frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 12 September 2025
DOI 10.3389/fsufs.2025.1634747

OPEN ACCESS

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RECEIVED 25 May 2025
ACCEPTED 28 July 2025
PUBLISHED 12 September 2025

CITATION
Brander SM, Langellotto GA, Mistry MT, Singleton SL, Hainey MA, Kashiwabara LM, Arthur K, Granek EF, Baird K, Palazuelos R, Campos N, Trim H, Sommer L, Harper S and Tetteh GR (2025) Reining in plasticulture from land to sea: Pacific Northwest (USA) perspectives on agriculture and aquaculture. *Front. Sustain. Food Syst.* 9:1634747. doi: 10.3389/fsufs.2025.1634747

Reining in plasticulture from land to sea: Pacific Northwest (USA) perspectives on agriculture and aquaculture

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Plastic use in food production—known as plasticulture—has transformed agriculture and aquaculture globally. Plasticulture gained momentum in the mid-20th century with the development of novel plastic materials, and by 2009, U.S. farmers used over 200 million pounds of plastic films annually. Though plastics have increased yields and efficiency, they now pose environmental hazards through the release of microplastics (MPs) and chemicals. Despite extensive documentation of MPs in the environment, their role in U.S. food production and impacts on crop, livestock, and aquaculture health remain underexplored. In regions like the Pacific Northwest (PNW), with robust agricultural and aquaculture sectors, plastics from films, mulches, cages, and ropes are significant sources of MPs. Soil amendments like biosolids and compost also contribute MPs from household waste. Agricultural plastics accounted for 3–5% (10–18 million tons) of global plastic production in 2018 and are projected to increase due to growing food demand. Aquaculture uses an estimated 2.1 million tons of plastics annually, but detailed data on MP generation is lacking. Despite known environmental concerns, a sustainable circular model for plastics in food systems is still absent, but necessary. While biodegradable products for use in farming and aquaculture have been introduced, high costs, regulations, and practical limitations hinder widespread adoption. Until recently, the American Society for Plasticulture (ASP) primarily focused on new plastic innovations rather than sustainability. Now, growing awareness of plastic pollution and health risks has led to increased scrutiny. In the PNW—home to key specialty crops and 6% of U.S. aquaculture operations—there is an urgent need for coordinated efforts to reduce plastic contamination. Shifting toward sustainable practices is challenging but critical to protect ecosystems, food safety, and public health, and possible through regional and state-level regulations on composting, wastewater and biosolids mitigation, and movement to more sustainable replacements where feasible. As our knowledge of micro and nanoplastic impacts on the food supply at sea and on land increases, approaches to reduce the use of plastics overall and to limit leaching and fragmentation into crops, seafood, and meat is essential to protecting human and environmental health. Regulatory efforts at the regional, national and global levels are needed to enhance food safety.

KEYWORDS

agriculture, aquaculture, microplastics, nanoplastics, chemicals of concern, soil pollution, food supply

Introduction

Plastic pollution has become one of our greatest environmental problems, contributing to an exponential increase in non-biodegradable waste and exacerbating climate change by necessitating the extraction of fossil fuels for its production and via alterations to the ocean carbon pump and soil carbon cycling and storage (Brander et al., 2024; Zhu and Rochman, 2022). After approximately two decades of research, it is now demonstrably clear that impacts from micro/nanoplastics and associated chemicals extend from land to sea, impacting both wildlife and humans (Thompson et al., 2025). Although many pathways for MPs to the environment have been described and characterized, the role that food production plays in the transport of MPs to waterways and terrestrial ecosystems, as well as MPs' impact on crop production, aquaculture activities, and environmental health, remains relatively unexplored, particularly in the United States (FAO, 2021, 2024). However, the demand for plastics to facilitate the production of food and non-food crops continues to increase, and the hazard of plastics fragmentation and leaching of chemical components is now widely demonstrated worldwide (United Nations Environment Programme, 2022; Briassoulis, 2023). In regions such as the Pacific Northwestern United States, where both farming and aquaculture are of critical importance, plastic waste, microplastics generation, and leaching of plastic-associated chemicals are of concern for both (Goldberger et al., 2015, 2019). For agriculture alone this load is projected to increase by over 6% from 2023 to 2030 with growing global populations and food demand. In 2018, agricultural plastics were estimated to account for 3–5%, ∼10–18 million tons, of total global plastic production (Hofmann et al., 2023; FAO, 2024, 2021). Microplastics from such products originate in part from the use of plastic films and mulch as well as soil amendments including biosolids (sterilized sludge from wastewater treatment) and compost that often contains remnants of plastic refuse from households (Jin et al., 2022; Golwala et al., 2021; Vithanage et al., 2021). Notably, a recent survey conducted in Ireland found that the number of farmers reporting an increase in plastic use and an increase in the concerns about plastics' impacts sat at 80% and 88%, respectively (Hofmann et al., 2023). Thus, it is clear that desire for change is building, but practitioners lack the ability to make better choices either due to availability, expense, or both.

In aquaculture a variety of plastic materials from cages, ropes, etc. are prone to fragmentation. The use of plastics in multiple types of products and soil amendments creates a pathway for MPs to contaminate soils and waterways via both point and non-point sources. The long-term impacts of MNPs on crops, livestock, and soil ecosystems remain underexplored, particularly in the U.S. The PNW, an agricultural hub for crops like hops, hazelnuts, berries, apples, pears, onions, and alfalfa, and aquacultural hub for shellfish like oysters and geoducks, requires more research to assess MNP risks (American Farmland Trust, 2024)[1]. Plastics have been integral to farming, enhancing yields and resource efficiency (FAO, 2024). Agriplastics account for 3.5% of global plastic use and 14% of plastic pollution, with most ending up in landfills, buried, or burned due to contamination (FAO, 2021). Recycling remains challenging, as used mulch can gain 200% weight from organic contamination alone (United Nations Environment Programme, 2021, 2022).

Fisheries and aquaculture combined are estimated to use at least 2.1 million tons of plastic per year (United Nations Environment Programme, 2021), and concerns about impacts both to seafood, in terms of food safety, and to surrounding ecosystems are increasing, particularly in the context of concerns about multiple stressors from the relatively rapid advancement of climate change (Fred-Ahmadu et al., 2024). For aquaculture alone, exact estimates of plastic used or microplastics generated annually are unavailable, but are likely a considerable fraction of that total since global marine and coastal aquaculture production grew by 64% in volume over the period of 2009–2019, compared to only 4% growth for wild-capture fisheries production (Skirtun et al., 2022; FAO, 2021).

Ultimately, MPs generated during food production result from the use of plastic products by farmers and aquaculturists as well as inputs from households (e.g., MPs in biosolids or compost) with no clear end game for sustainable reuse or disposal, nor a plan toward circularity (Figure 1). The advent and rapid adoption of plasticulture in the production of food has been compared to an agricultural transformation on par with the Green Revolution, during which we became more reliant on technology to grow crops globally (Jensen, 2000). The development of novel plastics formulations (e.g., polyvinylchloride, polystyrene, polyolefins, methyl acrylates) that have become common use

1 American Farmland Trust. Available online at: https://farmland.org/pnw (Accessed December 2024).

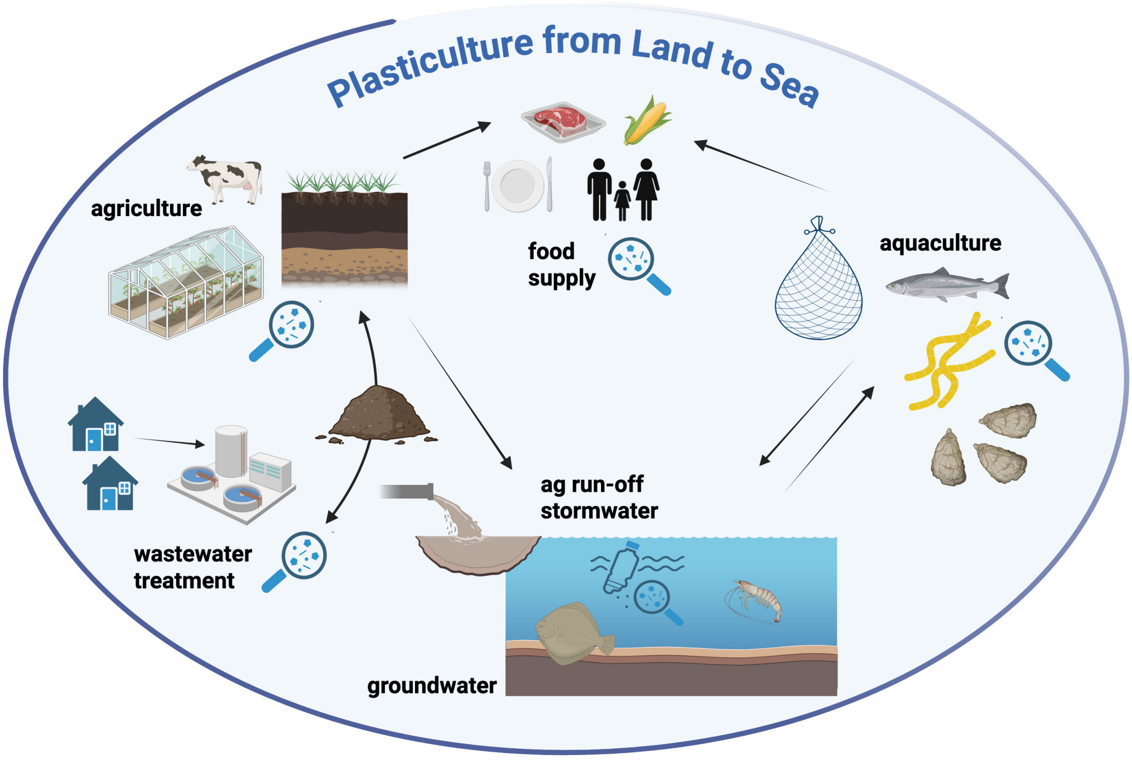

FIGURE 1
The plasticulture cycle, with contributions from homes, municipal wastewater, run-off and storm water, and aquaculture, ultimately contaminating our food supply and leading to increased exposure in humans and wildlife.

for agricultural and aquaculture purposes, catalyzed a major period of growth in the plastics industry starting in the 1930s (Brydson, 1999). The 1940s and 1950s saw material improvements and manufacturing efficiencies that made plastics more widely accessible and affordable, as well as the introduction of novel materials, such as nylon (Brydson, 1999). But it wasn't until the 1960s that plastics were widely adopted and incorporated into food production, particularly to modify and control changing environmental conditions. Both terrestrial crops and seafood production were early targets for plasticulture, including plastic mulches, row coverings, greenhouses, and poly tunnels for farming (FAO, 2021) as well as pond liners, cages, and synthetic ropes used in aquaculture (National Aquaculture Association, 2025). Given the high value of many specialty crops and growing reliance on seafood as a protein source, entrepreneurs who were able to modify microclimates to accelerate growth, improve product quality, and/or extend the growing season were able to access economic premiums for their products (Skirtun et al., 2022; Tarara, 2000).

The 1960s also marked the formation of professional organizations focused on agricultural plastics. The first recorded workshop on the use of plastic films in agriculture was held in 1960, and was soon followed by the formation of the National Agricultural Plastics Association (NAPA) in 1962. The organization brought together university, grower, and industry stakeholders to discuss improving "general agricultural horticultural practices through the use of plastic products at lower cost to the ultimate consumer" (Lamont and Orzolek, 2009). In 1990, the organization's name was changed to the American Society for Plasticulture (ASP) to better reflect the organization's scope of activities (Lamont and Orzolek, 2009). Although there is not a specific organization dedicated to promoting plastic use in aquaculture, this sector was established as a national policy priority in the United States in 1980 (National Aquaculture Association), long before plastic pollution or microplastics were identified as either environmental or health concerns. Notably, the vast majority of papers published through ASP between 2000 and 2009 focused on novel plastic formulations and uses, with few papers (5%, $n = 189$) addressing alternatives to plastics and no papers addressing plastics recycling or reuse, or acknowledging the issue of plastic waste generated from food production (Figure 2). Eventually, APS was subsumed into the American Horticultural Society, and became the Plasticulture Professional Interest Group, which continues to facilitate information exchange and networking around the use of plastics in horticultural research and industry.

Over the decades during which plastic use has skyrocketed, research published through agricultural professional organizations focused on improved production practices using plastic films as greenhouse glazing material, mulches, or row covers, or has touted the benefits of using versatile plastic materials for increased efficiency, allowing for the construction of durable and/or rust-resistant nets, cages, and tanks (AGRU America, 2024). In the early 1960s, most greenhouse structures in the US were glass. Low-cost single layer polyethylene (PE) structures started to appear in

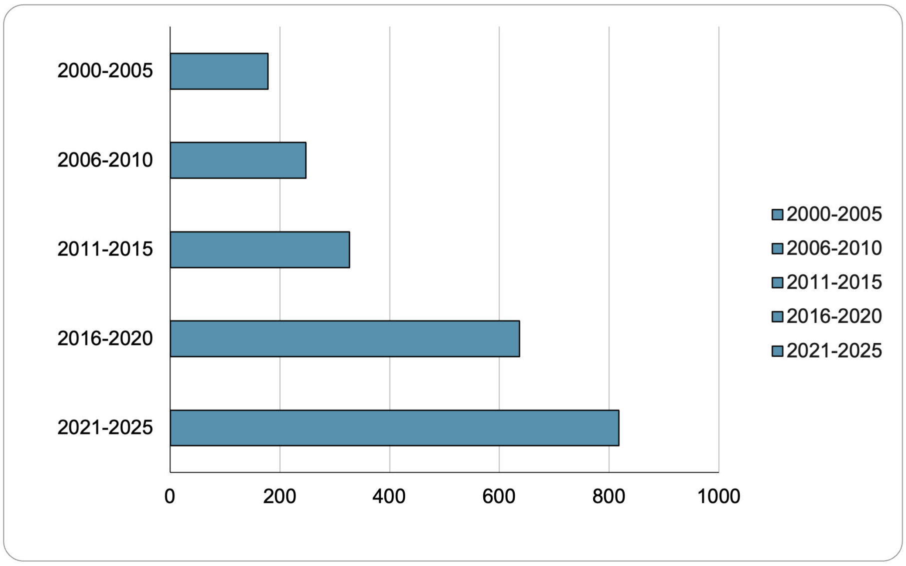

FIGURE 2
Bar graph quantifying research papers in different areas related to plasticulture. Search terms in Google Scholar for each period of years include: plasticulture OR agroplastic* OR agriculture AND plastic OR aquaculture AND plastic OR agriculture AND plastic AND waste.

the 1960s, but they were usually temporary, and used to produce seedlings in the spring. Double layers of plastic produced a warmer interior with less condensation, and reduced energy costs by as much as 30%, compared to single glazed glass covers (Figure 3).

