such as inflammatory bowel disease [203]. These two studies provide evidence supporting the presence of microplastics within the human body and the negative effects thereof. As the environmental concentration of microplastics continues to rise, it is probable that their levels within human tissues will also increase. Moreover, given that humans occupy the terminal position in the food web, the detection of microplastics in human bodies suggests prior contamination within preceding links of the food, which has subsequently been transmitted to humans. This underscores the necessity for expanded research into the prevalence of microplastics in farmed animals of all types, which constitute key components of human food. To put it another way, there is a strong potential in reducing human MP and NP exposure by ensuring that the concentration in farmed animals is controlled.

Recent studies have shown the presence of an average amount of 1.5 microplastic particles per gram in the intestines of chicken stomachs and the amount of 105 particles per gram in chicken excrement [101]. Also, in the case of sheep, the average amount of microplastic particles is 2000 particles/kg in pasture soil and 1000 particles/kg in the feces of sheep kept in southern Spain [204]. Research conducted in five cities in Indonesia has reported different amounts of microplastics in the intestines of local ducks in this country, with the highest amount equal to 49 particles for each duck and the lowest amount equal to 11 particles for each duck, which are mostly string polymers. Poly(ethylene), poly(ethylene terephthalate), poly(amide), and poly(vinyl chloride) were the most abundant polymers [205].

For animals, eating microplastic particles can have destructive effects. As a unique pollutant, microplastics can cause various types of physiological damage. The health risks include inflammatory responses, metabolic disorders, and intestinal barrier dysfunction, which slows down growth and reproduction [206].

From a cellular point of view, animals that have been exposed to microplastics have a higher rate of cell nucleus abnormalities, which can be due to the mutagenic effects of microplastics, and the number of changes in their red blood cells is also observed to be more, which is also related to the toxicity for cells caused by microplastics [168].

The size of microplastic particles is another aspect that needs further investigation. Most of the studies on microplastic particles concentrated on particles with a size of 5 µm and with a consumption amount between 10^5 and 10^6 particles per day, but it should be noted that particles with a size greater than 5 µm make up about 50% of all microplastics, by number. A large number of microplastics, more than 80% of them, have been observed in the digestive tract, and a number of smaller sizes with a diameter of less than 3 µm have been found in muscle tissue. Because smaller particles are more harmful to human and animal health, there is an urgent need to investigate the risks of digesting microplastics in small sizes [1].

Studies have shown that there is a direct relationship between exposure to microplastics and, as a result, changes in the microbial population of the digestive system on the one hand and increased liver diseases on the other hand [1].

Microplastic particles can infiltrate the animal organism via water, food, or air, and they have been detected in multiple organs including the intestines, liver, kidneys, lungs, spleen, heart, ovaries, and testicles, of a great number of species. These particles induce biochemical alterations, physical damage, and impairments in organ functionality. They possess the ability to traverse the placental barrier, potentially impeding fetal development. Furthermore, due to their capacity to accumulate various pollutants on their surfaces, microplastics can amplify the impact of these contaminants [71]. Still, due to the small number of studies conducted and the large dispersion in the number and type of particles, dimensions and duration of exposure, the information is still scattered, which necessitates action to control MP and NP affecting farmed animals.

3.12. Legal Framework

National laws can help reduce plastics and microplastic pollution; however, a global approach is needed, due to the mobility and longevity of the particles.

An early instrument is the "Constitution of the Oceans", the United Nations Convention on the Law of the Sea (UNCLOS). A good overview of global and regional legislation is given by da Costa et al. [168]. Sharma et al. [207] have summarized legislation in the Mediterranean area.

