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Review

# Micro(nano)plastics cycle in ruminant farming systems

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**Abstract:** Plastic manufacturing is growing at a faster pace than the majority of synthetic substances. Upon release, plastic materials degrade into smaller fragments known as microplastics or nanoplastics, depending on their size. Addressing micro(nano)plastics pollution necessitates a comprehensive, collaborative approach within the Planetary Health framework. This approach acknowledges the interconnectedness of environmental compartments, global animal and human health, emphasizing a nuanced understanding of micro(nano)plastics' movements and impacts on ecosystems. Our review investigates the pathways of micro(nano)plastics contamination within ruminant farming systems, evaluating their impacts on both biotic and abiotic components. We highlight the pervasiveness of plastic contaminants in all environmental compartments of ruminant farming systems, affecting biota, soil properties, and ecosystem services. These contaminants may be transferred to the human food chain through the consumption of animal-derived foods, raising potential health concerns for animals and human beings. Additionally, these contaminants may act as carriers for various chemical and biological environmental pollutants. Despite ongoing research, the cycle of these pollutants in ruminant farming systems remains fragmented and complex. Future efforts should apply the Planetary Health holistic approach to develop effective monitoring, mitigation, and management strategies.

**Keywords:** microplastics; nanoplastics; Planetary Health; soil; ruminants; milk

## 1. Introduction

The 2030 Agenda for Sustainable Development, adopted by all 193 United Nations members in September 2015, emphasizes a unified commitment to bold, transformative actions through universally applicable Sustainable Development Goals. All economic sectors must address these global agreements, particularly the plastics manufacturing sector, whose production processes and products themselves can have significant, long-term environmental drawbacks. To date, approximately 8300 million metric tons (Mt) of plastics have been generated. Plastics production has rapidly increased over the years, second only to materials like steel and cement used extensively in construction [1]. Of the total plastic waste, approximately 9% is recycled, 12% incinerated, and 79% accumulated in landfills or the natural environment. If current trends continue, around 12,000 Mt of plastic waste will exist in landfills or the natural environment by 2050. Once released, plastic debris persists and accumulates in environmental compartments worldwide, eventually entering the food chain and affecting humans. Smaller fragments, known as microplastics (MPs) or nanoplastics (NPs) based on size, are defined by the European Food Safety Authority (EFSA) as plastics with diameters ranging from 0.1 to 5000 micrometers (μm) for MPs and 0.001 to 0.1 μm for NPs [2]. To understand plastic pollution and its environmental fluxes, a model of the MP cycle has been proposed [3]. This framework examines the dynamics of MPs, encompassing their fate, transport, and effects, and incorporates source-receptor models [4,5]. Within this model, environmental compartments affected by plastic pollutants are termed “MP receptors” and include air, water, sediments, and biota. The exposure of these receptors depends on transport processes, pathways, and MP concentrations in the environment. Consequently, this model provides a structured approach to understanding the life cycle of MPs and NPs, from their release to their effects on organisms. This holistic approach helps researchers, policymakers, and environmental scientists to understand the complexities of micro(nano)plastics pollution and to develop strategies for monitoring, mitigation, and management. Micro(nano)plastics significantly impact Planetary Health, defined as “the health of human civilization and the state of the natural systems on which it depends” [6], owing to their widespread presence and potential ecological and human health effects. Effectively addressing this issue necessitates a collaborative, holistic perspective, considering the interconnectedness of environmental compartments, animal and human health, and a comprehensive understanding of micro(nano)plastics movement through ecosystems.

The ecosystem impacts of MP and NP pollution, as detailed in **Table 1**, also extend to ruminant farming systems. These systems, frequently described in the literature as cattle and small ruminant farming [7,8], represent complex artificial ecosystems comprising living organisms (cattle, sheep, goats, microorganisms, plants) and non-living components (soil, water, air). Nutrient cycling within ruminant farming involves all these components, which can serve as entry points and modulators of MP/NP distribution. Within this framework, ruminants occupy a central role due to their unique digestive system, enabling the conversion of plant biomass into animal-derived food products and contributing to nutrient cycling through excretion [9]. Ruminants can be utilized as sentinel animals in environmental monitoring due to their physiology, behavior, and ecological role [10,11]. They are also key sources of animal-origin foods like meat, milk, and dairy products, making them valuable as early warning systems for human health risks. Similar to nutrient cycling, the micro(nano)plastics cycle involves all biotic and abiotic components of ruminant farming systems. **Table 1** demonstrates that all living organisms are exposed to MPs, which are significant contaminants within the One Health framework—another framework closely related to Planetary Health that addresses and links human, animal, and environmental health. Nevertheless, their hazardous transfer levels are debated, and the adverse effects of current environmental MP concentrations on animal and human health are not fully understood [12]. To gain a complete understanding of the impact of plastics on ecosystems, including those involved in ruminant farming, it is crucial to acknowledge key characteristics that set plastics apart as unique environmental contaminants:

- Plastic particles are composed of polymers and contain various additive chemicals.
- Plastic particles vary in volume, shape, and surface based on their size.
- The surface of plastic debris can adsorb chemicals, including heavy metals and pesticide residues, and create a specific microhabitat for microbial communities, known as the ‘plastisphere’ [13].

- Leaching can occur, releasing chemical contaminants, plastic components (such as monomers and additives), and microbes into the environment.

**Table 1.** Key points regarding the intersection of Planetary Health and micro(nano)plastics.

| Key points | Descriptions |
|---|---|
| Environmental Contamination | Micro(nano)plastics have become pervasive in all environmental compartments |
| Ecosystem Impacts | Micro(nano)plastics can have detrimental effects on ecosystems. They may disrupt food webs, harm biota, and accumulate in soil and change its abiotic properties, affecting ecosystems services (e.g., biogeochemical processes). The long-term consequences of these ecological impacts on Planetary Health are still being studied |
| Wildlife, Livestock and Human exposures | Micro(nano)plastics can enter the human food chain through the consumption of contaminated water and foods of animal origin. Knowledge gaps about MPs distribution in swine and cattle tissues. Limited available information about estimated daily intake of MPs from animal-origin products. Potential risks associated with exposure to micro(nano)plastics as well as adverse effects on animal and human health are active research topics. |
| Global Collaborative Solutions | Micro(nano)plastics pollution requires international cooperation. Collaborative efforts should involve research, policy development, and technological innovations, seeking to diminish plastic consumption and enhancing waste handling and developing sustainable alternatives |
| Preventative Measures | Promoting a circular economy, reducing single-use plastics, enhancing recycling infrastructure, and developing eco-friendly materials are crucial strategies to prevent the generation and accumulation of MPs and NPs in the environment. |

Thus, MPs and NPs can function as carriers of environmental pollutants, like pesticides and heavy metals, as well as antibiotic resistance genes and pathogens [14,15]. Within the micro- and nanoplastics cycle in ruminant farming systems, continuous adsorption and leaching of chemical and biological agents via MPs and NPs could result in chronic exposure with unpredictable cumulative effects on animals and humans (as consumers of animal-derived foods). We investigate the routes of MPs contamination in ruminant farming systems, considering impacts on both biotic and abiotic components, as depicted in **Figure 1**.

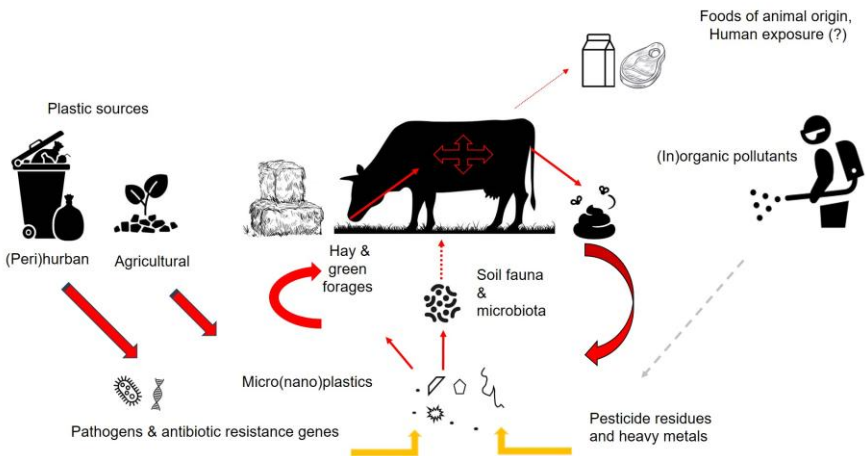


**Figure 1.** Schematic representation of the micro(nano)plastics cycle in ruminant farming systems.

Specifically, this review synthesizes current findings on the presence and effects of micro- and nanoplastics in domesticated ruminants, focusing primarily on cattle as environmental receptors of these contaminants. This discussion excludes MP exposure through freshwater and air pollution [16]. However, irrigation water, especially recycled wastewater, is a significant source of MPs in farmland soils. MPs concentrations are typically three times greater in recycled wastewater than in desalinated brackish water [17]. Furthermore, MP levels are higher in soils exposed to irrigation water compared to deeper soil layers [18]. Spanish research showed that the characteristics (shape, color, size, and type) of MPs in cropland soil matched those in the irrigation water used [19].