Plastic use in the industry has been the standard in commercial aquaculture operations for decades. Although indigenous aquaculture practices emphasize sustainability and a small ecological footprint, current approaches are reliant on technology involving plastic use to maximize production.

Many early plasticulture studies focused on improving long-term stability of plastic films, which ultimately complicated plastics recycling due to the number of plastic types and chemical additives involved. The life span of films was increased from 5 months to 4 years via the addition of coatings and approaches such as air inflation to constrain film movement. These enhancements reduced energy costs and issues from condensation. Plastic mulches also increased in popularity from the late 1970s through the early 1990s, reaching 3 million pounds (out of total annual use of 60 million pounds of mulch by the end of the 20th century (Giacomelli et al., 2000). By 2009, U.S. farmers were using 200 million pounds of plastic films each year for growing crops (Figure 3). Biodegradable plastic mulches, consisting of biobased (e.g., starches) and synthetic polymers (e.g., polylactic acid), were introduced in the 1980s and promoted to be an ecologically sustainable alternative to polyethylene plastic mulch (Goldberger et al., 2015). However, the perceived complexity of selecting appropriate biodegradable mulches, relatively high cost of materials, labor, and specialized equipment to use biodegradable mulches, concerns related to the negative environmental impacts of synthetic chemical additives, and unpredictable breakdown have limited their widespread adoption (Goldberger et al., 2015). Similarly, the ease of use and durability of plastic materials adopted in aquaculture practices have led to their widespread incorporation across species and life stages (FAO, 2021).

Even when accounting for a brief pause in plastics manufacturing during the 1970s oil crisis, by the turn of the century, 180 kilotonnes (396 million pounds) of plastic films were sold to agricultural markets, including mulch films (37% of sales), plastic covers for crop storage and silage protection (34%), 19% for greenhouses, 5% for water conservation, and 4% for fumigation and sterilization (Laverde, 2002; Lamont and Orzolek, 2009). Today, increasing concerns related to plastic pollution, the contributions of plastics to climate change, and the impacts of plastic additives and particles on human health have renewed calls to rein in agricultural and aquacultural plastics use (MINAGRIS, FAO, 2021). Given the ubiquity of plastics used in terrestrial and aquatic systems, as well as the short-term economic advantages that strategic use of plastics can confer to producers, the transition to new production models and plastics alternatives will be challenging. However, even industry organizations and registered industry political action committees have recently started working to reduce plastics, perhaps to get in front of impending legislation. In the Pacific Northwest, in particular, the considerable size of both the aquaculture [6% of US operations and 18% of sales [United States Department of Agriculture (USDA), 2024] and agricultural industries [more than 90,000 farms cultivating over 40 million acres of land [United States Department of Agriculture (USDA), 2024], as well as increased pressures on producers due to climate change, presents the need for a united approach to reduce contamination of the food supply from plasticulture, and to protect sensitive ecosystems and the health of human consumers.

Plastics in agriculture in the U.S. Pacific Northwest

The geographic and climatic diversity and fertile soils of the Pacific Northwest supports an enormous variety of agricultural

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FIGURE 3
Representative images of a historically used glass greenhouse (early 20th century time period) vs. a current greenhouse using a synthetic liner for its walls, and typical polyethylene sheet mulching rows. From commons.wikimedia.org (greenhouse photos), Gail Langelotto (mulch).

commodities [300+ in Washington, 250+ in Oregon, and 185+ in Idaho; United States Department of Agriculture (USDA), 2025], including many specialty crops. Yet ongoing changes to global climate and increasing population size have increased pressure on the agricultural industry and on farmers, leading farmers to become more reliant on plastic products despite their potential negative consequences (Okeke et al., 2023). In the Pacific Northwest, more severe winter storms coupled with overall lower precipitation, and warmer summers coupled with frequent wildfires, invasive pests, and pathogens [United States Department of Agriculture (USDA), 2025] are significantly impacting growers, causing greater reliance on plastics in production systems (Tarara, 2000). The productive oceans and complex and extensive coastlines of the Pacific Northwest offer vast opportunities for aquaculture of diverse shellfish species.

These rich agricultural and aquacultural practices utilize plastic products of different types. One common use of plastic in farming with high rates of shedding micro and nanoplastics (MNPs) is mulch films, typically composed of polyethylene or polyvinyl chloride in the US. These films, used to increase water retention and reduce weed growth, have become more critical due to climatic changes to temperature and precipitation. These plastic mulch films can fragment into smaller pieces in <1 year, depending on the material type, making them a major source of MNPs to soil and surrounding areas. For example, the tensile strength of even some biodegradable mulches, such as those made from PBAT and PLA, can counterintuitively increase with weathering and be altered by differing temperatures or humidity levels (Hayes et al., 2017; Yu et al., 2024). While mulch film collection programs exist in some states (Madrid et al., 2022), they are not easily recyclable due to residual soil. Furthermore, it is laborious and expensive to remove mulch films from the soil between growing seasons given that these films easily break apart at 8–50 μm thickness leaving small pieces that are impractical or impossible to remove from soil (Yan et al., 2014; Sarpong et al., 2024; Dada et al., 2025). When they are removed, recovered mulches have 30–80% surface contamination, making recycling challenging (Sarpong et al., 2024). A survey of farm soils ($n = 69$) across 19 Chinese provinces found that degraded mulch film can account for 10–30% of MPs in agricultural soils (Ren et al., 2021), though this is likely an underestimate given

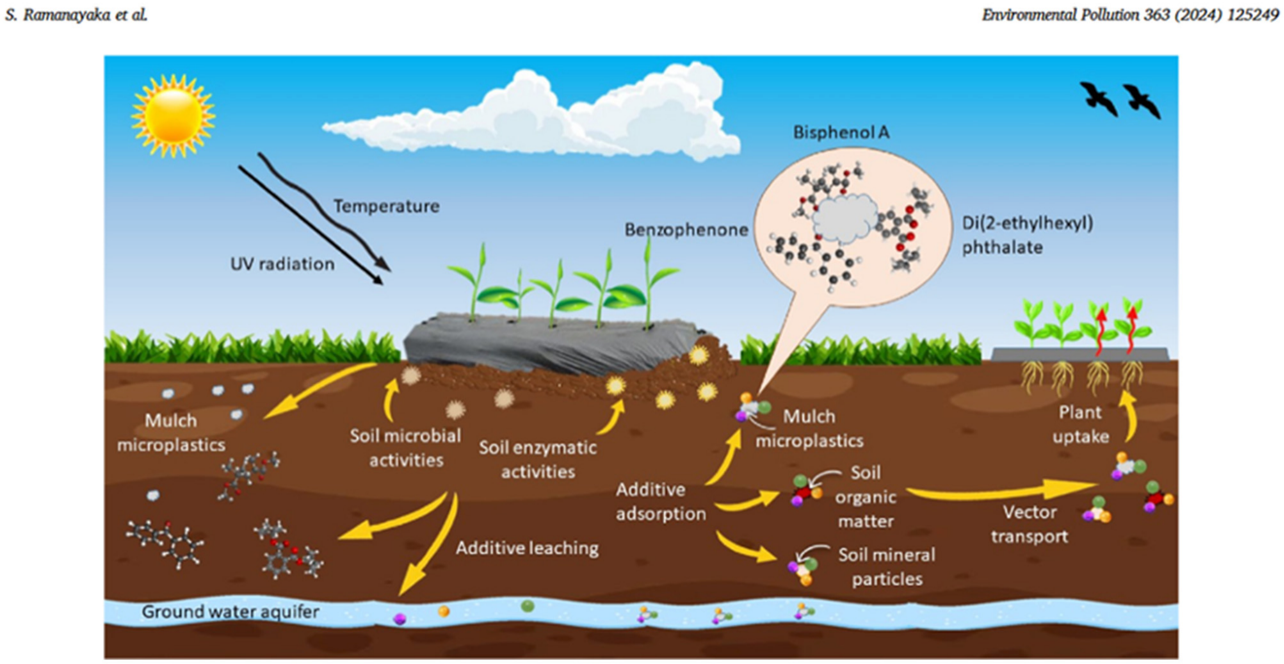

FIGURE 4
Schematic representation of plastic additives leaching from plastic mulch films, factors affecting for leaching, their fate, and translocation in environment. Reprinted under a Creative Commons CC-BY license from Ramanayaka et al. (2023).

that continual breakdown into nano-sized particles eventually renders the debris undetectable while producing orders of magnitude more particles (Cunningham et al., 2023). For example, degradation of the estimated 5 trillion pieces of MPs in the environment could result in 5×10^{15} pieces of nanoplastics (NPs) (Eriksen et al., 2023). When compared to soils amended with compost made from greenhouse and garden clippings, soil using plastic mulch contained more than double the number of MPs (2,243 particles/kg compared to 888 particles/kg) (van Schothorst et al., 2021). While the breakdown of plastic mulch has been explored and uptake by organisms such as earthworms is documented, little is known about groundwater impacts from plastic particles and associated chemicals such as plasticizers and UV stabilizers (e.g., Ramanayaka et al., 2023, Figure 4). Factors influencing MP concentration in soils include soil texture, crop type, irrigation method, cultivation method, prolonged mulching duration. Crops such as potatoes, which are commonly grown in the Pacific Northwest [United States Department of Agriculture (USDA), 2024], rely on mechanical harvesting which tears the plastic covering, increasing the concentration of plastics in the soil (Miao et al., 2024).

Plastics in organic agriculture

Many organic farms in the Pacific Northwest depend on plastic products. These include mulch for weed control to avoid pesticide use given limited organic-certified herbicides (Dentzman and Goldberger, 2020). Black polyethylene plastic, used since the 1950s, generates up to 120 pounds of plastic waste per acre. With over 228 K acres of organic farmland in Oregon, this amounts to ∼27 million pounds annually. Mulch is difficult to recycle due to contamination and removal costs (OSU Small Farms, 2015). Though the USDA's National Organic Program (NOP) allows biodegradable, biobased plastic mulch, only paper mulch is compliant, as biobased plastic alternatives (e.g., PBAT) still contain fossil-fuel components (OSU Small Farms, 2015). Economic pressures to enhance crop health and water retention make transitioning to sustainable alternatives challenging. While paper mulch is available, the limited data available suggests that paper mulches do not suppress weeds as well as plastic mulches, and underperform plastic mulches in terms of yield (Coolong, 2010; Marble et al., 2019). Though recent studies suggest soil-biodegradable plastic mulches may be viable alternatives, with some improving soil stability, water retention, and nutrient uptake, these mulches still degrade into micro- and nanoplastics (MNPs), potentially impacting soil and organism health (Bandopadhyay et al., 2018).

Another commonly used product type, plastic nets, provide protection from abiotic damage (e.g., hail, sun, or wind) as well as biotic pests, primarily birds and insects. Nets are used primarily in high value specialty crops, including tree fruits, berries, and ornamental plants, due to the costs associated with their purchase and installation. In some orchard systems, netting can represent up to 25% of production costs in the first 3 years of use, with costs increasing on hilly sites, as crop height increases, and with irregular farm layouts. Plastic nets are woven or knitted in a way that allows gasses and liquids to move through the material (Castellano et al., 2008). The most common types of plastic nets are made of HDPE, although non-woven layers may be made of polypropylene (Castellano et al., 2008). Nets that are manufactured to protect crops from sun or hail tend to be woven and more resistant to breakage than knitted nets used to protect crops from insects or wind (Briassoulis et al., 2007). UV stabilizers are often embedded in plastic nets, to slow their breakdown over time, but ultimately their lifespan does not exceed 6 years, and these chemicals gradually leach out of products into soils, etc. (Castellano et al., 2008). Compared to studies of plastic mulch breakdown and pollution in agricultural systems (reviewed in Sa'adu and Farsang, 2023a), studies have yet to examine how plastic fibers shed from nets in the field. Instead, researchers have derived estimates of net performance (Castellano et al., 2008) based upon ISO testing of net properties (e.g., Briassoulis et al., 2007). In addition, there has been limited research on (Mukherjee et al., 2019), and limited adoption of biodegradable nets in farming systems, likely because of their scarcity in the marketplace and the high costs associated with agricultural nets, in general. However, some argue that the higher costs of biodegradable nets are recovered due to reduced disposal costs (Scarascia-Mugnozza et al., 2012).

Types of plastics in agriculture

Additional plastics products and types can be found in each step of crop production and can be grouped into three main categories based on their physical properties, including flexible products *e.g., films, tunnel and greenhouse films*, semi-flexible products, *e.g., tubes and drip line*, and rigid products, *e.g., bottles, baskets* (FAO, 2021). These can then be further classified into the following additional categories: protective cultivation films: PE (polyethylene), PVC (polyvinyl chloride), Protective Cultivation panels: PVC (polyvinylchloride), RFP (rigid fiberglass), PC (polycarbonate), PMMA (acrylic panels), nets, piping, irrigation/drainage, packaging, fertilizer, and other [Environmental Investigation Agency (EIA), 2023] (Table 1).

The types of plastic and how much or often they are used vary across regions and countries, influenced by factors such as the level of mechanization, the length of supply chains, and the reliance on exports, although a 2021 Food and Agriculture Organization report found that films represent the largest quantity of non-packaging plastics used in agriculture worldwide (FAO, 2021). In the PNW, a recent research project in Washington State assessed the types of agriplastics used by farmers and the challenges they pose. Researchers interviewed 59 farmers across 14 counties, representing a range of agricultural operations, including vegetable farms, livestock ranches, dairies, orchards, and flower farms. The top 10 waste items were identified and greenhouse films were the most used plastic. Other commonly used items included nursery trays, drip tape, bags (e.g., for soil amendments and feed), row cover, landscape fabric, silage film, plastic twine, packaging materials (such as produce bags and waxed boxes), and super sacks (Zero Waste Washington, 2025). The interviews revealed significant challenges in managing these materials. Most farmers dispose of their agriplastics in landfills as they have few options for handling the soil-contaminated materials (Zero Waste Washington, 2025).