At the moment, we have an unprecedented chance to stop microplastic pollution, through the UNEP's "Intergovernmental Negotiating Committee on Plastic Pollution" [208]; in March 2022, the work of the INC commenced, to develop an internationally binding agreement to stop plastic pollution. This instrument, which is intended to be based on a comprehensive approach for the full life cycle of plastics, including the production, design, and disposal, is scheduled to be ready by the end of 2024. The first session of the INC (INC-1) took place in Punta del Este, Uruguay from 28 November to 2 December 2022, followed by a second session (INC-2) from 29 May to 2 June 2023 in Paris, France, and a third session (INC-3) from 13 to 19 November 2023 in Nairobi, Kenya. The fourth session (INC-4) happened from 23 to 29 April 2024 in Ottawa, Canada, and the fifth session (INC-5) has been scheduled for 25 November to 1 December 2024 in Busan, Republic of Korea [208]. The process is designed to be open and inclusive, and stakeholders have the opportunity to engage. Market incumbents have strong vested interests, as one can see, e.g., from the two pictures in Figure 3, taken at (INC-4).

Figure 3. INC-4 in Ottawa in April 2024, where the polymer industry "fights" to maintain the status quo. Despite scientific evidence that microplastics harm children and contaminate food, a producers' association tries to convince delegates of the opposite. Copyright Saloni Sharma, go!PHA.

We can see a recurring pattern: the "Carbon footprint" was purportedly invented by "big oil" to place the responsibility for emissions on the shoulders of individuals (Kaufman). At the INCs, the plastic industry is promoting more plastic waste collection and recycling, yet it needs to be understood that merely doing more of this, does not solve the plastics crisis. We need to limit the production of plastics, as research suggest that a 10% increase in production volume will lead to a 10% increase in pollution [209]. Approx. half of the macroplastic articles found in nature are "branded", and there are a few companies that make huge volumes of plastic packaging which end up in nature. Brands can take a leading role in implementing sustainable alternatives and substitutes, without having to wait for legal enforcement.

Scientific evidence on the dangers and effects of microplastics are as certain as evidence of climate change, yet the deniers are many and the INCs are heavily attended by lobbyists. An initiative worth mentioning at this point is the "The Scientists' Coalition for an Effective Plastics Treaty" [210], whose goal is to achieve an effective global plastics treaty anchored in and centered around robust evidence-based decision-making and the precautionary principle. At INC-4, 60 scientists from a total of over 350 scientist members around the world were present, supporting fact-based solutions.

3.13. Solutions to Deal with Microplastics

Calero et al. [211] mention operation clean sweep (OCS)™ as an initiative by the plastic industry to reduce pellet spills and leakages, as well as the Extended Producer Responsibility Principle (EPR). To reduce the pollution caused by microplastics, various solutions have been proposed, which can be classified into three separate categories: containment methods, mitigation methods and separation methods [212].

Preventive measures encompass recycling and appropriate waste management practices. In the lifecycle of the majority of plastics, correct disposal entails the physical separation of materials. Recent research has indicated that landfill effluents contain significant quantities of microplastics, leading to contamination of nearby water bodies and soil, thereby contributing to the spread of microplastic pollution. Further investigation is required to fully comprehend the impact of landfill design on the seepage of microplastics. Recent findings suggest that containment strategies may not be the most effective approach for mitigating microplastic pollution. Reduction techniques encompass a series of proactive measures aimed at diminishing the presence of microplastics by impeding their dispersion. Landfilling is hardly a sustainable solution. In contrast to the engineering-focused inhibition method, the reduction approach is characterized by its reliance on legal and regulatory frameworks. In light of mounting evidence highlighting the detrimental consequences of microplastics on the environment, certain governments have prohibited the incorporation of microplastics as the primary constituent in cosmetic products and have implemented legislation to curtail or phase out plastic usage in the foreseeable future, e.g., for single-use articles. Furthermore, more stringent regulations have been implemented to ensure proper waste disposal and mitigate the issue of microplastic pollution. To augment these regulations, several governmental bodies have endorsed educational initiatives aimed at enhancing waste management practices, including recycling and the utilization of separate waste receptacles. Nevertheless, the recycling infrastructure is constrained by material restrictions and the quality of the recycled materials it generates. While abatement methods can help reduce the amount of human-caused microplastic pollution, they are ineffective against microplastics originating, e.g., from landfill sources or from plastic materials that are still in use [212]. Due to the fact that the majority of water extracted from wastewater treatment centers is used in the agricultural sector, even the leakage of small amounts of microplastics can have many destructive effects on agriculture and, consequently, on the livestock sector.