## 2. Methodology

Relevant literature, primarily spanning the years 2017 to 2024, was systematically compiled through searches of scientific databases such as Web of Science, Scopus, ResearchGate, and Google Scholar. The search terms included various combinations of keywords and topics, such as “microplastic agricultural soil,” “microplastics analytical methods,” “microplastics ruminants,” “microplastics milk,” “nanoplastics,” and “microplastics feces.” The search prioritized articles investigating the interplay of micro(nano)plastics with all biotic and abiotic elements within ruminant farming systems, as well as studies detailing primary exposure pathways. Furthermore, the bibliographies of significant publications were manually screened to locate additional relevant research. The gathered literature underwent critical analysis, thematic grouping, and structured organization to effectively meet the aims of this review (**Figure 2**).

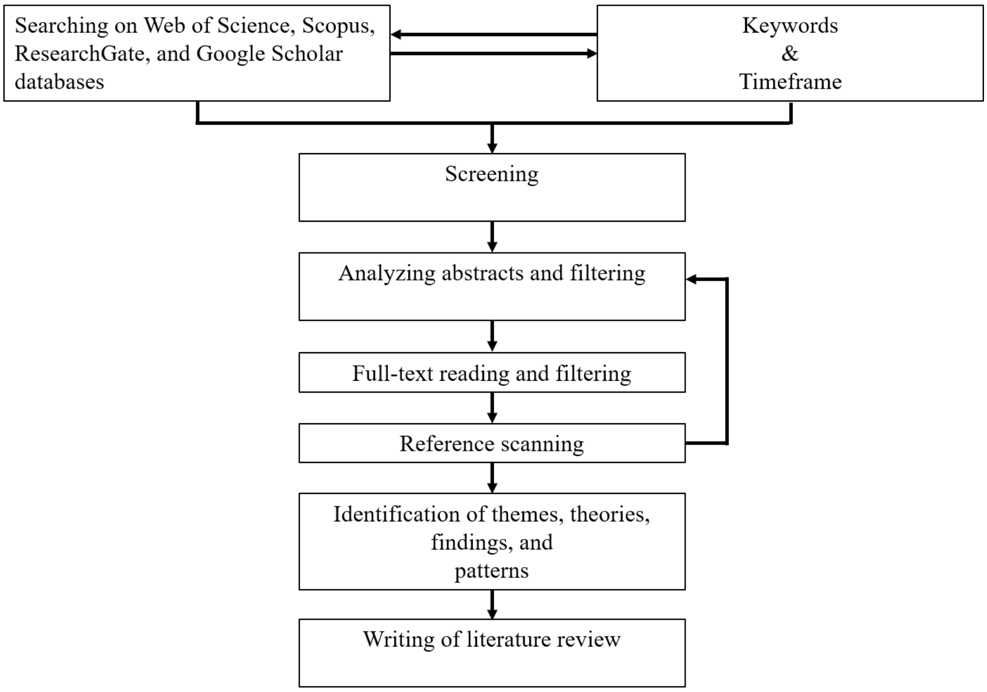


**Figure 2.** Flowchart of literature review methodology.

## 3. Microplastics in farmland environment

A farming system is an assemblage of interdependent components with complex interactions, including soil, crops, livestock, power, labor, capital, and other inputs. The term ‘farm’ describes a land management and decision-making entity that includes the family residence, crop production, and animal husbandry, generating agricultural goods for consumption or market [20]. Ruminant farming systems are a dynamic component within the agro-zootechnical industry. Advancements in animal science and technology, particularly in breeding, feeding, and health, have driven global increases in ruminant productivity. Future ruminant production is expected to show more pronounced differences between rich and developing nations, and between highly efficient production systems and smallholder and agro-pastoral systems [21]. MPs pollution affects all components of farming systems, especially soil, plants, and animals [22]. Due to its extensive surface area and its role as a primary source of water and nutrients for plants, soil serves as a major environmental reservoir for MPs in agricultural areas [23]. Contamination of agricultural soil by MPs can be attributed to waste disposal sites that receive waste from rural, urban, and industrial regions. Spreading sewage sludge on farmland is a major global source of initial microplastic pollution [24]. Industrial effluents, paint wastes, discarded plastics, household materials, and fertilizers introduce plastics into agricultural soils. This process is facilitated by biological agents and vertical transport into aquifers [25].

The advent of the ‘plasticulture era’ has significantly impacted agriculture, particularly horticulture, leading to an exponential growth in plastic film consumption over the past decade. Plastic materials are essential in both storage and watering systems due to their cost-effectiveness, technical versatility, ease of setup, and efficiency. Asia (70%) and Europe (16%) stand out as the main consumers of plastic films, which are extensively utilized in the cultivation, harvesting, and processing of agricultural products. These films are particularly significant for preserving winter cattle feed through ensiling grasses or crops, a process that aims to maintain nutritional values and impede fermentation [26]. It’s worth mentioning that biodegradable mulch films typically release a higher average number of MPs than non-degradable films. This is due to the more rapid plastic fragmentation caused by exposure to natural solar light (especially the UV component), a process that is influenced by mulching duration and the amount of mulch films and plastic material [27].

Agricultural soils are susceptible to accumulating plastic residues through crop rotations, potentially making plastics available within the growth environment of crops. The knowledge gap regarding the complex interactions within the soil ecosystem and the impact of MPs pollution is significant. As non-natural foreign materials, MPs have the potential to alter the still poorly understood relationships between the biotic and abiotic components of the soil system. The environmental impact of MPs on soil can affect biotic targets, such as soil microbial communities and meso-macrofauna communities [28,29], as well as abiotic targets, including soil carbon and nutrient cycling [30]. MPs can also act as vectors or carriers for pesticides [30] and other environmental pollutants [31], potentially prompting changes in the reactions of flora and fauna species and terrestrial environments, as detailed in the following subsections.

### 3.1. Soil microbiota effects: Focus on arbuscular mycorrhizal fungi

Soil microorganisms can be affected by MPs, altering microbial metabolic systems and leading to functional changes. The presence of MPs in soils can impact soil properties such as aggregation, structure, and water interaction, consequently affecting microbial metabolic activity. MPs' surfaces can harbor microbes carrying antibiotic resistance and microbial transfer genes, contributing to the spread of pathogenic microorganisms and antibiotic resistance. If sewage sludge containing MPs is used as a soil amendment, it may disperse genetically diverse microbes within soil ecosystems. Further studies are needed to assess the real impacts at the ecosystem level and potential health effects on receptors, including soil biota and domesticated ruminants [15]. Microorganisms could degrade MPs, producing volatile organic compounds (VOCs) like methane and ethylene, which can serve as markers of MPs presence in soil samples. However, the mechanism behind soil microbial mediated VOCs production from MPs is poorly understood, involving microbe-microbe and plant-microbe interactions that are influenced by various factors, including pH, moisture, organic carbon content, clay minerals, and microbial diversity [32,33]. Research indicates that MP contamination can enhance microbial respiration, potentially due to the leaching of additives that serve as substrates for soil microbes [34]. Machado et al. [35] highlighted the complex nature of these interactions, noting a significant relationship between MP concentration and microbial activity, with different MP types producing varying effects on soil biophysical environments. Interactions may also occur with arbuscular mycorrhizal fungi (AMF), a key group of symbiotic fungi that form mutualistic associations with the roots of most terrestrial plants. AMF play a crucial role in plant nutrition, stress tolerance, soil health, and ecosystem stability. However, the impact of MPs on AMF remains still poorly understood. MPs can alter soil properties and plant growth, potentially affecting AMF abundance and activity. Hypothesized effects include direct MP toxicity (from additives and breakdown products) and indirect effects via changes in plant hosts and soil environments. Research suggests that MPs can alter AMF communities and influence crucial ecosystem functions like nutrient cycling and soil aggregation.

MPs can also indirectly influence AMF by altering plant growth, reducing root diameter, and modifying soil properties such as bulk density, pore structure, and water transport [36]. Giambalvo et al. [37] found that polypropylene (PP) microfibers negatively impacted maize growth, and neither nitrogen fertilization nor AMF inoculation effectively mitigated these effects. Notably, AMF inoculation did not alleviate PP's adverse effects on biomass, and PP contamination did not inhibit AMF root colonization. Similarly, Kanold et al. [38] observed decreased AMF colonization in tomato plants. Porto et al. [39] reported that mycorrhiza did not alleviate PP-induced water stress in soybeans but mitigated the impact on reduced biological nitrogen fixation. Further research by Kanold et al. [40] on *Sorghum drummondii* revealed that high MP concentrations (3%) reduced AMF root colonization and altered AMF community composition, favoring *Gigaspora* sp. and negatively affecting *Glomus* sp. However, the alpha diversity (i.e., the mean species diversity in a site at a local scale) of the AMF community within plant roots was not affected.

Future research on MPs and AMF interactions is crucial for understanding MPs' ecological impact. Key areas of focus include mechanistic pathways, particularly how MPs influence AM fungal community structure and function, as well as AM fungi's role in regulating MP bioavailability to plants [41]. Investigating physiological responses is essential, especially regarding AM fungi's reactions to MP pollution under environmental stressors like drought and heavy metal contamination, while also identifying stress-tolerant AM fungi from contaminated regions [42,43]. Comparative studies on species-specific responses will help determine which AM fungal species are most resilient to MPs across varying environmental conditions [44,45]. Additionally, research should assess how MPs impact the interactions between AM fungi and indigenous soil microorganisms, potentially affecting nutrient exchange and plant health [46]. Exploring multi-inoculation strategies by combining AM fungi with other beneficial microorganisms could offer solutions for restoring MP-contaminated soils through synergistic effects [47]. An integrated approach is necessary to fully understand these interactions and develop sustainable strategies for agriculture and soil conservation in MP-polluted environments.