Another MNP source in agriculture is biosolids, which trap 95% of MNPs from industrial and household wastewater during wastewater treatment and are then used as agricultural fertilizers. In the U.S., 53% of municipal biosolids are applied to farmland, with nearly 50% in Washington and over 70% in Oregon, amounting to 40,000 dry tons annually (National Biosolids Data Project, 2023). These biosolids contain high MNP concentrations, primarily microfibers from laundry (Geyer et al., 2022). Microfibers are highly toxic, causing oxidative stress and growth limitation in organisms (Granek et al., 2022; Siddiqui et al., 2023). Proposed U.S. regulations for washing machine filters to reduce microfibers entering biosolids have yet to pass due to industry opposition (OR SB 405, CA AB 1628). Compost also contains MNPs, with biosolid-derived compost contributing ∼1,750 particles/kg compared to 888 particles/kg from garden waste (Hermann et al., 2011). The increasing use of newer plastics, such as PLA, exacerbates contamination. Studies indicate polyester and polyethylene fragments (from traditional plastics) alter soil properties, reducing bulk density and changing water retention (de Souza Machado et al., 2019; Lehmann et al., 2019). Municipal compost programs in the PNW collect food waste, inadvertently increasing MNP contamination.

Ultimately, food production in the Pacific Northwest and globally is being impacted by plastic pollution (Figure 5). Recently the impacts on both crop and seafood production were quantified and estimated to be 109.73–360.87, and 1.05–24.33 million metric tons for crop production and seafood, respectively (Zhu et al., 2025). It is clear that new approaches are needed for food production that reduce plastic use and subsequent fragmentation and leaching of microplastics and plastic-associated chemicals.

Plastics in aquaculture in the U.S. Pacific Northwest

The farming and management of shellfish and finfish species along the Northwest Pacific Coast of the United States has been practiced since time immemorial. Beginning with innovative methods developed by First Nations people (clam gardens), and later modern farming of shellfish (100–150 years ago), managing and celebrating shellfish is an intrinsic part of the Pacific Northwestern cultures and an essential local resource (Groesbeck et al., 2014; Lepofsky et al., 2021; Reeder-Myers et al., 2022; Gordon et al., 2023).

In present times, among the U.S. West Coast states, according to farm self-reporting for the 2018 aquaculture census, the value of aquaculture products sales was $23 million for Oregon, $207 million for Washington, and $106 million for California. This is an increase from the USDA 2013 consensus finding the combined aquaculture value of California, Washington, and Oregon of $176 million. In 2018, in Alaska—where finfish aquaculture is prohibited, aquaculture sales at the 22 reporting farms reached $1.8 million; however, with over 60 farms in the state, this is likely a vast underrepresentation (Ehrhart and Doerr, 2022). Aquaculturists utilize plastic materials (Table 2) as they contend with strong tides and currents, which can impact shellfish beds, as well as harmful algal blooms depending on oceanographic conditions and other abiotic factors such as ocean acidification. Yet along the US. West coast are some of the most stringent aquaculture regulations in the US which facilitates the protection of water quality and habitat.

TABLE 1 Lists of common agricultural plastics and their respective categories along with their intended use, benefits and plastic alternatives, when available.

Category	Agricultural product	Intended use/benefit	Plastic alternatives	Notes	Sources
Protective cultivation films (PE and PVC)	Greenhouse Permanent structure with climate control components (e.g., heat, fans).	Designed primarily for environmental control of temperature and moisture. Protects and enhances plant growth, extends cropping seasons, and increases yields.	Glass panels	Glass panels are costly. Glass offers better environmental control than PE, but less than PVC.	Environmental Investigation Agency (EIA), 2023; Roberts, 2000; Wells, 2000
	High/low tunnel, hoop house Semi- permanent, greenhouse- like structure without climate control components.	Designed primarily for season extension. Protects and enhances plant growth, extends cropping seasons, and increases yields.	No known alternatives.	In addition to the plastic film covering, high and low tunnel ribs are often made from PVC piping.	Environmental Investigation Agency (EIA), 2023; Roberts, 2000; Wells, 2000
	Plastic mulch A layer of material applied to the soil surface.	Reduces weed growth, prevents insect pests and vectors of plant disease, eradicates soil-borne pathogens, which reduces the need for pesticides. Reduces evaporative water losses, which reduces irrigation inputs. Warms soil for earlier start to the growing season.	BDM and organic mulches, including crop residue, sawdust, leaf mold, compost, hay and straw. Cover cropping or green mulches can also be used as an alternative to plastic mulch.	Many BDM are commercially available, made from plant-based starches and biodegradable polymers (e.g., PLA, PBAT).	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Schonbock, 2012
	Vineyard, berry crop, and orchard covering	Reduces insect pests, environmental damage from frost or sun. Increased environmental control of light wavelengths and temperature. Improved color, sweetness, and overall crop quality.	No known alternatives.	Depending upon the timing of installation, use of crop coverings can limit yield in pollination-dependent crops, including berries and orchard fruits, by excluding pollinators.	Environmental Investigation Agency (EIA), 2023; Vox et al., 2016
Protective cultivation panels (PVC, FRP, PC, PMMA)	Greenhouse Permanent structure with climate control components (e.g., heat, fans).	Designed primarily for environmental control of temperature and moisture. Protects and enhances plant growth, extends cropping seasons, and increases yields.	Glass panels	Glass panels are costly. Glass offers better environmental control than PE, but less than PVC.	Roberts, 2000
Nets (PE, HDPE)	Shade Net and Shade Cloth Woven, cloth-like material with varying degrees of opacity.	Protects crops from sunscald, limits evapotranspiration, and may reduce incidence of pests or disease.	Burlap or jute-based fabrics. Agrivoltaics.	Agri-voltaic arrays provide shade and can benefit low-growing crops and livestock.	Environmental Investigation Agency (EIA), 2023; FAO, 2021
	Anti Wind Net and Windbreak Woven lattice made from sturdy materials.	Protects and enhances plant growth, extend cropping seasons, and increase yields	Wood-based windbreaks. Living windbreaks include perennial plants, shrubs, and trees	Living windbreaks may also provide additional sources of farm income from the sale of harvested seeds, fruits, nuts, fuel, and flowers.	Environmental Investigation Agency (EIA), 2023; FAO, 2021
	Anti hail net Woven, cloth-like material.	Protects and enhances plant growth, extends cropping seasons, and increases yields.	Anti-hail insurance	Actuarial models can predict when anti-hail insurance makes more economic sense than anti-hail nets.	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Rogna et al., 2023
	Anti bird net Mesh netting	Mesh netting that excludes birds from foraging on crops.	Use of deterrent methods (e.g., visual scares, noise, chemical repellents) and creating and restoring natural habitats.	Deterrent methods keep birds away from specific areas. Creating and restoring natural habitats provides alternative areas for birds to thrive, reducing the need for bird netting.	Environmental Investigation Agency (EIA), 2023; FAO, 2021

(Continued)

TABLE 1 (Continued)

Category	Agricultural product	Intended use/benefit	Plastic alternatives	Notes	Sources
Piping, irrigation, and drainage (PE, HDPE, PVC)	Irrigation tape Thin flat plastic tubing.	Flexible tubing used to direct precise amounts of water to plant roots. Improves water use efficiency.	Soil management practices that promote on-site water conservation, such as hydrological keyline design or dry farming.	Biodegradable options have been explored for research, but suffered issues during manufacturing. More permanent irrigation systems would eliminate the need for retrieval and disposal, but these permanent systems do not meet all farmers' needs.	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Hofmann et al., 2023; Hiskakis et al., 2011; del Carmen Ponce-Rodríguez et al., 2021; Davis et al., 2023
	Water Reservoir Infrastructure, often lined with plastic, designed to store substantial amounts of water for irrigation.	Prevents water scarcity in drought-prone areas by ensuring farmers have continuous access to water, ultimately enhancing crop yields and profitability.	Concrete reservoirs and compacted earth reservoirs. Soil management practices that promote on-site water conservation, such as hydrological keyline design or dry farming.	Weed management prevents water loss to vegetation. Covered reservoirs limit evaporative water loss and block sunlight necessary for weed growth.	Irrigation Reservoirs, 2025; Sahoo et al., 2021
	Channel lining	Plastic layer added to irrigation canals prevents soil erosion and water seepage and loss into the soil.	Compacted earth or concrete linings are historical alternatives, but are not as effective as plastics and geotextiles.	Weed management prevents water loss to vegetation. Solar photovoltaic arrays can be situated above channels, to prevent evaporative water loss.	Samir et al., 2023
	Drippers	Thin-walled tubing meant to direct precise amounts of water to plant roots. Improves water use efficiency	No known alternatives.	Soil management practices that promote on-site water conservation, such as hydrological keyline design or dry farming, may lessen the need for irrigation.	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Hofmann et al., 2023; del Carmen Ponce-Rodríguez et al., 2021; Davis et al., 2023
Packaging (PP)	Bags/sacks Plastic film or woven bags	Ensures safe containment of inputs (e.g., seed, compost, feed, fertilizer etc.) during transport, storage and use, minimizes risks of exposure.	Burlap, cloth, or paper sacks Use manure or produce compost on-site. Buy unbagged products, in bulk.	Will generally need a protected area or open shed, with a level pad and roof or protection from rain, if opting to buy in bulk.	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Marinac, 2025
	Agrochemical containers	Hold and store pesticides, fertilizers, and other agrochemicals	Steel tanks. Sprayer provider services can limit the need for agrochemical containers on every farm. Refillable containers to limit waste.	Regulations related to the containment, storage, and transport of hazardous materials preclude most forms of non-plastic packaging. Recycling is limited, due to concerns related to residues.	Environmental Investigation Agency (EIA), 2023; FAO, 2021
	Tanks for liquid storage	Allows for transportation of water throughout the farm and the collection of rainwater for livestock, crops or emergency water use.	Steel tanks	While steel tanks offer durability, plastic options often provide cost effective solutions, and easier handling for transportation.	Environmental Investigation Agency (EIA), 2023; IBC Tanks, 2024; Galle, 2023
	Crates	Reduction of food loss during post harvest transportation and storage.	Wooden crates. Burlap, jute or cloth sacks.	Crates have a higher reduction in food loss compared to sacks.	Environmental Investigation Agency (EIA), 2023; FAO, 2021
Coatings	Slow release fertilizers	Polymer coated fertilizer to control the release rate of chemicals.	Organic coatings made from plant-based starches, gums, rubber, cellulose, or lignin. Use of leguminous and non-leguminous cover crops can substitute for slow-release fertilizers.	Fertilizers may be overapplied as a form of farmer-managed "crop insurance." Informed use of soil tests can limit over applications.	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Lawrencia et al., 2021

(Continued)

TABLE 1 (Continued)

Category	Agricultural product	Intended use/benefit	Plastic alternatives	Notes	Sources
	Protective seed coating	Polymer seed coatings improve germination, pesticides in the coatings can assist the survival of seedlings.	Organic coatings made from plant-based starches and gums.	Timing planting to optimal environmental conditions can improve germination of uncoated seeds.	Environmental Investigation Agency (EIA), 2023; FAO, 2021; Afzal et al., 2020
Other (PE, PP, PVC)	Silage films	Plastic film that provides protection from air and rain. It also is used to aid the fermentation of biomass for animal fodder and avoid the need for storage buildings	Biodegradable films	Biodegradable films have been found to be effective for bales that are not stored outside for extended periods, and when used within 6 months.	Environmental Investigation Agency (EIA), 2023; FAO, 2021
	Fumigation films	Plastic sheets used to trap fumigants and control soil-borne pests prior to replanting. They also help control fumigation emissions in the atmosphere.	Mustard and sorghum, as meal or cover crop, can act as a biofumigant.	Methyl bromide and other soil fumigants have been or at risk of being phased out, which may reduce use of fumigation films.	Environmental Investigation Agency (EIA), 2023
	Bale twines and wraps	Twine and net wraps used to bind hay bales together. Prevents bale deterioration.	Natural fibers for bale twine and wraps include abaca (i.e., Manila hemp), wool, cotton, sisal, straw, jute, hemp, and coir.	Twine collection and recycling programs are available in a few regions of the U.S. and Canada, supported by community non-profits.	Environmental Investigation Agency (EIA), 2023
	Nursery trays/pots Containers used to start and grow seedlings and young plants.	Allow efficient propagation, production, transportation, and staging at the point of sale. Used for ornamental nursery plants, as well as by propagators or other crop plants.	Biodegradable pots and trays. Soil blocking. Buy bare-root plants, if possible.	Biodegradable pots and trays are commercially available, made from plant-based starches and biodegradable polymers (e.g., PLA or PBAT). Soil blocking decreases plastic use but may not meet all farmers' needs.	Environmental Investigation Agency (EIA), 2023; Hofmann et al., 2023
	Strings and ropes	Used to support and trellis climbing plants, train young plants to upright growth habit.	Natural fibers for string and rope include abaca (i.e., Manila hemp), wool, cotton, sisal, straw, jute, hemp, and coir.	Natural fibers need to be replaced every 1–2 years, but have the advantage of being less likely to cut into plant stems than plastic ties.	Environmental Investigation Agency (EIA), 2023
	Boxes	Optimizing the cost and fuel needed to transport products—by using lightweight packaging for final products to be distributed or sold to consumers.	Non-waxed Cardboard boxes	Waxed boxes cannot be recycled or composted due to their polyethylene coating.	Environmental Investigation Agency (EIA), 2023; FAO, 2021
	Fittings Connect pipes and tubing in irrigation systems.	Allows for modification to existing irrigation systems.	No known alternatives.	Soil management practices that promote on-site water conservation, such as hydrological keyline design or dry farming, may lesson need for irrigation.	Environmental Investigation Agency (EIA), 2023
	Non-woven protective textiles or "fleece"	Protect crops from extreme cold and/or sunlight	Cotton batting and cheesecloth are suggested, though untested, alternatives.	Designing appropriate windbreaks and intermixing low- and high-growing crops may provide some protection for the low-growing crops.	FAO, 2021

PE, polyethylene; PP, polypropylene; PC, polycarbonate; RFP, rigid fiberglass panel; PVC, polyvinyl chloride; PMMA, Poly(methyl methacrylate); BDM, biodegradable mulches; PLA, polyclactic acid; PBAT, polybutylene adipate-co-terephtalate.