Naturally, advanced wastewater treatment centers reduce the output concentration to the extent of one microplastic particle per liter of treated water as an order of magnitude [213], which seems like a very small amount. But, considering the large volume of water consumed in the agricultural sector, even the use of this purified water will cause the entry of more than hundreds of thousands of microplastics into every cultivated acre per year for a product such as wheat, and, for products that have more water requirements, such as rice, fruits and dried fruits, these values will be much higher [213]. On top of this, there is the emission of airborne micro- and nanoplastic particles, as well as microplastic freight from seed coatings and other sources, bringing MP and NP exposure to farmed animals of all kinds, through their fodder.

The use of different operating units in wastewater treatment (instead of using only one treatment process) has been promising in reducing the number of microplastics, and the use of special filters to separate microplastics based on their size is effective (note that sometimes, flocculants also contain synthetic polymers, which counteracts the measures of reducing these very materials). The separation of sludges and separation methods based on sedimentation are also effective. Studies have been conducted to use enzyme systems to break down microplastics (e.g., esterase lipases, depolymerase, and PETases), which can be effective in increasing the efficiency of the separation system and preventing water pollution, but their large-scale and comprehensive use is still a big challenge [214,215].

In the field of livestock and poultry, the use of plastic materials to as little as possible an extent in different stages should be considered. Using fodder that has been less exposed to plastic materials, and the physical or chemical removal of plastic materials from grain, fodder and water can partially prevent microplastics from entering the animal body. In materials where plastics are currently used, the use of alternative methods can be effective. For example, instead of using plastic films in the preparation of silages, substitute materials or natural and biodegradable polymers such as polymers from the PHA (poly(hydroxyalkanoates)) family should be used, or cement or metal-made silos can be deployed instead of making silage in plastic bags. It is also recommended that natural polymers such as chitosan-based polymers should be used in the packaging stage of animal materials [216], yet such substitutes and alternatives are not fully available.

The separation of microplastics from waste and wastewater prevents them from entering the ecosystem. In ideal conditions, the outflow from wastewater treatment centers should be free of any solid particles and toxic substances, and should have a neutral effect on the environment after discharge [217].

Bioplastics, i.e., bio-based and biodegradable plastics, as alternatives and substitutes to fossil, non-degradable polymers, can be part of the solution, too. Different standards for biodegradation, depending on the system (e.g., soil, home composting, industrial composting or marine environment), exist [218]. Amongst bioplastics, poly(hydroxyalkanoates) (PHAs) can play a dominant role, in that they are bio-based and completely biodegradable, also in the marine environment.

For a review on remediation and utilization strategies for microplastics, see Thacharodi et al. [219].

3.14. Strategies to Reduce Microplastic Freight in Farmed Animals

Agriculture is a large user of plastic articles, and pastures and primary agricultural products are extensively used to feed farmed animals. According to a 2019 study by the FAO, global agricultural value chains used 12.5 million tons of plastic products in plant and animal production and 37.3 million tons in food packaging [220].

Hofmann et al. [221] recently presented strategies for how plastics can be used more sustainably in agriculture.

Farmers who breed animals or operate aquacultures currently have limited options to reduce the amount of micro- and nanoplastics to which their animals are exposed, and consequently, the contamination of the products by these particles. Following the classic waste hierarchy, limiting the use of plastic items where feasible can be a starting point. Avoiding plastics in ensiling is one strategy, and the proper disposal of fishing gear and other plastic items at the end of their useful life is another approach. An estimated half of the plastics used in agriculture is mulch films, where no fossil, non-degradable materials should be used. Collecting littered plastics in the environment of the animals can also contribute to a reduction in secondary microplastic formation. If plastic waste was declared and handled as dangerous waste—which it actually is—littering would be dramatically reduced.

Oxodegradable products—which fortunately are already banned in many jurisdictions—should be avoided completely, as they produce huge numbers of MPs and NPs, while deceiving users of their apparent "degradability".