### 3.2. Effects on soil meso-macrofauna communities

Meso-macrofauna serves as a network for spreading MPs throughout the soil, facilitated by predator-prey dynamics [48,49]. Despite being perceived as inedible, soil fauna like earthworms and nematodes ingest MPs, causing health concerns such as stunted development, irregular conduct, elevated oxidative stress markers, and mortality [50]. Sensitivity to micro-nano structures may influence the recognition of toxicity [51]. MPs can enter the food chain, potentially reaching humans, as demonstrated by Huerta Lwanga et al. [52], who showed the transport of MPs from earthworms to chickens. Meso-macrofauna inadvertently ingest MPs and transfer them to upper trophic levels within land-based food webs. Earthworms and nematodes, common soil dwellers, have been experimentally shown to take in MPs, indicating their significant role in terrestrial microplastic contamination. Additionally, earthworms can act as a filter, accumulating both MPs and NPs from the soil [53].

### 3.3. MPs, nutrients, and soil abiotic interactions

As plastics undergo degradation, characterized by an increase in particle number and a reduction in size, soil biota may ingest them. However, due to their elevated carbon-to-nitrogen (C/N) ratio, this ‘food source’ could result in a deficiency of nitrogen and other essential nutrients for those consuming it. Organisms feeding on degraded plastics might seek alternative soil nutrients, leading to immobilization—the conversion of inorganic to organic compounds inaccessible to plant roots—which can adversely affect plant production. Furthermore, the high carbon content of plastics may introduce challenges in accurately quantifying soil organic carbon, a parameter critical for assessing land fertility and potentially impacting crop production [54,55]. Human activities on soils, such as plowing and harvesting in agriculture, can significantly influence the fate of MPs. Practices like moldboard plowing, involving the inversion of the topsoil layer, can transfer surface-bound MPs to the plowing depth. Similarly, soil cultivation for harvesting sub-surface plant portions (e.g., potatoes, carrots) can lead to the incorporation of MPs into various soil horizons. Soil processes such as cracking and wetting/drying cycles influence where microplastics end up and what effects they have. Cracks often develop during dry periods in agricultural soils rich in expanding minerals, potentially creating conduits for plastic particles to migrate further down into the soil profile. Earthworms, microarthropods, and decomposing roots contribute to the formation of large biopores in soil. Like macropores, biopores can potentially facilitate the movement of MPs within the soil [28,56].

### 3.4. Contrasting MPs abundance in farmland soil: Two examples

It's important to recognize that the amount of microplastics in agricultural soils varies significantly across different locations, probably influenced by factors like how the land is cultivated, the types of fertilizers used, and specific sampling sites. For example, studies comparing the presence and distribution of MPs in two Chinese cities in different regions, Shanghai and Wuhan [57,58], as well as in two distinct sites in northern and southeastern Germany [59,60], have been reported.

#### 3.4.1. China

Located on the southern mouth of the Yangtze River and intersected by the Huangpu River, Shanghai is China's most populated urban area. As of 2021, the city proper housed 24.89 million residents, while the entire Shanghai metropolitan region contained 39.3 million people. Wuhan lies in the eastern part of the Jianghan Plain and along the central section of the Yangtze River. As the largest city in central China, it plays a vital role as a hub for the region's economy, culture, and education, with an urban population exceeding 10 million. Both studies [57,58] concern the occurrence and characteristics of MP pollution in typical farmland soils of suburban areas. In **Table 2** are reported the main findings of the cited studies.

**Table 2.** Comparison of MP pollution in farmland soils of Shanghai and Wuhan (China).

| Parameter | Shanghai (Suburbs) | Wuhan (Suburbs) |
|---|---|---|
| Population (City) | 24.89 million (2021) | > 10 million |
| MP Size Range | 0.03–5 mm | < 0.2 mm (70%) |
| MP Concentration | 62.50–78.00 items/kg (vegetable soils) | 2020 items/kg (dry weight) |
| Main Polymers | Polypropylene (PP), Polyethylene (PE), Polyester or Polyethersulfone (PES) | Polyamide (PA) 32.5%, Polypropylene (PP) 28.8% |
| Primary MP Shapes | Fibers, Fragments, Films | Fibers, Microbeads |
| Soil Layer Variation | Concentration & size increase from deep to topsoil | Not specified |
| Potential Source | Plastic greenhouses | Not specified |

The marked differences in MP concentration, size distribution, and polymer types between Shanghai and Wuhan suggest region-specific sources and environmental conditions influencing MP accumulation in farmland soils. For example, variations in dominant size ranges and polymer compositions may reflect differences in local agricultural practices and surrounding plastic use. In Shanghai, the observed increase in MP concentration toward the topsoil hints at the influence of plastic greenhouse cultivation. These findings are supported by the review conducted by Ren et al. [17], which highlights the current situation of macro- and microplastics (MPs) in farmland. The review summarizes information from 163 publications with 728 sample sites across China and employs a modeling method to quantify the sources of MPs. The report provides evidence that plastic pollution is ubiquitous in soil and represents an environmental risk to soil quality and functioning. This highlights the urgent need to quantify plastic debris emissions from various agricultural activities and to regulate the input of plastics from multiple sources into farmland soils. The variability in plastic data across studies reveals a significant knowledge gap, largely stemming from differences in the methods used for microplastic extraction and detection. This discrepancy reduces data comparability, indicating the need for standardized extraction and detection protocols to minimize uncertainty.

### 3.4.2. Germany

The prominent differences in MPs' abundance in farmland soils are consistent with other studies, such as the comparison between farmland in northern and southern Germany. Soil samples from northern Germany were collected in Schleswig-Holstein, comprising 15 farmlands studied by Harms et al. [59], while those from southern Germany were gathered in Middle Franconia agricultural sites covering an area of 0.5 ha, as reported by Piehl et al. [60]. The latter study examines a unique site subjected solely to conventional agricultural practices, including rain-fed irrigation, plowing, harrowing, sowing, fertilization, herbicide application, and harvesting. Notably, this site did not involve the use of MP-containing fertilizers (e.g., sewage sludge or organic fertilizers) or plastic-based agricultural inputs (e.g., mulching films, greenhouses, or nets). More details regarding both studies are reported in **Table 3**.

**Table 3.** Comparison of MP pollution in farmland soils of northern and southern Germany.

| Parameter | Northern Germany (Schleswig-Holstein) | Southern Germany (Middle Franconia) |
|---|---|---|
| MP Size Range | 1–5 mm | 5–50 mm |
| Mean MP Abundance | 3.7 ± 11.9 items/kg (dry weight) | 0.34 items/kg (dry weight) |
| MPs Detection | Detected at all 15 sites | Significantly lower density |
| Main Polymer | Polyethylene (PE) | Polyethylene (PE) |
| Prevalent MP Shape | Films | Films |
| Fertilizer Use | Not specified | No compost/sewage sludge |
| Potential Source | Greenhouse covers, mulching films, fertilizer bags, pesticide cans | Greenhouse covers, mulching films, fertilizer bags, pesticide cans (no compost/sludge link) |

The tenfold difference in mean MP abundance between Northern and Southern Germany, despite similar conventional farming practices, suggests that specific inputs—such as the use of compost or sewage sludge—may significantly influence MP contamination levels. The dominance of polyethylene (PE) films in both regions indicates a common, agriculture-related source likely tied to plastic films used in cultivation. Differences in MP size ranges between the regions may reflect varying degradation pathways or source materials. Notably, the high variability in MP levels across Northern sites points to localized hotspots, underscoring the need for targeted monitoring and management strategies. The prevalent shape of PE particles in both studies was in the form of films, suggesting a potential link between arable land contamination and the widespread use of greenhouse covers, mulching films, fertilizer bags, and pesticide cans in Germany [61]. While the quantity of MPs exhibited great variation among sites, the average concentration in North Germany was higher than that in the southern sites. However, when referring to previously reported Chinese results, the content is considerably lower.

Studies from both China and Germany reveal significant regional differences in MPs contamination of farmland soils, influenced by local environmental conditions, agricultural practices, and pollution sources. In China, research from Shanghai and Wuhan shows clear variation in MP concentration, size, and polymer types, likely reflecting differences in plastic use in agriculture—such as greenhouse cultivation in Shanghai. These findings align with national-scale reviews indicating widespread MP presence in Chinese soils, though methodological inconsistencies hinder cross-study comparability. In Germany, MP levels also vary markedly between northern and southern regions. Northern sites often exposed to compost and sewage sludge, exhibit significantly higher MP abundance than southern sites, which lack such inputs. Despite similar conventional farming methods, this suggests that fertilizer type plays a key role in MP contamination. Polyethylene (PE), particularly in film form, dominates in both regions, pointing to common sources such as mulch films and greenhouse covers. Notably, even the higher MP levels in Germany remain lower than those reported in Chinese farmland, underlining possible differences in pollution intensity and regulatory practices.