In current shellfish aquaculture, various plastic components and equipment have become critical to shellfish farms' success, growth, and ability to keep operating costs as low as possible. Oyster farming, in particular, is currently dependent on many plastic items such as rope, cages, PVC pipe, identification tags, repurposed tires, styrofoam dock floats, packaging, and storage containers, with limited readily available cost-effective alternatives (Figure 6). However, product trials are occurring on the Eastern Seaboard of the United States with the eastern oyster (*Crassostrea virginica*). If successful, these materials and methods could be adopted in PNW

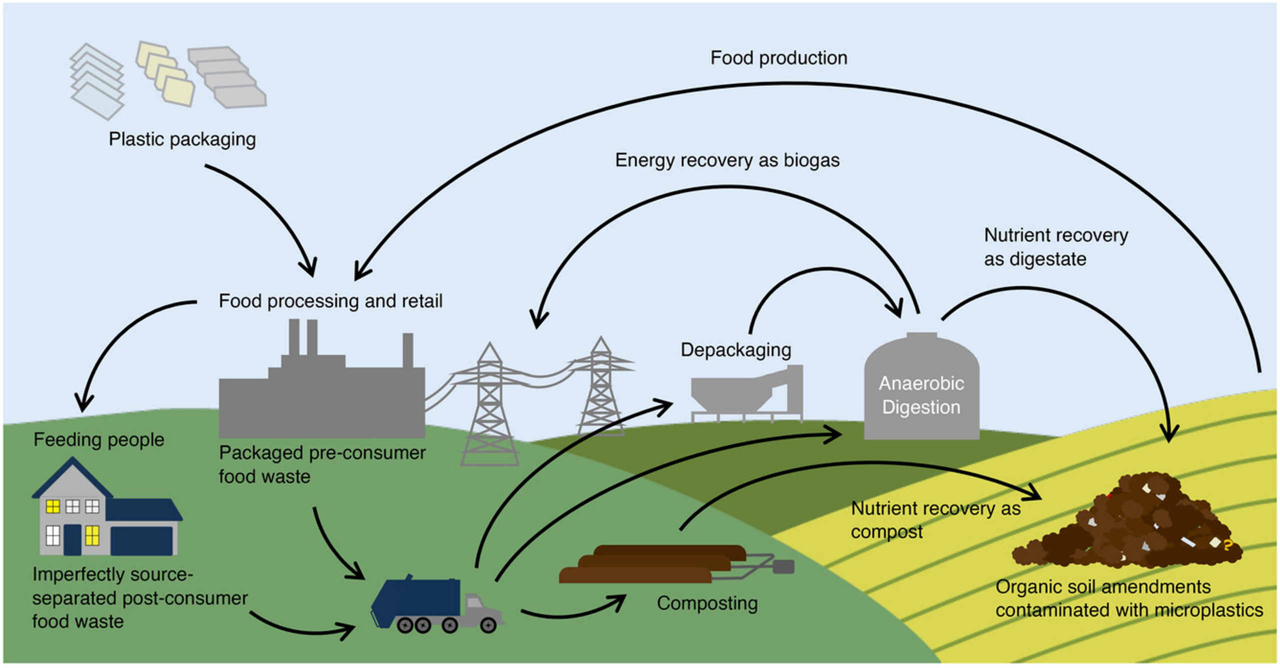

FIGURE 5
Conceptual diagram showing flows of food waste and microplastics to composting and anaerobic digestion and on to agricultural soils; reprinted under a Creative Commons Attribution—Non-Commercial-No-Derivs license, from Porterfield et al. (2023).

shellfish farming. Deer Isle Oyster Company is trialing a plastic-free oyster ranch using various new and old materials such as cedar wood floats and frames, perforated aluminum, mushroom mycelium inoculated hemp-chafe buoys (mycobuoys™), hemp line, basalt mesh, and painted cork—with mixed success. Their trials are ongoing (Barrows, 2025).

Geoduck farming also relies heavily on plastic equipment, such as large PVC tubes and plastic netting, used to protect growing geoduck clams. Despite the direct use of PVC in native sediments, geoduck farming has minimal effect on benthic communities when grown outside of eelgrass meadows and may provide environmental benefits such as increased water filtration (NOAA Fisheries, 2024). All bivalve farming includes the use of plastic items and tools, some of which have become critical to production, such as grow-out cages and other protective structures that need to be lightweight and able to withstand environmental conditions. Alternative materials such as metal or wood rust or break down quickly, increasing farm costs, and are heavier than plastics, potentially making physical work more dangerous and strenuous on facility staff and machines. Items like rope and consumer packaging, currently made from plastics, might have higher potential for successful replacement with non-plastic materials, such as wool or basalt rope and wood or waxed paper-board packaging.

Sea urchin ranching (*Strongylocentrotus purpuratus*) is a growing industry in the Pacific Northwestern States, especially Oregon, borne from an ecologically unstable wild urchin population explosion. The extirpation and near-extinction of the purple urchin's top predator, the sunflower star (*Pycnopodia helianthoides*) by Sea Star Wasting Disease (SSWD) resulted in a dramatic trophic cascade transforming dense kelp forests into overpopulated urchin barrens (Schultz et al., 2016; Gravem et al., 2021). Live, but starving urchins on these barrens are collected by divers and fattened up on commercial diets or red macroalgae such as dulse (*Palmaria palmata*) in land-based operations. After a few months, the collected urchins are full of uni (roe) ready for market (Oregon Kelp Alliance, 2023). These urchin ranchers rely on numerous plastic products ranging from mesh to hold algal fronds, plastic totes and PVC pipe, to the product (uni) packaging. While the former items are proving to be essential to basic urchin husbandry, items like plastic uni packaging could be swapped for traditional materials like bamboo, or modern ones such as waxed paperboard to create a minimal-plastic standard for this growing industry.While the sources of microplastics in aquatic environments are also derived from airborne (atmospheric deposition) and terrestrial origins, the use of plastic materials in the ocean and estuaries leads to the release of plastic fragmentation and microplastic particles directly into these aquatic ecosystems (Rossatto et al., 2023; Tursi et al., 2022). Plastics can be dislodged from aquaculture structures during storm events or large debris impacts and these macroplastics can entangle marine life, affecting swimming ability and potentially food acquisition. Larger plastics, when weathered by marine salt, wave and wind energy, acidifying waters, and UV from solar radiation, are broken down into microplastics, which can be ingested or inhaled by marine organisms. Shellfish such as bivalves and shrimp are not immune to pollution exposure (Traylor et al., 2024) and have been recognized as important indicator species of MNP presence in the environment (Li et al., 2019; Siddiqui et al., 2022, 2023). For example, shrimp exposed to HDPE microplastics have altered enzyme activity and

TABLE 2 Description of plastic products used in aquaculture, and their benefits, drawbacks and potential alternatives.

Industry and type of plastic	Benefits to production	Drawbacks	Notes	Alternatives	Alternatives
Oysters, geoducks, and other bivalves					
PVC pipe plumbing	Essential for hatcheries, cost, ease of use	Becomes brittle over time, MNP shedding	Molluscs are extremely sensitive to metals -metal pipe is not an option	Aluminum	Mercer, 2023
PVC pipe stakes (oyster stake cultivation)	Cost, ease of use	Becomes brittle over time, MNP shedding, alteration of estuarine sediment bed	Used for securing clutch w/spat in grow-out locations	Cedar stakes	Mercer, 2023
PVC protection tubes (geoduck farming)	Cost, ease of use	Becomes brittle over time, MNP shedding, alteration of estuarine sediment bed	To protect juvenile geoducks from predators	Fiberglass	NOAA Fisheries, 2024
Mesh spat-bags (oysters)	Cost, ease of use, potentially reusable	Becomes brittle over time, MNP shedding	Used for protecting loose spat at small stages	PHA/PHB, mycelium, or help-based	Mercer, 2023
Grow-out cages (oysters)	Cost, ease of use, reusable over many seasons	Becomes brittle over time, MNP shedding	Used for protecting oysters until harvest for sale	PHA/PHB, mycelium, or kelp-based Perforated Aluminum	Mercer, 2023; Barrows, 2025
Rope	Essential to production, cost, ease of use, reusable over many seasons	Becomes brittle over time, MNP shedding	Multi-use item	Wool and basalt rope are promising alternatives	Mercer, 2023; Barrows, 2025
Broodstock and larval culture tanks	Essential to production, cost, ease of use, reusable over many seasons	Becomes brittle over time, MNP shedding	Essential to self-sustaining operation	Fiberglass	Mercer, 2023
Consumables	Gloves, pipette tips, algae bags	Typically, 1-time use	Essential to self-sustaining operation	Algae bags could be replaced with reusable alternatives—alternatives can be expensive	Mercer, 2023; Algae Culture in Biotechnology, 2025
Used tires	Low/no cost boat dock bumpers, retaining walls	Leaches chemicals and tire wear particles	Protects expensive equipment, low-cost erosion management	It could be replaced with rubber bumpers and concrete blocks	Personal observation of tires used as bumpers and retaining wall structure in Oregon
Styrofoam floats	Low cost, if wrapped properly can last a long time	If outer protectant is compromised, it will shed polystyrene beads and chunks, Can leach chemicals	Very buoyant, boring organisms like boring clams and shipworms, can burrow into structure causing damage	It could be replaced with hard plastic or steel floats	Snow and company[2]
Sea urchins					
Plastic mesh feeders	Low-cost, customizable	Becomes brittle over time, MNP shedding, urchins chew on plastic, fragmenting it	Used to hold macroalgae	Could be remade with PHA/PHB	Personal observation of trial urchin farming in Oregon
Uni packaging	Low-cost, lightweight	One-time use, hard to recycle once dirty	Clear materials show aesthetic presentation of uni products – important to the industry	Reduce plastic packaging. Swap for wood, waxed paperboard, biopolymers, algae, or mycelium-based packaging	Grown Bio, 2022; Pumpkin, 2008
PVC pipe plumbing	Essential for husbandry tanks, cost, ease of use	Becomes brittle over time, MNP shedding	Echinoderms are sensitive to metals, like copper	None known yet	Ladouceur and Ghobrial, 2021

gene expression indicating increased stress, as well as evidence of histopathology (Niemcharoen et al., 2022, Figure 7).

Filter-feeding shellfish, including oysters, mussels, and geoducks, filter hundreds of liters of water each day, concentrating the MNPs they capture, if not egested (Rochman et al., 2015). Other filter feeders, such as colonial and stalked ascidians are suggested to be better indicators of MNP presence in the environment as

2 Snow and Company. Available online at: https://www.snowboatbuilding.com/aquaculture (Accessed Jan 2025).

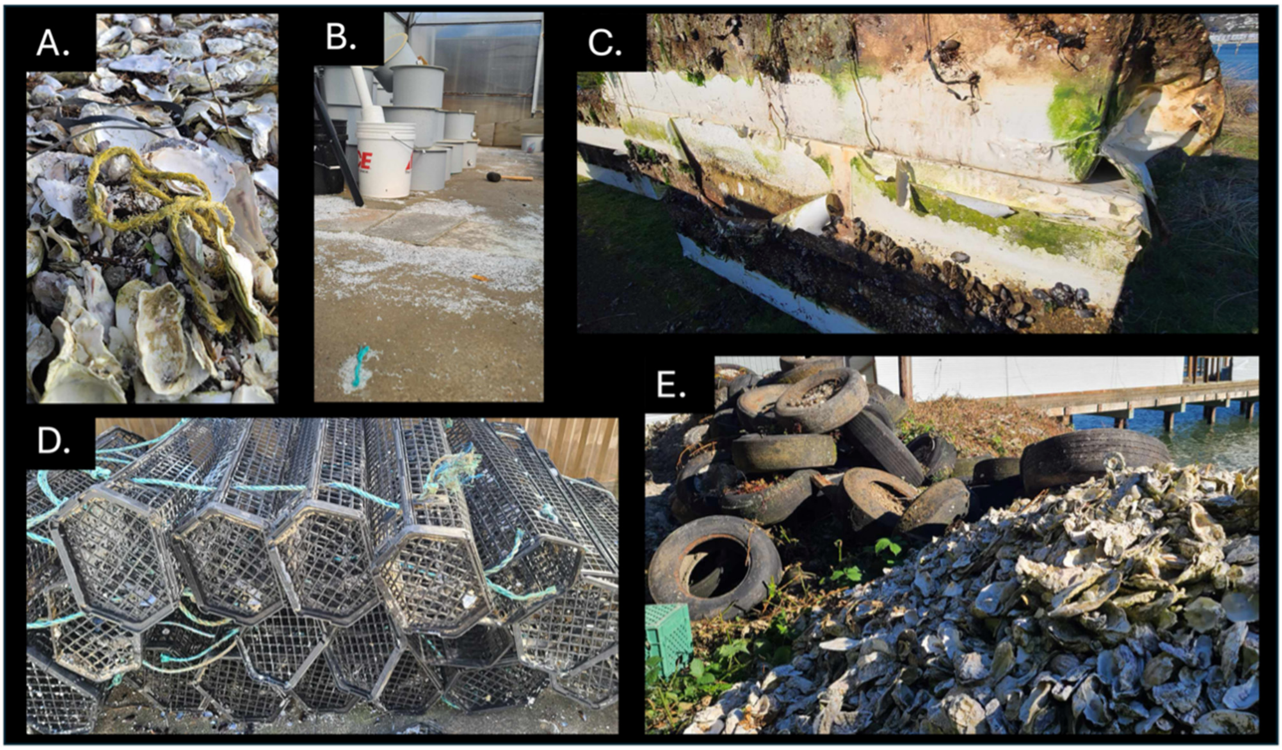

FIGURE 6
Figure displays various types of plastic pollution sources commonly used in the Pacific oyster industry, such as **(A)** frayed yellow polypropylene rope, **(B)** PVC shavings and rope trimmings, **(C)** degrading plastic-wrapped polystyrene block floats, **(D)** plastic AP6 oyster baskets with teal polypropylene rope, and **(E)** discarded automobile tires. Photograph credit: MacKenna Hainey.

they are less selective and tend to reject/egest MNPs at a lower frequency when compared to bivalves (Messinetti et al., 2019; Ward et al., 2019; Harel et al., 2024). These ascidians often co-occur where bivalves are grown. While some particles are successfully excreted from the body after a few hours or days through depuration, some MNPs remain within the bodies of these organisms and are subsequently consumed by their predators (Weinstein et al., 2022; Liu et al., 2023). Some studies conducted in major aquaculture hubs have documented that a significant portion of microplastics found in aquaculture areas are directly derived from these materials, often termed aquaculture-derived microplastics (AD-MPs). However, while the mechanisms and pathways of breakdown are well-described, quantitative rates of breakdown under field conditions are less frequently reported, and most available data are from laboratory or regional surveys outside the U.S. (Lin et al., 2022, 2023). Once ingested, these microplastics can lead to a false sense of satiation that can cause reductions in feeding, successful settlement, and growth rates; inflammation when microplastics irritate internal tissue or organs, reproductive effects, and DNA damage (Bringer et al., 2021; Horn et al., 2020; Siddiqui et al., 2023; Cunningham et al., 2024; Hutton et al., 2024). This raises concerns about the health and quality of the shellfish and risks for consumers, including humans and long-term environmental accumulation (Smith et al., 2018).