Asking suppliers for coated seeds that are free from conventional plastics can help reduce the emission of microplastics into arable soil. Biodegradable plastics for items that are intended to remain in nature—e.g., protective covers for young trees and strings for vineyards—are another contribution farmers can make. While biodegradable plastics can also produce MPs and NPs, the difference is that these will have a significantly lower residence time in nature, and therefore have less negative impact. The formation of MPs and NPs cannot be avoided, but we can control the duration of how long they will be around. The rate of biodegradation of, e.g., PHA, PLA, PBAT, TPS, and other bioplastics, depends on the environment, with warm, humid compost being an ideal location for fast mineralization, and cold seawater a system where more time is needed, yet the MPs and NPs will not be persistent, as is the case with those from fossil, non-degradable plastics. It goes without saying that bioplastic formulations should not contain problematic additives, and that more-stringent regulation—for all polymer-derived products—should be enacted.

3.15. Technological Solutions against MPs and NPs

Technological solutions have significant potential to mitigate microplastic pollution. Innovative wastewater treatment technologies, such as advanced filtration systems, can effectively capture microplastics before they enter natural water bodies. For instance, membrane bioreactors and nano-filtration techniques are highly effective in removing even the smallest microplastic particles from wastewater, but are not yet state-of-the-art techniques. For drinking water, boiling was recently identified as possible means to precipitate microplastics [222], and there will be more energy-efficient ways with better scale-up potential. Additionally, novel materials, such as biodegradable polymers, offer promising avenues for reducing persistent microplastic and nanoplastic particles, attacking the problem at the root. Limiting the type of additives in plastic products and declaring all plastic waste as dangerous goods can also help improve its management, thereby reducing micro- and nanoplastics formation and spread. An "end of pipe" solution, where MP and NP are removed once they have spread in the environment cannot be the sole solution; instead, the entering of plastics into the environment needs to be curbed, and technology to capture macroplastic and other plastic debris can be implemented, in addition. Plastic waste should be declared as hazardous waste, and managed accordingly.

3.16. Behavioral Aspects

Behavioral interventions and public awareness campaigns can also play a crucial role in reducing microplastic pollution, particularly by addressing the impact of microplastics on farmed animals and their subsequent entry into the human food chain. Initiatives promoting sustainable consumption habits can significantly mitigate the release of microplastics by encouraging the adoption of alternatives to plastic products and the reduction in single-use plastics. Public awareness campaigns that educate consumers about the importance of recycling, and proper waste management can further decrease the amount of plastic waste entering the environment. Additionally, fostering community engagement in environmental conservation efforts, such as local clean-up events and plastic reduction challenges, can enhance collective action against microplastic pollution. Targeted campaigns highlighting the health risks associated with microplastics in farmed animals can also drive consumer behavior changes and support for stricter regulations on plastic use in agriculture and aquaculture.

3.16.1. Specific Policy Recommendations

Policymakers and relevant stakeholders at the international, national, and local levels should adopt a multi-faceted and evidence-based approach to tackle the complex issue of microplastic pollution. At the international level, a globally binding agreement, such as is being developed by UNEP's Intergovernmental Negotiating Committee on Plastic Pollution, should enforce strict regulations on plastic production, emphasizing the reduction in single-use plastics and the promotion of biodegradable alternatives and substitutes. National governments should implement Extended Producer Responsibility (EPR) policies to ensure that manufacturers are accountable for the entire lifecycle of their products, thereby incentivizing the design of more sustainable packaging solutions and other more environmentally friendly goods. Locally, municipalities must enhance waste management infrastructures, including advanced wastewater treatment facilities capable of effectively filtering microplastics, and promote community-level education programs to raise awareness about proper waste disposal practices. Additionally, agricultural sectors should minimize the use of plastic products, opting for natural and biodegradable materials to reduce the microplastic load in soil and water systems. These coordinated efforts across all levels of governance are essential to mitigate the pervasive impact of microplastics on environmental and human health.