## 4. MPs in plants used for forage

The fodder for domesticated ruminants comprises various plant-based foods produced in agricultural crops, including green fodder, pastures, hay, and silage. The vegetation characteristic of a specific region, habitat, or period can be considered a receptor for MPs. Therefore, the influence of MPs on the growth of land plants and the dynamics of plant communities is more likely to be observed in regions with higher levels of MPs pollution. This raises concerns for natural reserves located near agricultural fields or cities [28]. The transmission of MPs from plants to animals was first reported in the works of Liebezeit and Liebezeit [62], which demonstrated that MPs were found in both commercially manufactured and artisanally produced honey [63]. This contamination occurred due to the presence of MPs in the inflorescences of various plant species, transported to beehives by bees during pollination. In further detail, Sanders and Lord [64] highlighted the migration of MPs found in the transmitting tracts of inflorescences, from plants to the ovary, due to their size compatibility with pollen. The interaction between plants and MPs has significant effects, as reported in **Figure 3**.

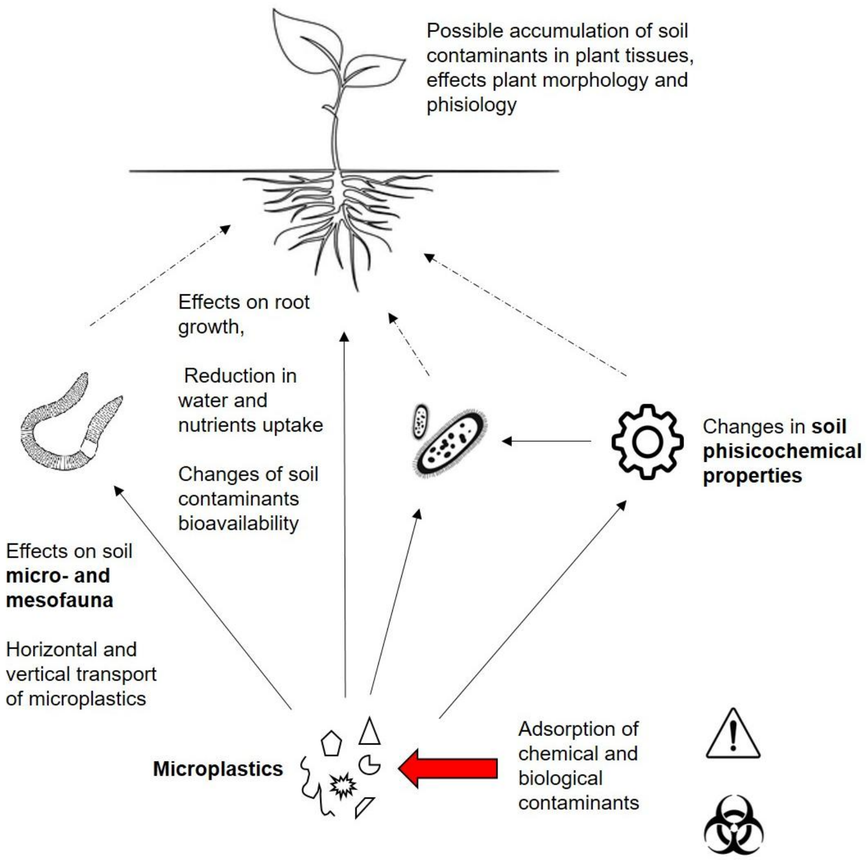


**Figure 3.** Schematic causal model of MPs interactions with biotic/abiotic component of soils and plants.

The impact of MPs on plant performance begins with alterations to soil biophysical conditions caused by plastics, affecting both bulk soil and the rhizosphere. These alterations encompass physical, chemical, and biological effects within the soil, subsequently perceived by plants. This perception leads to changes in biomass distribution, shifts in tissue chemistry, and symbiotic relationships. Roots play a vital role in the assimilation of plastics, as their transfer from roots to shoots is facilitated by transpiration. Comparative studies examining particle sizes consistently reveal that smaller particles exert more pronounced negative effects on plants. The uptake of nanoparticles faces a primary barrier at the rhizodermis (i.e., the root epidermis). While the mechanisms underlying nanoparticle uptake in plants remain incompletely elucidated, it is acknowledged that particles within the nanometer range may penetrate plant roots, potentially inducing modifications in cell membrane structure, intracellular molecules, and the onset of oxidative stress [50]. The impact of plastics on plants stems from their ability to adsorb and/or internalize them as micro- and nanostructures, particularly in the form of aggregates following external or internal uptake [65]. The properties and characteristics of MPs influence the adsorption process through mechanisms such as adherence or entanglement, whereas internalization requires the particles to be in the nanometer size range (< 5 nm). As an example, the size of NPs is the property that allows the crossing of cell membranes, causing their aggregation in cell compartments (vacuoles and cytoplasm) in the roots of the garden onion *Allium cepa* [66]. Nevertheless, the threshold for cellular absorption has yet to be determined. Speculatively, due to their generally larger size compared to animal cells, plant cells may be capable of absorbing larger particles.

Although experimental confirmation for the transfer of nanoparticles from plants to ruminants is yet to be provided, if substantiated, the plant uptake pathway could represent an important route of plastic materials into ruminant farming systems.

## 4.1. Microplastic impacts on pasture, rangeland, and green forage species: Effects on germination, elongation, biomass, and photosynthesis

For grazing livestock, both pastures and rangelands are essential for livestock production. Pastures are managed lands where grasses and forage crops are cultivated, often with seeding, irrigation, and fertilization, to sustain livestock grazing. They are typically smaller, more intensively maintained, and sometimes enclosed. Rangelands, in contrast, are vast, natural landscapes with native vegetation, such as grasslands, savannas, and shrublands that support grazing animals with minimal human intervention. As noted by Halfar et al. [67], MP contamination varies across land-use systems, influenced by different management practices. Their study found that pastures exhibited a 44% contamination frequency, whereas rangelands had a significantly lower occurrence of 3%. These findings align with those reported in a study that presents data on the presence of microplastics (MPs) in soils under different land uses in the Central Valley of Chile [68]. This regional-scale study revealed clear evidence of MP contamination in croplands and pastures, while rangelands and natural grasslands showed no discernible pollution (**Table 4**). The stark contrast suggests that agricultural activities are a primary driver of MP accumulation in the region. Notably, no correlation was found between MP concentrations and proximity to urban areas, roads, or mining sites, challenging common assumptions about dominant pollution sources. The finding that croplands are particularly susceptible—despite the specific sources remaining unidentified—highlights the need for further investigation into agricultural practices contributing to MP presence. Overall, MP pollution appears to be closely tied to land use intensity rather than being uniformly distributed across the landscape.

**Table 4.** MP pollution in soils under different land uses in Central Valley of Chile.

| Land Use | Mean MP Concentration (particles kg$^{-1}$) | Prevalence of MP Pollution (%) |
|---|---|---|
| Croplands | 306 ± 360 | 57% |
| Pastures | 184 ± 266 | 44% |
| Rangelands | Not discernible | 3% |
| Natural Grasslands | Not discernible | 20% |

Green pasture provides significant benefits to ruminants, contributing to their health, well-being, and the quality of milk and dairy products. Recent in-depth studies on the direct utilization of pasture by ruminants in zootechnical production have led to an increased emphasis on incorporating grass into the daily ration of animals. However, the green forage comprises not only grass from the pasture but also other plants such as millet, soybean, wheat, alfalfa, and chicory, grown on agricultural soil. The environmental pollution affecting the evolution of their phenological stages can have implications. In whole plants, the tiny pores in cell walls and the existence of apoplastic barriers in the roots block the absorption of plastic particles larger than 6 nanometers [69]. However, plastic particles could fragment into smaller ones, posing a risk of possible contamination of crops and livestock feed that cannot be neglected. Even without being absorbed, plastic microparticles may accumulate on the root surface due to size-based exclusion, a phenomenon documented for inorganic colloids. The ensuing development of a coating layer around the roots has the potential to reduce water conductivity, thereby impeding plant transpiration, nutrient absorption, and overall growth [70]. Plastic particles as small as 5 μm have been found inside the seed coat of cress and attached to root hairs, causing short-term effects (lasting up to 24 h) on germination and root development [71]. Likewise, other research has documented restricted growth and changes in biomass distribution in wheat and spring onion exposed to different forms of macroplastics and microplastics [72]. The most interesting forage for feeding ruminants belongs to the grasses and legumes family. Gramineous plants typically dominate forage chains due to their early development. Among grasses, millet and barley are valued for their protein content, while oat (*Avena sativa*) and ryegrass (*Lolium* genus) are preferred for their net energy content. To the best of our knowledge, no specific studies on the presence and effects of MPs have been reported concerning these species. Only a few papers have been dedicated to investigating the effects of MPs on ryegrass germination at the laboratory scale. For instance, Boots et al. [73] carried out a mesocosm experiment to examine the biophysical responses of soil, investigating the effects of various microplastic types: biodegradable polylactic acid (PLA), conventional high-density polyethylene (HDPE), and MP clothing fibers. These MPs were introduced to soil inhabited by the endogeic earthworm *Aporrectodea rosea* (rosy-tipped earthworm) and sown with perennial ryegrass (*Lolium perenne*). When exposed to fibers or polylactic acid (PLA) MPs, seed germination rates declined, concomitant with a reduction in shoot elongation and a decrease in soil pH levels. Additionally, the size distribution of water-stable soil aggregates was modified in the presence of MPs. This study provides evidence that MPs made of high-density polyethylene (HDPE) and PLA, as well as synthetic fibers, can affect the development of *Lolium perenne* (perennial ryegrass) as well as key soil characteristics, which may in turn influence the functioning of the soil ecosystem. The nonlinear effects of microplastic doses with varying concentrations are particularly important in the uncertain context of environmentally significant concentrations, as they can exert distinct effects on plants. Great caution should be taken when applying results from laboratory experiments obtained using high plastic concentrations to field conditions. External accumulation and/or internal uptake of microplastics induce toxic effects on plants. The harmful effects of micro(nano)plastics on plants are evident in four key stress indicators: seed germination, shoot/root elongation, overall biomass production, and photosynthetic activity. **Table 5** summarizes the interactions between MPs, forage grasses, and soil health, highlighting the potential for negative impacts.