Globally and in the Pacific Northwestern U.S., seaweed farming has a long history in human cultures and plays a role in mitigating the effects of runoff while increasing carbon sequestration (Chung et al., 2011; Buschmann et al., 2017). Marine cultivation of seaweed reduces pressure on limited terrestrial resources needed to meet human food demands (Radulovich et al., 2015). In the United States, consumers prefer seaweed for its high nutritional value (Gómez et al., 2016), and Cornish (2017) found that it could support brain health. However, the effects of microplastics in seaweed on human health remain unknown (Xiao et al., 2024). Seaweed farming methods include vertical, garland, and longline systems (Mumford, 2019). Cunningham et al. (2024) found that the chosen method influenced protein content. In 2023, Washington and Oregon collectively produced 10,432 kg of primarily Pacific Dulse (*Devaleraea mollis*), Bull Kelp (*Nereocystis luetkeana*), Sea Lettuce (*Ulva*), and Giant Kelp (*Macrocystis pyrifera*), while California produced 144,242 kg from five longline farms and six land-based farms. The economic viability of longline farms in these states remains limited (Donovan, 2025). In Washington, Mumford (2019) identified Sugar Kelp (*Saccharina latissima*) among other cultivated seaweeds. These farms rely on nutrient inputs from riverine transport or upwelling to support kelp growth (Whiting et al., 2020). However, the longevity of seaweed-based materials, such as ropes, is dependent on variable ambient conditions (Arantzamendi et al., 2023).

Current seaweed farming infrastructure includes various materials. Pacific Sea Farms utilizes steel anchors, chains, connections, and an aluminum spreader, while buoys, lines, and totes for collection are plastic (Spranger, pers. comm.). Vashon Kelp Forest anticipates supplementing some plastic lines and buoys with steel buoys upon operationalization (Kollins, pers. comm.). Alternatives such as hemp lines for kelp aquaculture

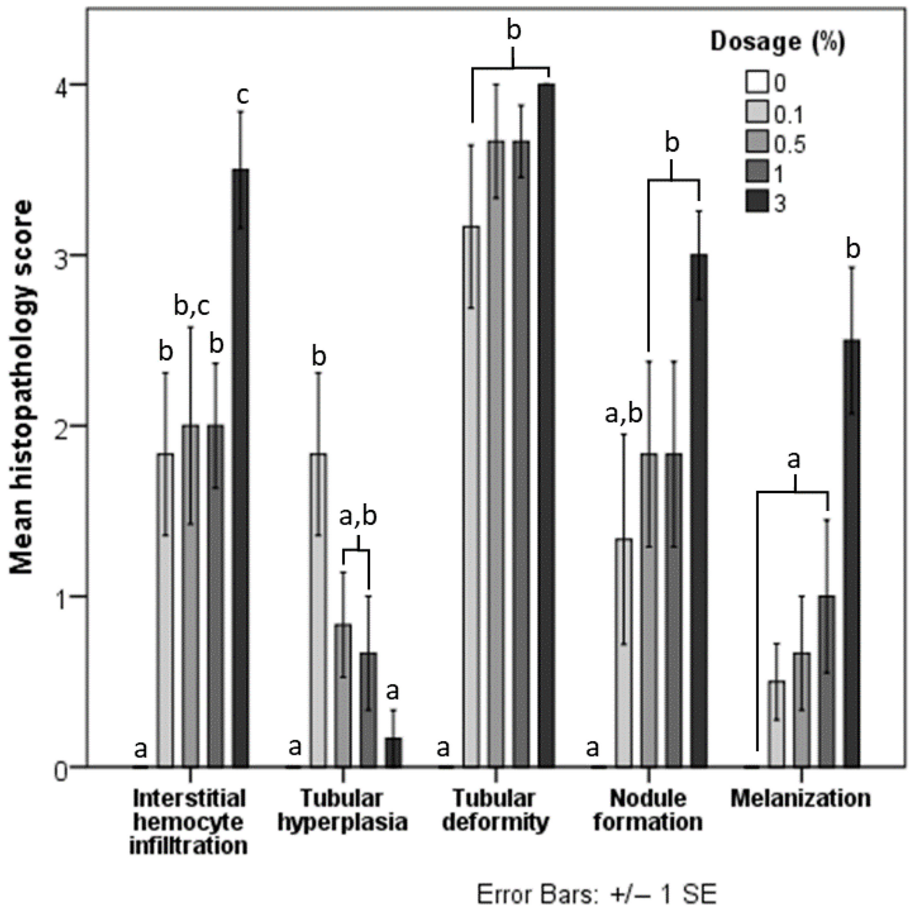

FIGURE 7
Mean histopathological score of each lesion in shrimp fed with five different doses of HDPE microplastics, representing a percent of a daily food ration. One daily food ration was 4% of shrimp total body weight. Different letters (a, b, and c) above bars of the same series indicate significant differences in the mean histopathological score between the different doses ($p < 0.05$). Reprinted under an open access Creative Commons Attribution (CC BY) license from Niemcharoen et al. (2022).

and water-resistant plant-based materials for totes may also be viable substitutes for plastic. While biodegradable materials are often proposed as a solution to plastic pollution, the potential for regrettable substitutes remains a concern. They also are still capable of breakdown into micro and nanoplastics, and in some cases exert adverse effects on biota (Hutton et al., 2024). Although seaweed-based plastics may serve as an alternative, their true biodegradability in the marine environment and their potential risks to sensitive species have not yet been studied in laboratory settings and require further investigation.

Known and suspected impacts

Impact on soil ecosystems

The potential impact of microplastics and their smaller counterparts, nanoplastics, on soil ecosystems is wide-ranging and concerning (Figure 8). MPs in soil are susceptible to photograph- and biodegradation causing them to release and adsorb plastic-associated chemicals (Vithanage et al., 2021). They can also alter soil pH and subsequently cause changes to soil organic matter content, changing the ratio of carbon to nitrogen C:N (Boots et al., 2019; Zhang et al., 2021). MNPs have varying effects on microbial biomass (Qi et al., 2022), however their presence in soil decreases biodiversity in soil microbial communities in a dose-dependent manner (Qi et al., 2022). Laboratory studies also demonstrate that nanoplastics may be taken up by crops such as lettuce, wheat, and rice, and these particles tend to accumulate in roots (Khalid et al., 2023). MPs reduced growth in strawberries (LDPE), rice (mulch film, PE), cotton root (PE, PP), and common bean roots/shoots (LDPE, PLA) (Meng et al., 2020; Liu et al., 2023; Pinto-Poblete et al., 2023).

Microplastic toxicity and impacts to bioavailability

At agricultural sites, MNP pollution originates primarily from mulch films, compost, and biosolid applications. Mulch films, widely used since the 1950s, are the most common source, followed by biosolids (Huang et al., 2020; Sa'adu and Farsang, 2023b). Farms with long-term mulch and biosolid use exhibit higher soil MNP concentrations, ranging from negligible to 1.27 × 107 particles/kg (Shi et al., 2024). Agricultural soils contain diverse polymers, including PE, PVC, PP, PET, PES, LDPE, HDPE, and PA (Huang et al., 2019; Sa'adu and Farsang, 2023b; Qiu et al., 2024). Most

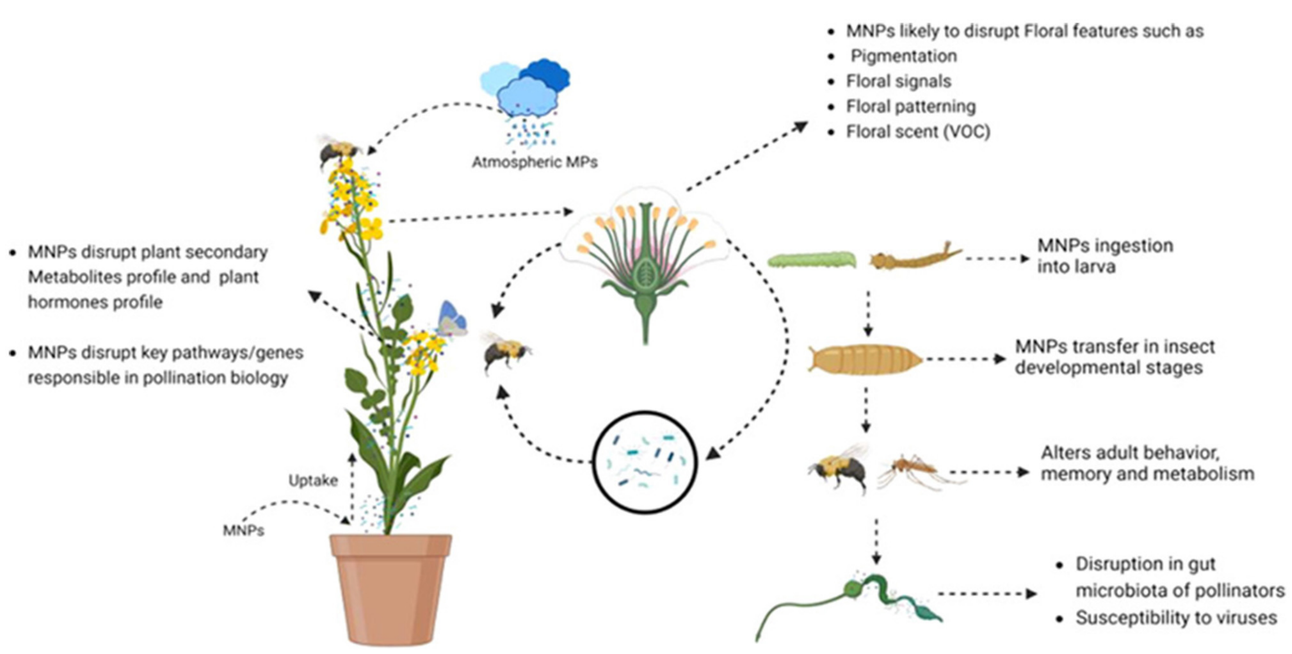

FIGURE 8
Overview of MNPs on pollination biology and plant–pollinator interactions. Plant exposure to MNPs shows growth retardation and morphological abnormalities in different tissues. Molecular profile of plant exposed to MNPs, which disrupt plant secondary metabolites and plant hormones that play key roles in pollination and pollinator attraction. Key genes and enzymes responsible for maintaining floral features such as pigmentation, floral signals, and producing or emitting volatile organic compounds (VOCs) are disrupted with MNPs exposure. MNPs negatively affect pollinator body size and disrupt the pollination process by altering pollinator behavior, memory, and metabolism. Reprinted with permission from ACS Publications, Shah et al. (2023).

studies focus on topsoil (0–30 cm), with limited research on deeper layers or groundwater contamination. In Europe, where biosolid use is extensive and regulated by heavy metal limits (Council Directive 86/278/EEC), MNP concentrations are higher (Gianico et al., 2021). In the U.S., biosolids are regulated under the Clean Water Act (40 CFR Part 503), but unclassified pollutants may still be applied due to regulatory gaps. MNP movement in soil is influenced by size and shape. Nanoplastics (1 nm to 1 μm) exhibit colloidal behavior, allowing them to migrate through porous soil matrices. Microplastics (1 μm to 5 mm) can also travel through soil, aided by earthworm activity, which transports smaller particles deeper and coats burrow walls with MPs (Rillig et al., 2017). A study in Chinese agricultural fields with 30 years of mulch film use found higher microplastic concentrations at deeper soil layers (Meng et al., 2020). Another study demonstrated that MPs measuring 0.05–0.25 mm accounted for 82% of total particles, with fibers as the dominant shape (86% of samples) (Zhang and Liu, 2018).

MNP bioaccumulation is difficult to quantify as traditional bioconcentration and biomagnification concepts rely on octanol/water partition coefficients, which do not apply to nanoparticles. Beneficial organisms such as earthworms are one of the more obvious concerns in terms of impacts. Plastic types including PLA, PE, and PS decrease earthworm survival, growth, and fitness, and LDPE aged, alone, and in combination with commonly used herbicides causes oxidative stress and changes in gene expression (Boots et al., 2019, Figure 9). Earthworms in soil spiked with tire particles showed significant increases in heavy metals—Zn, Pb, or Cd. These increases corresponded with increases in ingestion of smaller particles (Sheng et al., 2021). In the smallest size fraction, superoxide dismutase (SOD) significantly increased after both 14 and 28 days. SODs are enzymes that act as a first line of defense against reactive oxygen species (Song et al., 2009), so a decrease in SODs may have adverse effects on earthworms. Additionally, soil in this study did not increase in metals, likely due to the uptake by the earthworms. Tire wear particles (TWPs) have been found to impact some soil microbes and may further affect soil communities and ecosystems (Mayer et al., 2024).