3.16.2. Recommendations for Future Research

To address the remaining knowledge gaps in microplastic pollution, future research should prioritize several key areas. First, the development of standardized methodologies for sampling and analyzing microplastics across various environments (marine, freshwater, and terrestrial) is crucial to ensure data comparability and reliability. This includes refining techniques for detecting and quantifying smaller microplastics and nanoplastics from different matrices, amongst them tissues of farmed animals. Interdisciplinary collaborations should be fostered to integrate expertise from environmental science, toxicology, materials science, and socioeconomics, aiming to understand the broader impacts of microplastics on ecosystems, animals and human health. Additionally, longitudinal studies are needed to assess the long-term effects of microplastic exposure in different organisms and environments. Data collection efforts should be enhanced through the use of advanced technologies such as remote sensing and machine learning to monitor and predict microplastic distribution patterns. Funding priorities should focus on innovative solutions for microplastic mitigation, including the development of bio-based and biodegradable materials and effective waste management systems. Furthermore, research on the socioeconomic impacts of microplastic pollution will provide valuable insights for policy development and public awareness campaigns. The synergistic effects of MPs and NPs with other pollutants need to be studied in more depth; for instance, whether there are multiplicative effects, leading to more than additive toxicity. Research is needed to ensure a lower and controlled exposure of farmed animals to MPs and NPs. Strict limits for MPs and NPs in both feed and animal-derived products need to be worked out, as is the case today with many other pollutants like heavy metals. We need standards to quantify MPs and NPs in animal-derived produce such as eggs, milk and meat, with knowledge about safe or at least permissible levels. Coming back to the formulation of plastics, the industry has developed a huge library of thousands of additives, with a high number of problematic compounds amongst them [35], where no complete alternatives are in place yet. More efforts are required to develop bio-based and biodegradable additives to replace today's antioxidants, stabilizers, color additives, etc., where artificial intelligence might be used as a supporting tool.

4. Conclusions

The issue of environmental contamination caused by plastics has emerged as a significant focal point for various communities across the globe. Amongst other stakeholders, farmers are concerned about the impact of MPs and NPs on their animals, and how they affect their products. Water sources may contain a variety of plastic items and debris, plus their additives and adsorbed and absorbed toxins from the environment. At the global level, the issue of microplastics has become a topic of the day, and governments are enacting laws to reduce the pollution of microplastics. Technology for microplastic capturing is only at its very beginning. In most countries, the amount of production and consumption of plastic materials is very high for both economic and cultural reasons, with per capita plastic-waste volumes being correlated with GDP. On the other hand, only a small percentage of plastic material is recycled, and a large fraction is released into nature without serious supervision or is even discarded or buried illegally. The general expectation is that the level of pollution caused by microplastics in developing countries is higher than the global average, due to lack of collection and recycling infrastructure, but the problem is global, with, e.g., tire attrition waste and polyester textile fibers being emitted around the globe, and persistent MP and NP particles showing global dispersion. In the field of animal science, so far, only very few studies have been carried out on the level of contamination of water and fodder with microplastics and the amount and type of these substances in the body of livestock and poultry, as well as their presence in high-consumption products such as meat and milk, and the ultimate effects on consumers. Also, information about the effects of these particles on stable production, reproduction rate and animal health is not sufficiently available. It is necessary to understand the issue more clearly, but also to drastically reduce (micro)plastics emission into the biosphere.

International cooperation and collaboration are paramount in addressing microplastic pollution. It is essential for governments, NGOs, industry stakeholders, and scientific communities to work together to develop and implement effective strategies for reducing microplastic emissions and mitigating their environmental impact on a global scale. Raising public awareness and promoting education initiatives are equally important to engage individuals, communities, and businesses in efforts to reduce microplastic pollution. Encouraging responsible consumer behaviors, such as reducing plastic consumption, collection and recycling, and supporting initiatives that promote plastic waste reduction and environmental conservation, is vital for fostering a collective commitment to tackling this pressing environmental issue. Hopefully, INC-5 will bring a solid result; as this article has summarized, we know too well that microplastics in farmed animals are no good, and we now need to acknowledge this and act accordingly on multiple levels, to control the issue. It will not suffice to remove microplastic contamination; a holistic solution for the entire inventory of non-degradable plastics has to be found, and bio-based and biodegradable alternatives and substitutes need to be deployed to truly solve the underlying issue of micro- and nanoplastic pollution.

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