Most studies focus on the effects of plastics on the germination of terrestrial plants. Delayed germination has been observed for *Lepidium sativum* after contact with different levels of MP or NP particles. Possible mechanisms involve the obstruction of openings in seed capsules or on spore surfaces [71]. The observed effects on germination could result from the physical presence of MPs or substances released from these plastics. Adverse impacts on root elongation growth have also been reported, with impacts on morphology comparable to 'Stress-Induced Morphogenic Responses' (SIMR). SIMR refers to adaptive changes in plant morphology triggered by environmental stresses, including alterations in growth patterns and development [74]. MPs exhibit diverse effects on elongation growth, indicating potential similarities with the effects of other stressors.

Changes in plant biomass are dependent on a range of variables, including the specific type, physical form (shape or size), and concentration of the plastic polymer, as well as the length of exposure. An increase in root biomass, for example, might occur as plants compete for limited essential nutrients or water, the availability of which could be reduced by the presence of MPs. Consequently, the outcomes are likely to vary across different plant species. Some studies have indeed reported inconsistent or contradictory effects. Concurrently, a decrease in overall biomass has been noted in various plant species under drought conditions. Interestingly, the combined effect of microfibers and water scarcity has shown both beneficial and detrimental outcomes, depending on the particular plant species examined [75]. Therefore, it is clear that the intrinsic characteristics of plastics, alongside environmental factors such as water availability, are crucial in determining how plastics affect plants and macrophytes.

Findings regarding the impact of MPs on plant photosynthesis have also yielded mixed results, with both inhibitory and stimulatory effects reported. These diverse outcomes are likely attributable to variations in experimental setups and/or the specific properties of the MPs and the plant species studied, making it difficult to predict widespread effects of MPs on a global scale. Nevertheless, the incorporation of MPs into the food web may occur through plant uptake [72]. More recently, Zhu et al. [76] assessed the global implications of MP pollution for food security by analyzing a substantial dataset of 3286 data points. Their findings suggest that MPs lead to a reduction in photosynthetic activity, resulting in estimated annual losses of 109.73 to 360.87 million metric tons (MT) in crop production. A 13% reduction in MP levels could potentially alleviate this issue, saving an estimated 14.26 to 46.91 MT of crops annually.

**Table 5.** Overview of the impacts of microplastics on forage species, including observed effects, stress responses, and influencing factors.

| Topics | Key Information |
|---|---|
| 1. Forage Species Overview | • Grasses like Millet and Barley are high in protein.<br>• Oat and Ryegrass (*Lolium*) are high in net energy.<br>• Limited species-specific MP research exists, with some focus on ryegrass. |
| 2. Experimental Findings on Ryegrass | • Boots et al. [73] investigated biophysical soil response to PLA, HDPE, and clothing fibers.<br>• Explored the interaction between earthworms (*Aporrectodea rosea*) and ryegrass (*Lolium perenne*).<br>• Observed negative effects on germination and shoot height.<br>• Noted changes in soil pH and aggregation. |

**Table 5.** (*Continued*).

| Topics | Key Information |
|---|---|
| 3. MP-Induced Plant Stress Responses | • Four main impact plant physiological impacts:<br>• Germination,<br>• Elongation Growth,<br>• Biomass,<br>• Photosynthesis.<br>• Potential mechanisms include pore blocking in seeds, chemical leaching from MPs, and morphogenic stress responses (SIMR). |
| 4. Factors Influencing Biomass and Photosynthesis | • Influence of MP type, shape, and size.<br>• Impact of exposure duration and concentration.<br>• Role of environmental stressors like drought and water/nutrient availability.<br>• Effects can vary depending on the plant species and environmental context.<br>• Zhu et al. [76] estimated significant global crop loss due to MP-induced reduction in photosynthesis. |
| 5. Implications | • Findings from laboratory studies may not accurately reflect real-world field conditions.<br>• Dose-response relationships are complex and likely vary across different plant species.<br>• There is a need for more field-based and long-term studies specifically on forage species. |

## 4.2. MPs in hay and silage

Hay and silage represent essential preserved forage for ruminant diets, effectively meeting their nutritional requirements. These conserved forages undergo different harvesting, storage, and fermentation procedures. They function as crucial and reliable feed sources, vital for maintaining ruminant health and productivity, particularly when fresh forage is limited. The inclusion of hay is mandatory in the production of specific cheeses, such as Parmigiano Reggiano and Trentin Grana. Indeed, the use of substantial amounts of high-quality fodder is critical for numerous esteemed Italian dairy products. This practice serves as a fundamental link to the production regions, preserving the distinctiveness and typical characteristics of protected designation of origin (PDO) products. **Table 6** provides an overview of microplastic contamination in hay, pellet feed, and silage, highlighting key findings and implications for livestock exposure.

**Table 6.** Microplastics in livestock feed, key findings & livestock exposure risks.

| Topics | Key Findings | Implication/Callout |
|---|---|---|
| Hay & Fresh Feed: MP Presence | • Van der Veen et al. [77] (5 hay samples): Negligible MPs.<br>• Fresh roughage: No plastic particles detected.<br>• Absence of PVC-P, PE, Styr-P. | **Low MP Risk:** Unprocessed plant-based feed appears relatively clean. |
| Pellet Feed: MP Contamination | • Presence of PVC-P, PE, Styr-P.<br>• Absence of PMMA, PP, PET.<br>• Similar MPs found in animal tissues (meat, blood).<br>• No significant difference (conventional vs. organic). | **Likely MP Source:** Processed/pelletized feed is a probable route of livestock exposure. |

**Table 6.** (*Continued*).

| Topics | Key Findings | Implication/Callout |
|---|---|---|
| Silage: MP Sources & Processing | • Weithmann et al. [78] Biowaste processing (Compost & Biogas Plants): Potential for MP introduction.<br>• Energy crop-only biogas plant (plastic removed): No MPs in end-product digestate. | **Variable MP Risk:** Silage contamination likely depends on source and processing. |
| Overall Conclusions | • Fresh feed: Low MP risk.<br>• Pellet feed: Confirmed MP source.<br>• Silage: Risk level unclear, needs more research.<br>• - Potential MP origins: Packaging, handling, environment. | **Key Takeaways:** Fresh feed safer, pellets problematic, silage requires further study. |

Although silage is widely used in global agriculture and livestock production, the reviewed scientific literature did not provide specific findings on the presence of microplastics (MPs) in hay and silage. Comparative studies could offer potential directions for investigating this. However, the potential presence of MPs in hay, defined as fresh feed roughage available in bale or pellet form, might be inferred from a preliminary study conducted by I. van der Veen et al. [77]. This research aimed to screen various samples from livestock farms in the Netherlands to identify plastic particle contamination. Cows and pigs were chosen as indicator species due to their importance as sources of animal-derived foods in the global food supply. The study included the analysis of feed for these livestock. In the Netherlands, cows and pigs can be fed pre-consumer supermarket food waste, provided it does not contain animal products. The sample set encompassed different feed categories, including feed pellets, fresh feed roughage, and shredded supermarket feed. Plastic particles were not detected in any of the fresh feed samples, while PVC-P and PE were present in all other feed samples. Furthermore, Styr-P was found in all pellet samples, with the exception of one pig pellet sample. PMMA, PP, and PET were not detected in any of the analyzed feed samples. No significant differences in the types and concentrations of detected plastics were observed between feed samples from conventional and organic farms. The tested feed samples in this initial study were sufficient to suggest possible plastic ingestion by cows and pigs through their pellet feed. Notably, the five fresh feed samples consisting of hay showed negligible levels of measurable plastic. The types of plastics identified in all feed samples, excluding fresh feed, were consistent with those commonly found in beef and pork samples, as well as in all blood samples. However, several of these plastic polymers are routinely used in food packaging materials, and during meat processing, microfibers from synthetic textiles and airborne MP particles may contribute to the accumulation of plastic residues in meat products. This suggests that “internal” exposure likely originates, at least partially, from the feed.

The potential presence of microplastics (MPs) in silage might be inferred from the research conducted by Weithmann et al. [78] on organic fertilizers derived from recycled bio-waste, as composts and digestates can introduce MPs into the environment. Their study investigated two biowaste management systems: an aerobic composting facility (Plant A) and an anaerobic digestion facility (Plant B), the latter functioning as a biogas production plant. Furthermore, an agricultural digester (Plant C), processing only energy crops without the addition of biowaste, was included as a reference point. In Plant C, a sample ("Energycrop") was collected from the post-digester outlet, representing a final-stage sample. This agricultural biogas plant processes energy crops such as corn/grass silage and ground wheat, which are delivered in plastic wrappings that are removed before being introduced into the fermenter. The absence of plastic particles in the final digestate sample (Energycrop) from Plant C offers insights into the presence of MPs in forage preservation techniques, as this plant served as a 'control' fermenter.