Plant uptake through root systems raises concerns about trophic transfer. Abdolahpur Monikh et al. (2022) demonstrated NP movement from contaminated soil through a food chain involving lettuce (*Lactuca sativa*), black soldier fly larvae (*Hermetia illucens*), and roach fish (*Rutilus rutilus*). No acute toxicity was observed, but trophic transfer throughout this experimental food web was documented. Transfer of NPs to fish suggests they could also be transferred to terrestrial consumers, potentially including humans. Further research on lettuce by demonstrated that polystyrene nanoparticles could alter root metabolism and cause oxidative stress. These subtle yet potentially highly consequential responses are deeply concerning. MNPs can sorb chemicals, metals, and biomolecules depending on polymer type, size, and environmental conditions such as salinity and pH (Cui et al., 2023; Torres et al., 2021; Tourinho et al., 2019). The "Trojan horse effect" suggests MNPs act as carriers, releasing contaminants under changing conditions. Some studies indicate MNPs exacerbate toxicity (Horton et al., 2018; Peng et al., 2024), while others suggest they reduce bioavailability. This has been specifically demonstrated with mulch, which is demonstrated to fragment into smaller pieces,

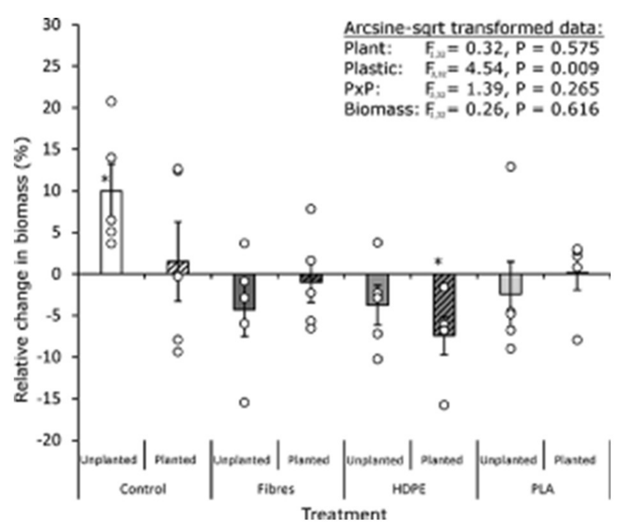

FIGURE 9
Relative change in biomass (%) of *A. rosea* after 30 days of exposure to different microplastics with *L. perenne* absent (unplanted: open bars) or present (planted: hashed bars). Data are means (±SEM, $n = 5$) and the superimposed circles represent the raw data. Included are results of an ANCOVA with initial biomass ("biomass") as a covariable; "P × P" is the interaction term between plant and plastic. *indicates a significant difference from zero change at $\alpha = 0.05$ based on a t-test (H_0: initial−final = 0%). Reprinted with permission from ACS Publications, Boots et al. (2019).

is extremely difficult to recover once mixed in with soil, and can both accumulate and release contaminants while in some cases lowering crop productivity and resulting in trophic transfer throughout the surrounding terrestrial food web (Khalid et al., 2023).

MNP exposures are complex and may result in physical or molecular effects caused by both the particle and associated chemicals. In terms of ingestion concerns, a study on mice co-exposed to PS MPs and Pb(II) found altered gut permeability and metabolism only in the co-exposure group (Shen et al., 2024). In an *in vitro* digestion model, different polymers released chemicals into simulated digestion fluids, with environmental samples showing the highest contaminant levels (Peters et al., 2022). Both inorganic and organic chemicals associated with plastics breaking down from agricultural products are a challenge. MNPs can influence metal bioavailability. PS MPs in soil reduced Cu2+ adsorption by blocking active sites and increased desorption through ion exchange and electrostatic interactions, enhancing its mobility and toxicity (Peng et al., 2024). In metal-contaminated soils, earthworms exposed to MPs had higher tissue metal concentrations and gene expression and enzyme activity associated with oxidative stress compared to metal-only exposures (Li M. et al., 2021). PCBs, a legacy contaminant that is still highly persistent in the environment, exhibited reduced bioaccumulation in earthworms when sorbed to LDPE MPs, with smaller MPs further decreasing uptake due to higher surface area (Velzeboer et al., 2014). PCB preference for MNPs over soil/sediment has been previously noted. Highly water soluble chemicals like thiamethoxam, a neonicotinoid insecticide, and tetracycline, an antibiotic, showed altered soil sorption in the presence of MPs, with some studies indicating reduced bioavailability (Hu et al., 2023; Ma et al., 2020). These findings have implications for pesticide efficacy, soil toxicity, and pollutant leaching into watersheds. MNP present in crop soils may alter pesticide efficacy by changing their bioavailability through several different mechanisms. One mechanism for altering bioavailability is direct sorption of the chemicals/pesticides to MNPs, as MNPs can act as a sink for many types of chemicals. Alternatively, hydrophobic MNPs may drive water soluble chemicals out of the soil pore water, further preventing them from interacting with their target organisms. MNPs may also agglomerate within or with soil particles, potentially blocking or altering the movement of water and chemicals through the soil, again preventing the pesticide or chemical from interacting with their target organism as expected. MNPs in soil creates a complex mixture that is difficult to understand and hard to replicate in the lab. Studies focusing on the toxicity of MNP mixtures will be important to predicting the impacts of agricultural soils polluted with MNPs to crop production as altered bioavailability could increase disease risk, crop injury, and yield loss, further highlighting the need for further research into MNP-chemical interactions in terrestrial systems.

Nano-encapsulated chemicals

Nano-encapsulated pesticides and fertilizers are another class of materials that contribute a small, but impactful, portion of plastic pollution to the environment, specifically to agricultural soils. These materials are formulated, or engineered, to be in the size ranges of other nanomaterials (<1,000 and 1> nm). Nano-encapsulated pesticides and fertilizer can be made from multiple types of materials including lipids, inorganics or clay-based materials, and are not exclusively made from conventional plastics (Nuruzzaman et al., 2016). Encapsulated nano-carriers are polymer-based nanomaterials that are formulated in one of four designs: nanocapsule, nanospheres, micelles or nanogels. These nanocarrier designs help disperse the active ingredients in various ways via controlled release of the active ingredients (A.I.), which are most often pesticides or fertilizers. The purpose of nanoencapsulation is to increase solubility, stability, dispersal, permeability, prolonged release (or slow release), increase bioavailability and reduced overall amount of A.I. application, among others (Kookana et al., 2014; Nuruzzaman et al., 2016). Multiple studies have shown the benefit of these nano-carriers with increases in agricultural yields while lowering the amount of overall pesticide used during application and the bonus of lowered toxic impacts to non-target species (Chaud et al., 2021; Grillo et al., 2021). However, the long-term impact and persistence of the leftover nanoplastic carriers after the release of the A.I.'s is not well-documented due to inherent complications of quantifying nanomaterials in the natural environment (Lead et al., 2018; Grillo et al., 2021). There is concern about nanomaterial applications since the designs for nanocarriers are intended to increase A.I. solubility and dispersion within the soil, ultimately leading to greater dispersion and solubility of nanoplastic materials (Lead et al., 2018). The current methods we have for assessing risks of conventional pesticides are not suitable for nanopesticides (Kookana et al., 2014) since these methods rely on chemical characterization based on sorption coefficients that nanomaterials inherently do not abide by (Lead et al., 2018). Overall, there is great concern for the environmental fate of these mobility-enhanced nanoplastics with A.I.'s, emphasizing the need to study their long-term environmental fate and toxicological impacts. This leads to the conclusion that nanomaterials must be designed and engineered with care and caution, to mitigate potential unforeseen negative effects long after their initial application.

Impact of plastics on soil microorganisms and agriculture

The microbiome plays a crucial role in agricultural and aquaculture systems, contributing to nutrient cycling, mineral weathering, and ecosystem stability (Philippot et al., 2024). Soil microbial communities drive nitrogen fixation, organic matter decomposition, and plant growth promotion, with nitrogen-fixing bacteria such as *Rhizobia* spp. and *Azospirillum* spp. converting atmospheric nitrogen into bioavailable forms (Fukami et al., 2018). In aquatic systems, microbes regulate water quality and nutrient cycles, supporting aquaculture operations (Alaa et al., 2023). Within these environments, plastic materials, whether or not purposely introduced, have been observed to serve as novel habitats for a myriad of organisms, scaling from micro to macro in size. Collectively these organisms and their ecological interactions constitute a dynamic global inter-kingdom assemblage referred to as the plastisphere (Zettler et al., 2013). The microbiome of marine plastic debris and aquaculture-associated plastics host a diverse assortment of taxa and function compared to ambient seawater (Zettler et al., 2013; Li C. et al., 2021; Singleton et al., 2023). Largely dominated by heterotrophic cosmopolitan bacteria (e.g., α-proteobacteria, Flavobacteriia, γ-proteobacteria), autotrophs (e.g., bacillariophyta, cyanobacteria) and various eukaryotic organisms (e.g., ciliates). Plastisphere communities, whether within freshwater or marine systems, are often enriched in functional traits related to pathogenicity, hydrocarbon degradation, cellulolysis, aromatic degradation, and saprotrophic activities. However, in contrast, freshwater plastic-associated microbiomes exhibit low complexity and high competitive ecosystem interactions (Li C. et al., 2021).

Although plastics can serve as a colonizable surface for some bacteria capable of overcoming hydrophobic surface properties, multiple reports have described plastic waste and/or residues to impact microbial dynamics, impacting species diversity and enzyme activity (Wang et al., 2023; Li C. et al., 2021; Zhang et al., 2021; Zhu et al., 2022, Figure 10). For instance, soil microplastic pollution can introduce selective pressures that favor plastic-degrading microbes and alter soil characteristics such as water retention, aeration, and heavy metal availability (Gkoutselis et al., 2021; Zhu et al., 2022). In Pb-contaminated sandy loam, microplastic amendments affected pH, microbial composition, and enzymatic activity, with certain bacterial orders enriched or suppressed based on polymer type (Feng et al., 2022). Plastic film mulching improves crop yield through moisture retention and weed suppression but alters soil porosity and aeration. Microplastics clog soil pores, reducing drainage and air exchange, while mesoplastics minimize these effects but still transport toxic chemicals (Ryan et al., 1988; Mato et al., 2001; Teuten et al., 2007; Li et al., 2014). These changes can impact microbial nutrient cycling and water retention (Feng et al., 2022; Fu et al., 2023). Plastic residues in soil can influence nitrogen cycling, with polypropylene (PP) increasing total nitrogen and polyphenol oxidase activity, while polyethylene (PE) has no significant effect (Fu et al., 2023; Liu et al., 2017). Plastics may also alter microbial community structure, with mixed effects on plant growth depending on bacterial, fungal, and protistan changes (Huo et al., 2022; Ranauda et al., 2024), although other findings suggest plastic contamination shifts microbial composition without directly impairing plant growth (de Souza Machado et al., 2019). The extent of these effects depends on soil conditions, plastic type, and particle size (Huo et al., 2022).

Microplastics disrupt microbial communities through structural changes, toxic additive release, and pollutant sorption (Fu et al., 2023). Factors such as crystallinity, hydrophilicity, and molecular weight determine plastic-microbe interactions, potentially displacing beneficial microbes crucial for biogeochemical cycling (de Souza Machado et al., 2019; Huo et al., 2022). Plastisphere communities often exhibit reduced diversity, favoring plastic-associated microbes over native species (Aralappanavar et al., 2024). Biodegradable plastics like polylactic acid (PLA) can enrich fungal taxa such as *Aspergillus*, *Fusarium*, and *Penicillium*, altering mycorrhizal interactions (Zhou et al., 2023). Like synthetic plastics, bioplastics release hazardous additives and sorbed pollutants during degradation (Hahladakis et al., 2018; Huo et al., 2022).

Plastic exposure often upregulates hydrolase and oxidase enzymes, affecting organic matter decomposition and nitrogen cycling. Urease, catalase, and phosphatase activities shift based on polymer type, with PA, PAN, and polyaramide increasing biogeochemically active nitrogen availability (de Souza Machado et al., 2019). PLA at 2% w/w enhances urease and phosphatase activity in sandy loam (Feng et al., 2022), while polystyrenpe nanoparticles suppress key nitrogen- and phosphorus-cycle enzymes (Awet et al., 2018). PP increases fluorescein diacetate hydrolase (FDAse) activity, whereas PE and PVC inhibit FDAse while stimulating urease and phosphatase activity (Wang et al., 2020; Fei et al., 2020; Wang et al., 2022). Differences in soil enzyme response may stem from polymer size, manufacturing additives, and treatment conditions. Plasticizers such as dibutyl phthalate (DBP) also affect nitrogen cycling. In a 60-day mesocosm study, DBP increased ammonium and reduced nitrate levels by shifting microbial nitrogen metabolism. Phthalate-containing PVC altered nitrogen-fixation and urea decomposition gene abundance, while plasticizer-free PVC had no effect, indicating DBP as the primary driver of observed changes (Zhu et al., 2022). These findings highlight the complex interactions between plastics, microbial communities, and soil health, underscoring the need for further research into long-term ecosystem impacts.

Plastic vectors for pollutant and pathogen transport

Depending on the environment in which plastic particles are deposited, plastics and associated biological agents can facilitate the migration of POPs and other micropollutants. Abiotic aging (or weathering) of plastics (UV-irradiation, thermal oxidation, oxo-oxidation, etc.) influence the adsorption and desorption