## 5. The intake of MPs by domesticated ruminants

### 5.1. Microplastic pathways in ruminants

Ingestion, respiration, and epidermal infiltration have been identified as pathways for the intake of MPs by macrofauna. Studies have reported that ingestion can lead to detrimental effects at various levels, encompassing biological effects from the cellular to organ scale, such as genotoxicity, inflammation, liver toxicity, gastrointestinal blockage, and lethality [79]. Additionally, trophic cascade effects have been observed. The toxicity of MPs ingested by macrofauna is exacerbated by the release of additives and toxic chemicals adsorbed from the surrounding environment, which can then be transferred [80,81]. Fragmentation of MPs during chewing and digestion, along with the large size of tissue and organs, increases the likelihood of transfer within macrofauna. Once ingested, MPs can accumulate in tissues, translocate to organs, be transmitted via gonads to offspring, and transfer to higher trophic levels. Excretion through respiration or feces allows MPs to re-enter the geochemical cycle, perpetuating their status as pollutants. Currently, there is limited information available on the potential long-term threat posed by MPs retained within animal bodies, such as in the digestive tract, gills, liver, muscles, and blood. The potential effects of MPs translocation on the homeostasis of individual organisms and the broader implications for population and ecosystem stability remain largely uninvestigated [82].

Ramachandraiah et al. [83] recently published a comprehensive review on MPs/NPs contamination in livestock production. The authors highlight that livestock animals can be exposed to MPs from various sources, including the atmosphere, freshwater, and terrestrial environments. Water, obtained from surface water sources such as rivers, creeks, lakes, and streams, is a significant freshwater source for livestock. Recent reports indicate the presence of MPs in surface water, and livestock may ingest these particles directly through drinking water or indirectly through contaminated animal feed, as water is commonly used in the feed mixing process [84]. However, this review does not cover the transmission of MPs through water consumption and air respiration. In domesticated ruminants such as cattle, ingested microplastics (MPs) accumulate in the rumen—a large forestomach with a capacity of 50 to 100 liters in adult animals. The rumen plays a crucial role in the microbial degradation of ingested feed prior to further digestion. Its contents are heterogeneous, consisting of undigested feed, saliva, gases (mainly carbon dioxide and methane), and a diverse community of microorganisms, including bacteria, protozoa, and fungi. While enzymatic hydrolysis, particularly of (hemi)cellulose, has been extensively studied, other polymer-degrading rumen enzymes have received less attention. Ruminant diets can include natural plant-derived polyesters like cutin, suggesting the presence of hydrolytic enzymes within the rumen [85].

Ruminal impaction can result from accidental ingestion of larger plastics such as plastic bags, bottle caps, and ropes [86]. This condition occurs when non-digestible plastic materials accumulate in the rumen, leading to various health issues including ruminal impaction, indigestion, and recurrent tympany, as well as systemic effects, reduced productivity, and potential risks to human health via the food chain (**Figure 4**).

A recent study by Mayer et al. [87], aimed to determine if ingested litter causes pathological consequences in domestic ruminants. Five meadows in Northern Bavaria (Germany), along with the gastrointestinal contents of 100 slaughtered cattle and 50 sheep, were analyzed for the presence of persistent anthropogenic debris. Findings revealed that all meadows contained man-made debris, predominantly plastics. Anthropogenic foreign bodies were found in 30% of cattle and 6% of sheep, predominantly plastic netting from agricultural packaging. Notably, multifiber plastic rope of agricultural origin caused bezoar formation in two young bulls. Bezoars are solid masses of partially digested or undigested material that remain in the digestive system.

Although most literature on rumen impaction due to plastic ingestion focuses on cattle, cases involving small ruminants like sheep and goats have also been documented [88,89]. As previously mentioned, plastic materials can serve as a source of contamination by heavy metals and other organometallic compounds, which may either be intentionally added during manufacturing or adsorbed onto plastic debris surfaces. The potential risk of heavy metals leaching into rumen fluid and accumulating in food animal tissues remains poorly understood. Mahadappa et al. [86] conducted a study examining mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), and copper (Cu) concentrations in the rumen fluid, blood, liver, kidney, and muscle of buffaloes, comparing those with and without plastic waste impaction in the rumen. The study evaluated the relationship between heavy metal concentrations in rumen fluid and the functional parameters of the rumen. The analysis demonstrated a marked reduction in rumen protozoal density and motility, accompanied by significant increases in rumen fluid pH, methylene blue reduction time, and sedimentation activity in the group exposed to plastic waste (Group C), compared to the negative control group (Group A) and the group not impacted by plastic waste (Group B). Methylene blue reduction time and sedimentation activity tests are commonly used to evaluate anaerobic fermentation metabolism of rumen bacteria and rumen macrofloral activity. Concentrations of lead (Pb), mercury (Hg), and cadmium (Cd) demonstrated a statistically significant moderate to strong negative correlation with indicators of rumen function. Copper (Cu) content was notably higher in plastic waste. While concentrations of heavy metals in body fluids and tissues were significantly elevated in the plastic waste-impacted group (Group C), they remained below toxic levels. Interestingly, Hg, Pb, and Cd were undetectable in body fluids of the control group (Group A). These findings suggest that prolonged exposure to heavy metals from plastic waste can adversely affect buffalo health and productivity, thereby increasing the risk of these metals entering the food chain.

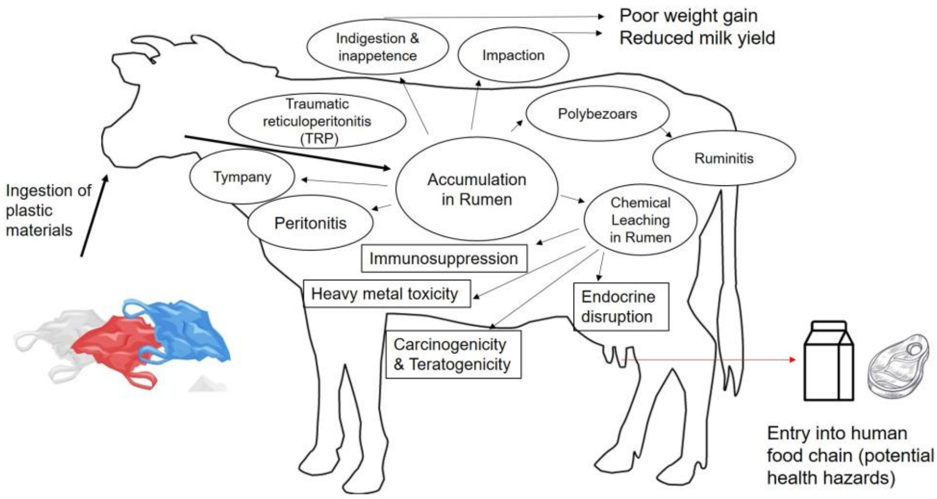


**Figure 4.** Pathophysiological effects of plastic ingestion in cattle. Ingested plastic accumulates in the rumen, causing conditions such as impaction, tympany, ruminitis, and peritonitis. These can lead to systemic effects including immunosuppression, endocrine disruption, and toxicity, ultimately reducing productivity and posing potential risks to human health via the food chain. (modified from [89]).

MPs present in the digestive system may undergo fragmentation into smaller particles, a process that can facilitate their absorption into the bloodstream or surrounding tissues [90].

## 5.2. Ruminant plastic ingestion: Implications & research needs

Studies investigating microplastics (MPs) in food originating from terrestrial animals are still scarce, despite the potential health hazards linked to their presence—even if only on the surface—owing to the harmful properties of particulate contaminants. The relevance of addressing this issue in meat is underscored by studies such as one conducted in Nigeria, which documented the ingestion of polythene bags by ruminants at the Maiduguri Central abattoir [91], and another from Ethiopia that reported on various foreign objects found in small ruminants (sheep and goats) slaughtered at the Addis Ababa municipal abattoir [92].

The accumulation of plastic bags obstructs the flow of ingested material, hindering the absorption of volatile fatty acids and subsequently reducing the rate of animal fattening. Livestock exposure to polythene materials is often facilitated by improper disposal practices in urban and suburban areas. In regions like the Sahel zone, where both animals and humans migrate from rural areas in search of water during the extended dry season (October to May), there is early depletion of available forage. This results in the careless disposal of polythene materials, frequently still containing food residues. A Nigerian study found that out of 300 sampled ruminants slaughtered during the observation period, 88 had polythene bags in their forestomachs. Cattle had a higher percentage (38.6%) compared to sheep (36.4%) and goats (25%). The higher incidence of foreign body ingestion by cattle may be attributed to increased pollution of grazing land and the higher feed quantity demand of cattle. Gender was found to have a significant interaction with the occurrence of foreign substances in the forestomachs of ruminant animals, with females exhibiting a higher frequency. This may be explained by the increased nutritional demands of females during pregnancy and lactation, as well as their longer lifespan for breeding purposes. The elevated incidence of foreign bodies documented in this study may be attributed to the predominant practice of free-range grazing among the animals, or potentially to insufficient forage availability. Additionally, deficiencies in essential nutrients, particularly minerals and vitamins, in the animals' diets could contribute to this phenomenon.

Plastic objects such as polythene bags and rubber materials are frequently ingested by grazing ruminants in numerous tropical regions and elsewhere around the world. This widespread occurrence underscores the high incidence of foreign body ingestion among domestic ruminants, resulting in poor body condition and reduced productivity. The post-slaughter examination method typically involves removing the rumen from the abdominal cavity and opening it. Any foreign bodies extracted are washed, dried, identified, and weighed. However, this method does not include a determination of MPs, indicating a gap in MPs research [93].

## 6. MPs in fecal matter

In numerous organisms, ingested MPs are naturally excreted through feces. A comprehensive review conducted by Perez-Guevara et al. [94] critically evaluates and compares various methodological approaches for identifying MPs in fecal matter, while also detailing the global levels and characteristics of MPs found in such samples. The review highlights the presence of MPs in the feces of both marine species and terrestrial livestock, referencing a study by Beriot et al. [90] that reported MP contamination in agricultural soils in Spain's Murcia region and the subsequent uptake of these particles by sheep. Due to the scarcity of literature examples, sheep are considered suitable subjects for study. Being ruminants like all bovids, results obtained from sheep can be extrapolated to other ruminant species. In the Murcia region, it is customary to let sheep graze on crop residues post-harvest, typically in areas distinct from their pens. Allowing sheep to roam fields and feed on leftover vegetable matter often results in the ingestion of MPs. Given that food remains in a sheep's digestive system for approximately 35 h [95], MPs ingested in one location can be excreted in another. This becomes particularly concerning when herds graze first on plastic-contaminated farmland and are subsequently moved to fallow or natural areas, simulating the free-ranging behavior seen in suburban regions of developing countries. Such movements contribute to the broader dispersal of plastic pollution (**Figure 5**). Fecal samples collected from five different herds all tested positive for MPs, with an average concentration of around $10^3$ particles per kilogram. The considerable variability in MP content among the samples may be due to differences in fecal organic matter, as well as factors such as the age of the animals. Older sheep tend to accumulate more plastic debris, resulting in higher concentrations of MPs in their feces.

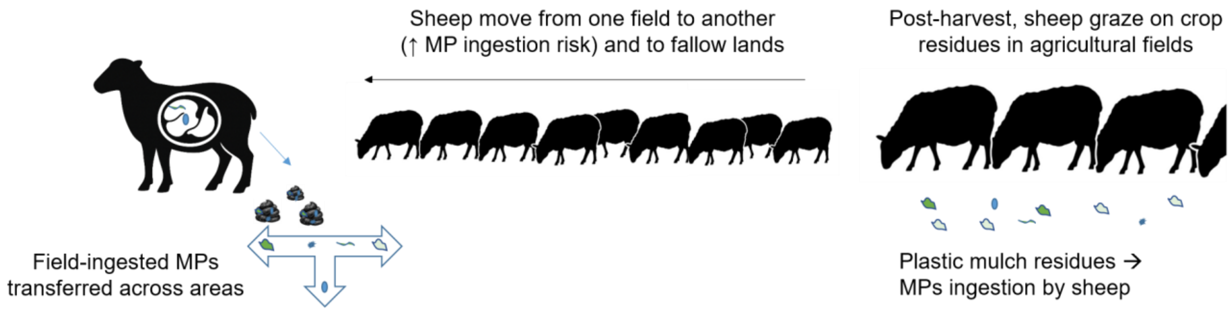


**Figure 5.** Transport of MPs by grazing sheep as proposed by Beriot et al. [90]. The figure depicts agricultural MPs present in post-harvested fields (by plastic mulch residues), grazing sheep as a vector for MPs ingestion, and sheep feces as a pathway for MPs dispersal in other areas including fallow lands.

Fecal matter can act as a marker for the presence of chemicals associated with MPs, such as plasticizers, dyes, flame retardants, and antimicrobial agents, as evidenced by a study involving two cattle herds on an American college campus [96]. MP contamination, particularly microfibers ranging from 0.5 to 15 mm in length, was detected in both herds at a similar incidence rate of 41%. On average, one polyethylene microfiber was found per 2 grams of feces. The source of these fibers was traced to mineral supplements available to the cattle year-round. Infrared spectroscopy confirmed that the plastic particles present in both the fecal samples and the mineral supplements shared identical physical and chemical characteristics.

Direct contamination of farmland soils and raw manure by MPs can arise from various sources, including discarded mulch films and agrochemical packaging bags left in farmlands [97]. This scenario presents an additional risk of farmland soil contamination when utilizing manure-based organic fertilizers. Composting stands as an effective and commonly employed technique for converting animal manure into high-quality organic fertilizers. Recent research has shed light on the impact of MPs on compost quality, composition, and the overall composting process [98]. Recent assessments have investigated the impact of polyethylene (PE), polyvinyl chloride (PVC), and polyhydroxyalkanoates (PHA) MPs on composting humification and the diversity of fungal communities [99]. Although the presence of MPs seems to decrease bacteria biodiversity in the thermophilic phase of aerobic composting, this process could contribute to reducing the abundance of MPs (PE, PVC, and PHA) and further improving their biodegradation by microbes [100].

## 7. MPs in milk and other animal origin foods: Occurrence and analytical aspects

Milk is a staple food with substantial social, cultural, and nutritional value. It is part of a globalized food production system that provides income to both small farmers and large dairy brands [101–103]. MPs contamination can occur at various stages throughout the dairy supply chain, including milking practices, technological processing, and packaging, all of which represent critical points of vulnerability. Advances in milk production—from farm-level operations to industrial processing—have introduced multiple factors that may contribute to MP contamination. These include intensive processing techniques, insufficient cleaning protocols, environmental exposure, improper handling, and the use of plastic-based packaging materials [104]. Given the global concern over plastic pollution, cross-continental comparisons of MP detection and characterization methods in milk are both relevant and necessary. Da Costa Filho et al. [105] analyzed Swiss cow milk samples and identified limitations in standard analytical techniques. MPs ranging in size from 20 to 250 µm were detected using Fourier Transform Infrared (FTIR) and Raman micro-spectroscopy, while µ-Raman spectroscopy enabled the identification of particles weighing less than 1 ng and as small as 1 µm, due to its high spatial resolution. The most commonly identified MPs included polyethylene (PE), polyester (PES), polypropylene (PP), polytetrafluoroethylene (PTFE), and polystyrene (PS), with smaller quantities of polyamide (PA), polyurethane (PU), polysulfone (PSU), and polyvinyl alcohol (PVA) found across farm-fresh milk, processed liquid milk, and reconstituted powdered milk samples (**Figure 6**).

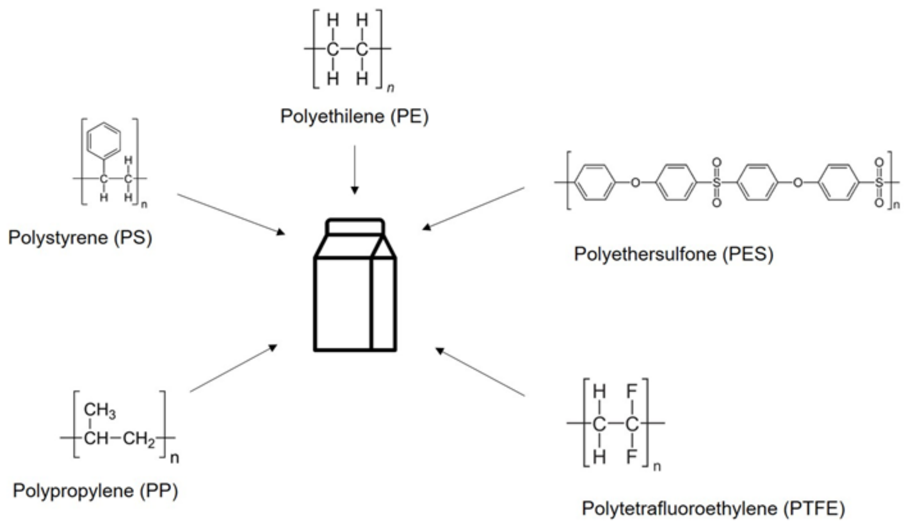


**Figure 6.** Main MPs polymers found in Swiss cow's milk samples by Da Costa Filho et al. [105].

The concentration of MPs identified in milk samples ranged from 204 to 1004 MPs per 100 mL. Comparable levels of MPs were found in both on-farm milk and liquid cow's milk samples. Reconstituted milk powders exhibited relatively higher levels of MPs compared to farm milk and ready-to-drink milk samples. Although the available data is limited, there was an observation that the quantity of MPs appeared to increase from farm milk to processed milk powders, albeit maintaining a similar order of magnitude in MPs concentrations. The lowest number of MPs was generally found in raw milk samples collected at the farm level, indicating that the primary contaminants are the main polymers present in the milking machine and ubiquitous in the farm environment (PE, PP, PES, and PTFE). In summary, there is a slight trend of increasing MPs with the degree of milk processing and packaging conditions.

Kutralam-Muniasamy et al. [106], who investigated the presence of MPs in commercially available milk and dairy products in Mexico using µ-Raman spectroscopy, reported comparable findings. Their analysis revealed a concentration range of 3 to 11 particles per liter, with an average of 6.5 ± 2.3 particles per liter—values lower than those previously documented in liquid food products. The study also presented a detailed profile of MP distribution based on particle shape, size, and color. Chemically, sulfone-based polymers were identified in the highest concentrations through Raman analysis. Generally, processed milk samples contained higher levels of MPs compared to whole milk, a difference attributed to contamination sources affecting the milk prior to packaging [107]. Research utilizing Fourier Transform Infrared (FTIR) spectroscopy has largely focused on branded milk products, often excluding farm-fresh samples, yet these studies remain significant for comparison with other consumables. In Ecuador, Diaz-Basantes et al. [108] assessed MPs in two commonly consumed beverages—milk and soft drinks—and found an average of 40 MPs per liter in skim milk, based on an analysis of ten commercial samples.