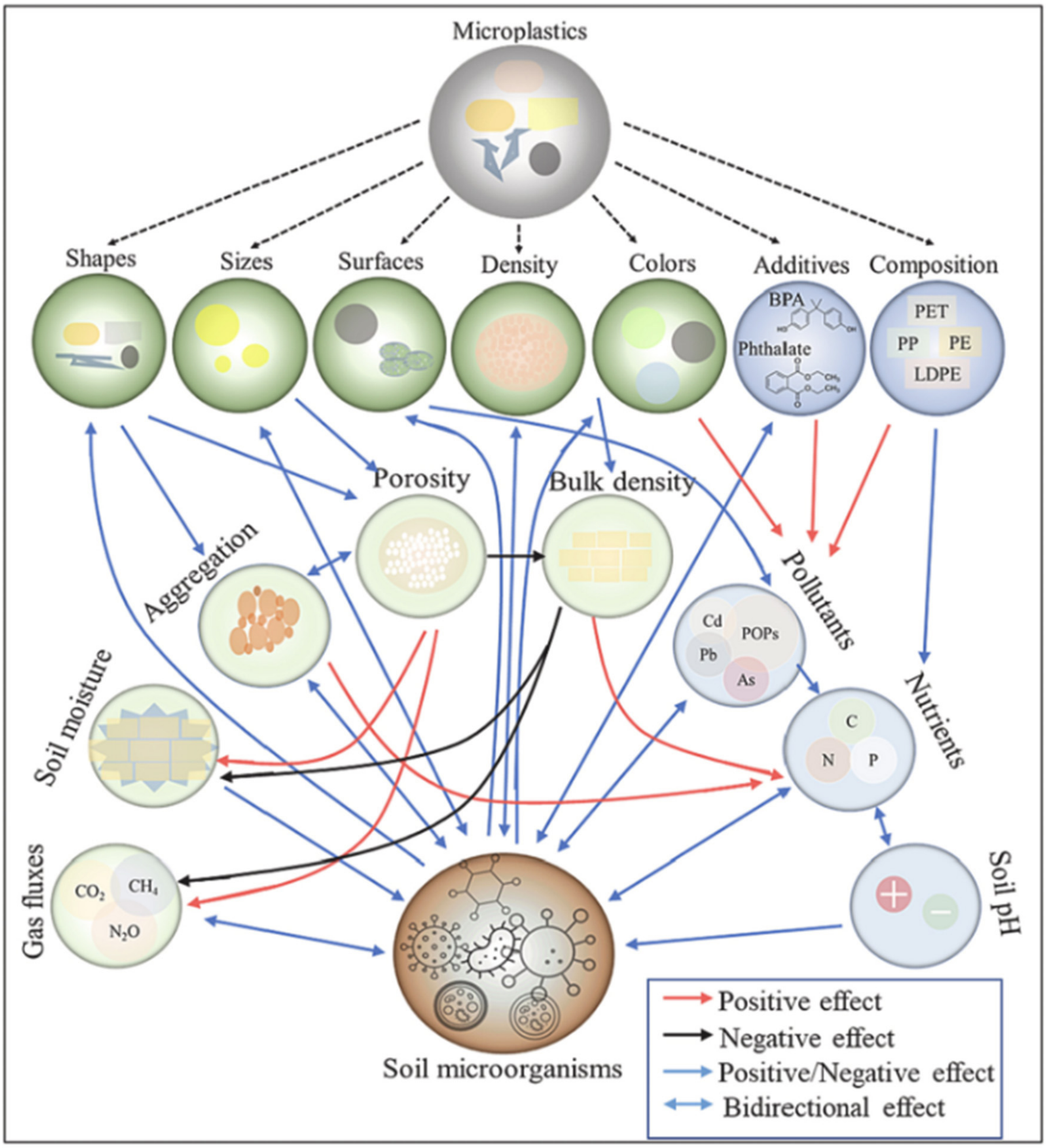

FIGURE 10
Potential mechanisms of interaction between MPs (gray circles) and microorganisms (brown circles) in the context of soil properties. Dark green and light green circles illustrate the physical properties of MPs and soil, respectively, while dark blue and light blue bubbles depict their chemical properties. Reprinted with permission under a Creative Commons CC-BY license from Aralappanavar et al. (2024).

of hydrophobic chemicals and potentially hazardous pollutants. While monitoring the chemical release of two synthetic (PVC, PET) and one biodegradable plastic (PBAT) immersed in natural seawater over ~1.5 years, Kedzierski et al. (2018) observed differential changes in the release of chemicals from the plastic polymers and their estrogenic activities. Although methanolic extracts of the three polymers did not elicit significant cytotoxic effects, significant estrogenic activity was observed in extracts obtained from two of the three polymers. Notably, estrogenic activity of PVC increased over time from 4.5% to 14.0% (14 to 63 days) and later declined. It is inferred that the increase in estrogenic activity is associated with the migration of polymer estrogenic compounds into the surrounding seawater as the plastic ages and the polymer structure degrades.

Once a chemical is plastic-sorbed in the soil or floating in the marine system, it may not remain permanently bound to the plastic (Ryan et al., 1988; Teuten et al., 2007). Biofouling of plastic materials has been observed to promote the absorption (or desorption) of various plastic-associated chemicals, whether by biofilm-forming bacteria or within the gut of macrofauna (e.g., polychaete worms) (Mukherjee et al., 2018). This is due to the production of biosurfactants and bioemulsifiers which increase the bioaccessibility of the soil, sediment, and plastic-bound compounds leading to increased chemical desorption into the surrounding soil or seawater (Teuten et al., 2007; Sachdev and Cameotra, 2013). An investigation by Wang et al. (2020) detailed this interaction through the assessment of copper ions (Cu^{2+}) and tetracycline (TC) co-absorption on virgin and biofouled PE. These chemicals often occur in agricultural soil from the use of copper-based pesticides and tetracycline-containing animal feed. In the soil, their interaction can impact the other's bioavailability leading to concerns of environmental contamination and the development of antibiotic resistance (Song et al., 2017). The development of biofilms on the surface of synthetic MP have been observed to influence adsorption properties of the plastic resulting in enhanced chemical adsorption of metal-ion containing compounds (Xu et al., 2018; Wang et al., 2020). The presence of microbial biofilms can enhance Cu-TC co-absorption and later desorption. Insights into microbial community disruptions aid in the assessment of risk related to the support of native microbial functions, agricultural soil health, and aquaculture water quality, highlighting the importance of microbiome-informed approaches in agriculture and soil/aquatic remediation efforts.

Among temporally abundant cosmopolitan bacteria and eukaryotes, exist rare plastic degrading species as well as an assortment of commensal opportunistic fungal and bacterial pathogens of human, aquaculture, agricultural relevance (e.g., *Vibrio* spp., *Aeromonas* spp., Phoma-like filamentous fungi and cryptococcal yeast) (Viršek et al., 2017; Gkoutselis et al., 2021; Singleton et al., 2023). In terrestrial systems, plastics disposed in landfills or other municipal areas have been observed to select for distinct fungal members which include a variety of plant and animal pathogens (Gkoutselis et al., 2021). In the marine system, buoyant plastics (e.g., PE, PP, PA, and PET) and their microbial hitchhikers, undergo indiscriminate dispersal by local and large-scale oceanic circulation, driven by surface currents and gyre systems (Hoseini and Bond, 2022). Greater insight into the abundance and persistence of pathogenic plastic-associated representatives and plastic transport research over the past decade have sparked debates concerning human, aquaculture, and ecosystem health (Viršek et al., 2017; Bowley et al., 2021). Moving forward, pathogenicity of abundant aquaculture-plastic colonizers and of plastic-associated pathogen transport on aquaculture systems should be further studied to support risk mitigation and comprehensive planning efforts in aquaculture.

Pollinators

The impacts of plastics on pollinators have been best studied in honey bees, mostly *Apis mellifer*a (the European honey bee). MPs have been found in 100% of sampled *Apis mellifera* hives studied in Copenhagen, Denmark (Edo and Fernández-Alba, 2020), São Paulo, Brazil (Rodrigues et al., 2024), Lima, Peru (Iannacone et al., 2024), the Campania region of Southern Italy (Schiano et al., 2024), and Gualaceo Canton, Ecuador (Arévalo et al., 2024), although the majority of MPs in honey bee hives likely originated from clothing, rather than agricultural plastics. A study of Finnish bumblebees found MPs on 78% of bees sampled (Helli, 2024). Unlike on honey bees, the most common MPs on bumblebees' bodies were plastic types used in agriculture, including PEs (52%) and PPs (33%) (Helli, 2024).

MPs reach *Apis mellifera* brains 3 days after oral ingestion (Pasquini et al., 2024) and ultimately affect learning, memory, and responsiveness to food stimuli (Balzani et al., 2022; Pasquini et al., 2024, Figure 11). Honey bees exposed to MPs experience oxidative stress and have altered gut microbiomes (Wang et al., 2022), reduced feeding rates, which reduces body size (Al Naggar et al., 2024), and are more susceptible to viral infections (Deng et al., 2021). Increased susceptibility to viral infections, in association with MP exposure, was also found in *Apis cerana* (the Asian honey bee, Deng et al., 2021). One additional study on *Apis cerana* found that bees fed sucrose with high concentrations of MP (50 mg/L of 100 nm diameter MPs) had impaired development of pharyngeal glands, which are critical to successfully provisioning larval brood cells with protein (Xue et al., 2025).

Because they are eusocial, the impacts of MPs on honey bees may not be comparable to impacts on other pollinators which are solitary, but these reports are still concerning given their importance as pollinators. Eusocial species exhibit reproductive division of labor that includes a sterile worker caste. In this social system, the loss of a few workers has little effect on overall colony health (Straub et al., 2015), which is why honey bees likely have a higher level of resilience to environmental toxins than other bees (Sgolastra et al., 2019). But more than 75% of bee species are solitary (Danforth et al., 2019), where a single female is responsible for building and maintaining a nest, foraging for pollen and nectar, provisioning brood cells, and producing offspring.To date, only a single study examined the impact of microplastics on a solitary bee, *Osmia cornifrons* (a solitary, cavity-nesting bee that caps brood cells with mud), exposed to one of three soil treatments: no MP, 0.5 g MP/kg soil, or 4.0 g MP/kg soil (Lin et al., 2024). Researchers found no effect of MP on measures of bee reproductive success (e.g., brood cell number, cocoon number, or number of daughters produced in the F1 generation), although there was a downward trend (Lin et al., 2024). However, Pasquini et al. (2024, Figure 11) observed that the response to sucrose was hindered by some plastics types, such as PMMA and polystyrene. More research is clearly needed in this area to determine what impacts microplastics may have on insects important to agricultural success.

Non-target aquatic organisms

Plastic usage from agriculture and aquaculture not only impact the systems they are used in but also contribute to plastic pollution in environmental systems. The majority of plastic debris, including MNPs, is overwhelmingly linked to terrestrial sources (Lassen et al., 2015). Stormwater and runoff carry debris from land to aquatic ecosystems, inadvertently exposing them and the organisms within them to plastic pollution. MNPs have been found in every ocean basin and in over 1,300 terrestrial and aquatic species globally (Bergmann, 2015). In the PNW, MPs have been detected in ecologically, culturally, and commercially valuable species such as marine amphipods, bivalves, gray whales, and in the edible tissues of Chinook salmon, lingcod, black rockfish, pink shrimp, Pacific herring, and Pacific lamprey (Baechler et al., 2020; Torres et al., 2023; Traylor et al., 2024).

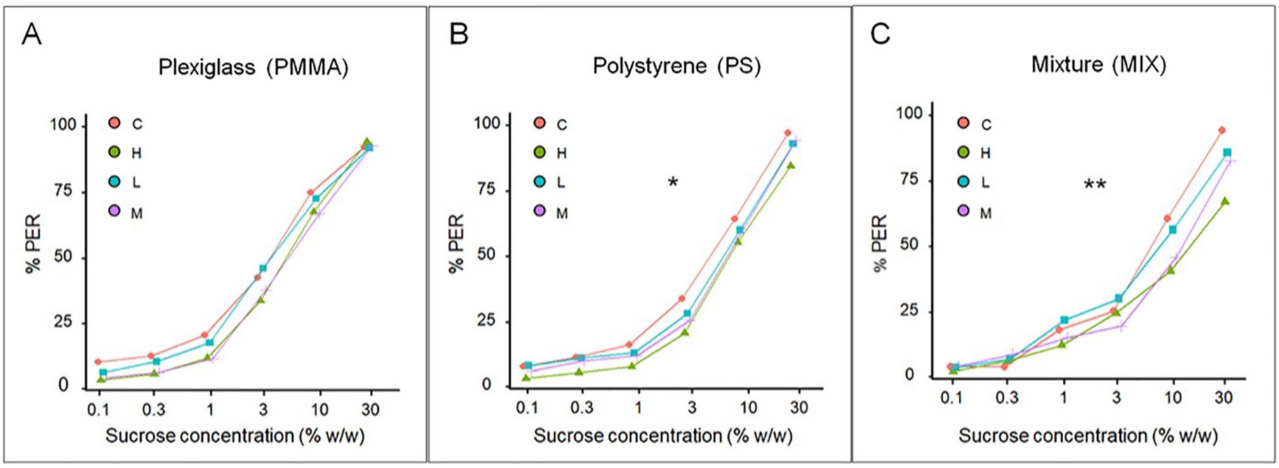

FIGURE 11
Effect of MPs microparticles on sucrose responsiveness in honey bees. Cumulative percentages of bees exposed to different concentration of MPs (High (H) = green, Low (L) = blue, and Medium (M) = purple line) and control bees (C = red line) showing PER to six sucrose solutions of increasing concentration. **(A)** Sucrose responsiveness of PMMA-treated bees was not affected compared to the control group, in all concentrations tested. **(B)** PS treatment affects sucrose responsiveness compared to control as the highest dose tends to reduce it. **(C)** MIX treatment significantly affects the performance of bees for both the high dose and the medium dose but not for the low dose. (*) $p < 0.05$; (**) $p < 0.001$. Reprinted with permission under a Creative Commons CC-BY license from Pasquini et al. (2024).

Though it is difficult to link MPs to a specific source and research on the impact of agricultural plastics on aquatic organisms is limited, laboratory studies identify numerous impacts of MNPs on aquatic organisms. Small schooling fishes and invertebrates are vital primary and secondary consumers in estuarine and marine ecosystems, acting as prey to salmonids and gray whales. *In vitro*, MP/NP exposure studies have found that PVC particles affect cell viability and redox homeostasis in fish cells (Espinosa et al., 2018). Laboratory studies on EPA test species: schooling fish inland silversides (*Menidia beryllina*) and invertebrate mysid shrimp (*Americamysis bahia*), identified effects of MNP exposures. After 7-day exposure to polyester or cotton, *A. bahia* and *M. beryllina* exhibit altered behavior with *M. beryllina* also exhibiting anxiety-like behaviors after a 21-day exposure to PLA or polyester microfibers. Individuals exposed to micro and nano PLA particles and polyester microfibers had differential gene expression related to muscle function and sensory detection, respectively (Hutton et al., 2024). Micro and nano tire particles also impacted growth and behavior in two indicator species, *M. beryllina* and *Americamysis bahia* (Siddiqui et al., 2022), with implications for predator-prey interactions in the natural environment. In *Daphnia magna*, tire particles from 12 tires were tested and all were found to have toxic effects after 24 h and even greater effects after 48 h. UV-exposed TWPs increased toxicity 10-fold in 4 of the tested tires (Wik and Dave, 2005). In the environment, microparticles are also known to biofoul and can act as a vector for viruses/bacteria. In the lab, rainbow trout co-exposed to microplastics/microfibers and a virus had significantly increased mortality compared to those exposed to either single stressor alone (Seeley et al., 2023).

The effects of MPs range from physiological, such as oxidative stress and growth, to mortality having implications for MP-exposed populations in the natural environment. The taxa used in these studies are often used as indicators of their aquatic environment indicating the ecological and economic implications of plastics exposure in these ecosystems.