Skim milk powder is extensively utilized in the food industry to improve the texture, consistency, and nutritional profile of various dairy products such as yogurt, ice cream, and cheese. It is also commonly incorporated into bakery items, confectionery, and infant formulas, offering a shelf-stable and convenient alternative for milk reconstitution in both culinary and nutritional applications. Recently, Zhang et al. [109] examined MP contamination in infant milk powder, focusing on its potential sources, particularly packaging materials. Their study assessed MP exposure in infants from milk powder, feeding bottles, and the preparation process. Using Fourier-transform infrared micro-spectroscopy in attenuated total reflectance mode (μ-FTIR-ATR), they analyzed 13 infant milk powders varying in packaging, processing techniques, and milk origin. Detected polymers included polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyamide (PA), and polyvinyl chloride (PVC). The results showed that the milk powder itself contributed minimally to MP exposure, whereas feeding bottles and the preparation process contributed 6.8 and 1.7 times more exposure, respectively.

Another recent investigation applied μ-FTIR-ATR to qualitatively and quantitatively assess MPs in 16 skim milk powder samples used for cheesemaking across eight European countries. The analysis identified 536 plastic particles composed of 29 different polymer types—primarily PP, PE, PS, and PET—categorized by three shapes (fibers, spheres, and irregular fragments) and six colors (black, blue, brown, fuchsia, green, and gray) [110].

Regarding cheese products, only one recent investigation has specifically examined microplastic (MP) contamination. This study utilized alkaline digestion followed by pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) to identify intentionally added MPs in cheese samples. Alkaline digestion was found to be a swift and effective technique for quantifying MPs, successfully detecting PET but not identifying polystyrene (PS), likely due to its degradation during the pyrolysis process. These findings underscore the necessity of optimizing Py-GC-MS methodologies to enhance the detection of MPs within intricate food matrices like cheese [111].

Generally, industrially processed products like honey and beer tend to show lower levels of MPs, although a direct comparison with milk has not been established. Conversely, the MP content in milk often rises from samples taken at the farm level to those that have undergone industrial processing, mainly due to contamination occurring during transportation and packaging. The researchers propose that this trend might be associated with less stringent environmental control measures in artisanal production environments, which are often less equipped than industrial facilities to prevent contamination. Kiruba et al. [112] analyzed around 13 brands (16 samples) collected from different parts of Tamil Nadu state, South India, using FTIR characterization. The findings revealed the presence of MPs (polyethylene, polypropylene, and polyacrylamide) with sizes less than 500 µm. The results showed that the variability in the total number of microplastics per liter ranged from 164 to 437. The study also estimated per capita consumption of MPs, calculated using the volume of the milk sample and the average milk consumption rate of individuals. To highlight the consequences of human consumption of MPs, it is noteworthy that the ingestion of MPs directly through milk could pose unknown risks to both adults and children. Limited evidence exists to substantiate the direct uptake of particles within the range of a few microns or less by cells in the lungs or gut, potentially entering tissues through paracellular transport, known as persorption. Following ingestion, MPs can serve as vectors for metals and organic pollutants, leading to various physiological consequences, ranging from oxidative stress to potentially carcinogenic effects [113].

A primary focus and significant challenge in current MP research is the establishment of standardized protocols and optimized analytical methods that facilitate the chemical identification and quantification of MPs. Effectively tracking MPs demands the use of appropriate analytical tools and methodological best practices to further our understanding. Additionally, suitable pretreatment techniques are crucial, particularly when dealing with complex matrices such as food products. **Table 7** provides a summary of the merits and drawbacks associated with current methodologies employed in the literature for MPs identification.

**Table 7.** MPs identification method, advantages, disadvantages.

| Identification Method | Advantages | Disadvantages |
|---|---|---|
| Visual inspection | Inexpensive, rapid analysis | Possible false-positive detection |
| Scanning electron microscopy | Not limited to particle size | Possible false-positive detection |
| Microscopy/FT-IR | Coupled with visual analysis, chemical confirmation of polymers, relatively rapid scanning | Limited to a size of ~20 µm |
| Microscopy/Raman | Coupled with visual analysis, chemical confirmation of polymers, possible detection to a few micrometers | Time consuming, expensive |
| Thermal decomposition/GC-MS | Mass measurements, ease of pretreatment | No information about size distribution, potentially biased by large particles, calibration required |

When analyzing food, sample preparation is necessary before identification methods can be applied. Food samples, particularly those from land animals, require additional steps to remove organic or biological material before isolating MPs particles for filtration. Standard protocols for the removal of these materials are referenced, despite being time-consuming. Digestion is the predominant methodology, employing acid, base, peroxide-based chemicals, or enzymatic agents to disintegrate materials. Subsequently, MP particles are isolated for subsequent filtration and analysis [114].

The two main methods for identifying MPs in food are stereomicroscopic inspection, with or without staining, and spectroscopic analysis using FT-IR or Raman based on IR absorption or reflection. Although destructive, thermal decomposition coupled with GC–MS is widely utilized for quantifying MPs in environmental samples. [115].

The latter technique was employed in a Dutch pilot study, which received extensive media coverage [77], indicating farm animal blood as a central matrix for determining plastics in livestock. Three reasons are reported: MPs' exposure via ingestion and inhalation (from feed, water, and air) is reflected in their concentration in the bloodstream, which facilitates systemic distribution to organs and muscle tissue, potentially leading to toxic effects. The meat intended for human consumption contains blood, serving as a link to human exposure. Twelve blood samples from cows, originating from six different livestock farms, were received for analysis. Four polymer types were identified in the bovine blood samples: plasticized polyvinyl chloride (PVC-P), polypropylene (PP), polystyrene-based polymer (Styr-P), and polyethylene (PE). Polypropylene was detected in four out of twelve samples, with concentrations ranging from 0.08 to 0.40 μg/g. No statistically significant correlation was observed between the age of the animals and the concentration of plastic particles. Notably, in all analyzed samples, at least three distinct polymer types were present at concentrations exceeding the established limit of detection (LOD). These findings indicate the internal exposure of cows, suggesting the presence of absorbable particles that permeate the bloodstream. The standard analytical approach involves the detection of MPs within tissues perfused by the circulatory system, as blood interfaces directly with the cellular structures forming muscle and organ tissues used in meat production. Notably, the identification of plastic polymers in these tissues represents a critical initial step toward establishing an exposure baseline, which is essential for conducting animal health risk assessments. After removing the outer parts of the meat to avoid potential contamination from plastic packaging, MPs were detected in meat samples sourced from supermarkets, butcher shops, and livestock farms. Most of the meat samples contained at least one type of plastic, with all samples containing PE. However, not all detected MPs can be solely attributed to the animal's body. Only the inner portion of the purchased meat sample was considered, yet plastic contamination could potentially occur during various meat processing steps in the production process. Food processing and preparation may either increase or decrease the levels of plastics, thereby influencing subsequent human exposure through meat consumption.

## 8. Conclusion

The pervasive presence of micro(nano)plastics across diverse environmental matrices and their potential consequences for ecological and human health necessitate a comprehensive understanding of their lifecycle, particularly within agricultural systems involving ruminants.

The ingestion of plastic debris by ruminants, often indiscriminate due to the ubiquitous nature of plastic waste in agricultural environments, poses a direct threat to animal health, potentially impairing rumen function and leading to the accumulation of heavy metals and other contaminants within animal tissues. While the direct transfer of micro(nano)plastics from feed and soil to animal products such as milk and meat is increasingly being documented, the precise mechanisms and extent of this transfer, as well as the potential for subsequent human exposure and associated health risks, remain largely unexplored.

Furthermore, the fate and effects of micro(nano)plastics within the soil environment of farmlands constitute a complex area requiring further investigation. Contrasting data on micro(nano)plastics abundance underscore the need for standardized methodologies in sampling and quantification to enable robust comparisons across different geographical locations and agricultural practices. The interactions of micro(nano)plastics with soil microbiota, particularly arbuscular mycorrhizal fungi, and their influence on nutrient cycling and soil abiotic components warrant in-depth studies to elucidate the long-term consequences for soil health and agricultural productivity.

Addressing the challenges posed by micro(nano)plastics pollution in ruminant farming systems demands a multidisciplinary approach. Future research should prioritize the development of standardized analytical techniques for the detection and characterization of micro(nano)plastics in various matrices, including feed, soil, animal tissues, and animal-derived food products. Furthermore, investigations into the toxicological effects of different types and sizes of micro(nano)plastics on ruminant physiology and soil ecosystems are crucial. Understanding the transfer mechanisms of micro(nano)plastics along the food chain, from soil to plants to animals and ultimately to humans, is paramount for assessing potential human health risks.

While the presence of micro(nano)plastics in ruminant farming systems is increasingly recognized as an emerging environmental and agricultural concern, substantial research is still required to fully elucidate the scope of the problem and to develop effective mitigation strategies. A holistic "Planetary Health" perspective, considering the interconnectedness of environmental, animal, and human health, is essential to address this complex issue and to ensure the sustainability and safety of agricultural practices in the face of escalating plastic pollution.

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