Livestock

Animals and animal products are an essential part of the United States economy, contributing $271.6 billion in 2024 [United States Department of Agriculture (USDA), 2024]. Livestock is considered the "missing link" between microplastic contamination and human health (Figure 12). Though to the best of our knowledge there is no specific literature on the occurrence of microplastics in livestock in the United States, various routes of exposure and studies from other countries indicate the presence of particles. Livestock are exposed to plastic pollution via ground water, soil, crops, and feed. Cow and sheep contain an average of 0.14 and 0.13 MP items/g of edible meat, with edible cow meat containing 0.19 items/g (Bahrani et al., 2024, Figure 12) similar to amounts found in some edible shellfish and fish tissue (Baechler et al., 2020; Traylor et al., 2024).

Livestock may be at particular risk of adverse effects of MNP pollution due to the various routes of exposure, and ruminants in particular, may have increased risk of affects due to their complex digestive systems (CITE). Chicken exposed to polyethylene microplastics can suffer from growth, metabolism, and antioxidant capacity effects (Li et al., 2023) Chicken meat quality and neural function can be impacted by microplastic exposures (Chen et al., 2023). In mammals, lambs exposed to polystyrene suffered damaged digestive systems resulting in decreased daily growth and lamb meat quality/nutrition (Chang et al., 2024). MPs have also been shown to impact neural function in pigs exposed to PET (Gałecka and Całka, 2024; Tassone et al., 2024).

Though there are few studies *in vivo* for microplastics and livestock, *in vitro* studies using mammalian tissue provide further

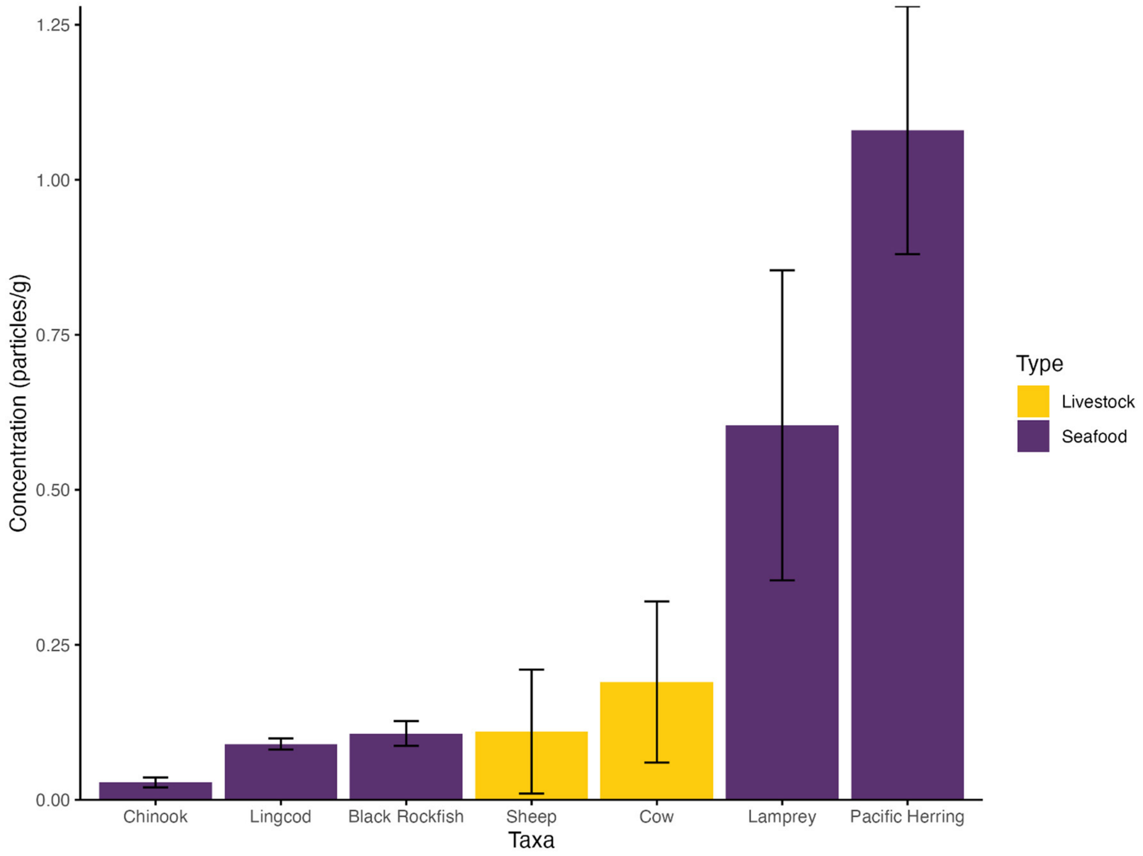

FIGURE 12
Mean concentration of MP particles in the seafood edible tissues compared to that meat from cow and sheep. Error bars indicate standard deviation (SD). Original figure using data from Bahrani et al. (2024) and Traylor et al. (2024).

insight into how mammalian livestock may be impacted in the future. MPs and NPs have also been found to impact cellular function in several ways. They reduce viability in human and mice cells in a concentration- and size-dependent manner, with smaller NPs having higher toxicity levels (Xu, 2003; Chen et al., 2017; Banerjee and Lee Shelver, 2021). NPs may reduce cell viability mechanically, via membrane disruption, or physiologically, by inducing oxidative stress or immune response (Banerjee and Lee Shelver, 2021).

Policy needs and the way forward

In 2023, the state of Washington introduced the Compost Reimbursement Program (CRP) to incentivize local farmers to use compost purchased from selected commercial facilities. The program prioritizes compost containing food waste feedstock and incorporates data collection through a Crop & Field Survey and soil sample analysis by the Washington State Department of Agriculture to evaluate four soil health criteria. This incentive, covering up to 50% of qualifying costs, appeals particularly to smaller farms that depend on subsidies to offset expenses. However, selected compost providers favoring food waste feedstock cannot guarantee material free from micro and nanoplastics (MNPs). This contamination arises from agricultural practices, such as using landscape fabric and plastic as weed barriers, which degrade into smaller particles over time. Farmers may also leave drip irrigation lines on the ground during winter, drained to prevent expansion damage. If post-harvest remains are sent to larger composting facilities, any contamination in the feedstock persists.

Larger farms often retrieve drip lines mechanically, but this process can damage the lines and leave plastic residue in the soil. To recycle these lines, they must be unearthed, a process that can be labor-intensive or involve machinery that risks further contamination. Drip lines, typically around 400 feet in length, require meticulous handling, making proper removal costly. Furthermore, the scarcity of recycling facilities in Oregon exacerbates the challenges of managing plastic waste, as degraded materials often remain onsite and break down into smaller debris (Vendries et al., 2020; Mistry et al., 2018). Additionally, commercial composting facilities frequently receive consumer-generated waste, including "compostable" takeaway containers that do not meet the criteria for healthy composting. Consequently, these materials may end up in compost used by farmers participating in programs like CRP. According to McKinsey and Company (2024), a McKinsey & Company report highlights that sustainable practices are increasingly adopted in North America to achieve higher yields. Among U.S.-based respondents, practices such as crop rotation (87%), variable rate fertilization (56%), and reduced or no tilling (78%) are common regenerative agriculture methods. Avoiding tilling minimizes the risk of plastic fragmentation and enables more effective removal of these materials.

The transition toward increased use of plastics, coupled with technological advancements such as lighter and cheaper greenhouse structures, benefits agricultural production (Scarascia-Mugnozza et al., 2012). However, disposal, reuse, and recycling remain challenging. Soil-contact plastics, such as mulch films, are particularly problematic for recycling due to residue soil contamination, leading to landfill disposal (Empson et al., 2021). While mechanical recycling is the most environmentally favorable option, inadequate infrastructure, economic constraints, and the high cost of cleaning soil-contaminated plastics pose significant barriers (Empson et al., 2021). Additionally, a large portion of plastic waste—estimated at 70% in 2023—remains uncollected, ending up in landfills, being openly burned, or leaking into the environment (Berger et al., 2023).

Many agricultural plastics require high quantities of raw materials. Currently, no recycled agricultural plastic waste is used for mulch films, greenhouses, and nets, despite the feasibility of incorporating at least 25% recycled content in most agricultural plastic products (FAO, 2024). Recognizing the environmental impact of agricultural plastics, there is growing interest in alternatives that do not rely on fossil fuels or synthetic polymers and that biodegrade over time (FAO, 2024). However, concerns remain regarding the longevity, cost-effectiveness, and large-scale availability of these alternatives, necessitating further research and life cycle assessments (Empson et al., 2021). Efforts are also underway to modify agricultural plastics to extend their lifespan and improve their potential for reuse and recycling. This applies particularly to products such as greenhouse covers, mulch films, irrigation drip tape, tree guards and shelters, ear tags, insulated fish crates and boxes, and bale films and nets (FAO, 2024). A 2021 comprehensive qualitative risk assessment identified polymer-coated fertilizers, pesticide containers, and mulching films as high-priority targets for sustainability improvements (FAO, 2021). Employing the 6R framework (refuse, redesign, reduce, reuse, recycle, recover), the assessment proposed alternatives and interventions for these products while emphasizing the need for context-specific solutions (FAO, 2021).

Outlook for biodegradation

Options for alternative materials in terms of bio-based plastics, as mentioned above, are somewhat limited due to rules governing particular types of farms (e.g., National Organic Program) and the expense of these newer materials. Additionally, these products are not necessarily safer, with such challenges already demonstrated in aquatic organisms (Hutton et al., 2024). For example, Vendries et al. (2020) call attention to the material attributes biobased, compostable and biodegradable, for much confusion exists about these terms and the implied end of use treatment. Biobased only describes the inputs or feedstock being sourced from plants, renewable agricultural, marine, and forestry materials. Feedstock by itself does not produce the desired attributes of compostability or biodegradation. For example, the common polymer mulch polyethylene (PE) can be sourced from both fossil and biobased feedstocks, with the final finished PE film performing identically, and neither are compostable or biodegradable. In compost and in soil they merely fragment into ever smaller particles (i.e., MNP). Further, not all biobased materials are 100% biobased. PE is a good example of blended feedstock used to lower the embodied carbon content.

Compostable plastic materials are those that have the potential to break down via biological processes to yield CO_2, water, inorganic compounds, and biomass. Such products generally cannot be composted in a backyard setting. Likewise, not all biobased materials are compostable, though many compostable materials are biobased. Therefore, not all biobased plastics are biodegradable. Figure 13 illustrates a comparison of life cycle impacts of different bio-derived and conventional polymers used in packaging. It reveals no clear ecological advantage through the full life cycle of the materials. However, feedstock substitution from fossil to bio-sources for the same polymer (e.g., fossil PE vs. bio-derived PE) offers advantage for GWP and simultaneously reveals burden shifting to other impact categories including ecotoxicity, human toxicity, eutrophication and land use (Vendries et al., 2020). It is therefore prudent to assess material substitution through a life cycle perspective that goes beyond basic carbon footprinting and including metrics relevant to agriculture. Results from this meta-review indicate that, as a rule, relying on any one attribute as a design or procurement parameter to achieve environmentally preferable outcomes is not scientifically supported (Vendries et al., 2020). Bio-based and synthetic plastics offer similar benefits in preserving soil moisture, regulating local soil temperatures, enabling drip irrigation and fertigation, and eliminating weeds. The bio-based polymers are less affordable due to limited supply and commercial adoption (Maraveas, 2020). Furthermore, although starch-based biodegradable mulches are potentially more sustainable than those made from traditional PE, uncertainties remain about their residence time and their effects on soil, crop and organism health (Dada et al., 2025). Given that recommendations regarding the global plastics treaty are centered around source (plastics) reduction and chemical simplification (Brander et al., 2024), it would be most beneficial for farmers and aquaculturists to revert to non-plastic materials where possible, especially given that prior to the 1960s and 70s, most food was produced without single-use plastics and the myriad of products relied upon today.

State and federal lawmakers (e.g., Deb Patterson, US Senator Jeff Merkley) support more sustainable practices, with preliminary data suggesting that switching to low-carbon-footprint materials may not significantly increase costs. Research in Mount Vernon, Washington, found that cellulosic-paper mulch improved soil conditions compared to polyethylene (PE) film mulch. PE mulching increased soil temperature, altering microbial activity, while soil-biodegradable plastics initially performed similarly but disintegrated over the season (Sintim et al., 2021). Paper mulch effectively inhibited light penetration for weed control but required structural integrity to increase its durability (Sintim et al., 2019). Biodegradable plastic mulches degraded faster in compost than in soil, making composting a preferable disposal method for these films in cooler climates (Sintim et al., 2020).

Rates and the extent of fragmentation and biodegradation of mulch varies across different climates, and the toxicity of

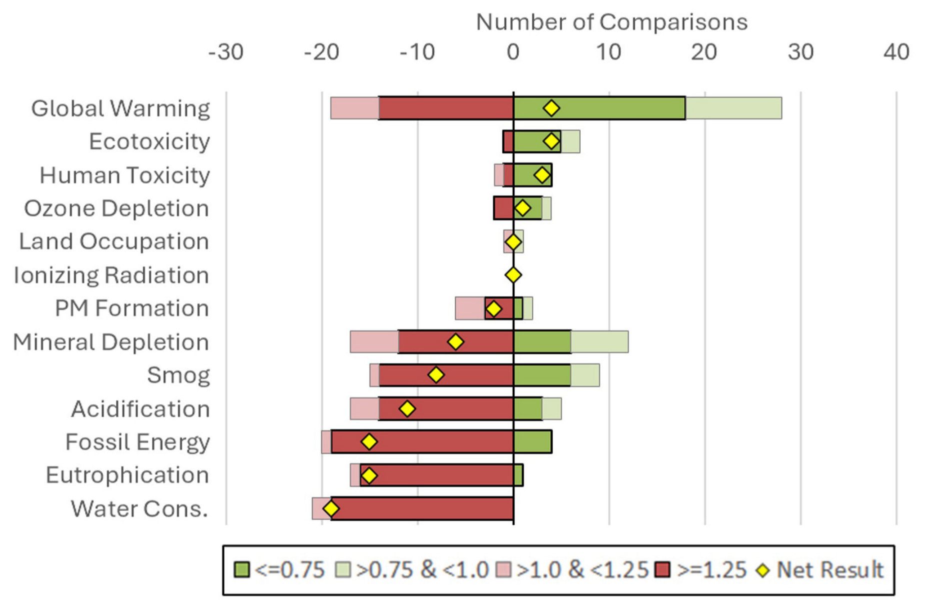

FIGURE 13
Comparisons of biobased packaging to conventional packaging of a different polymer. Reprinted with permission from ACS Publications, Vendries et al. (2020).

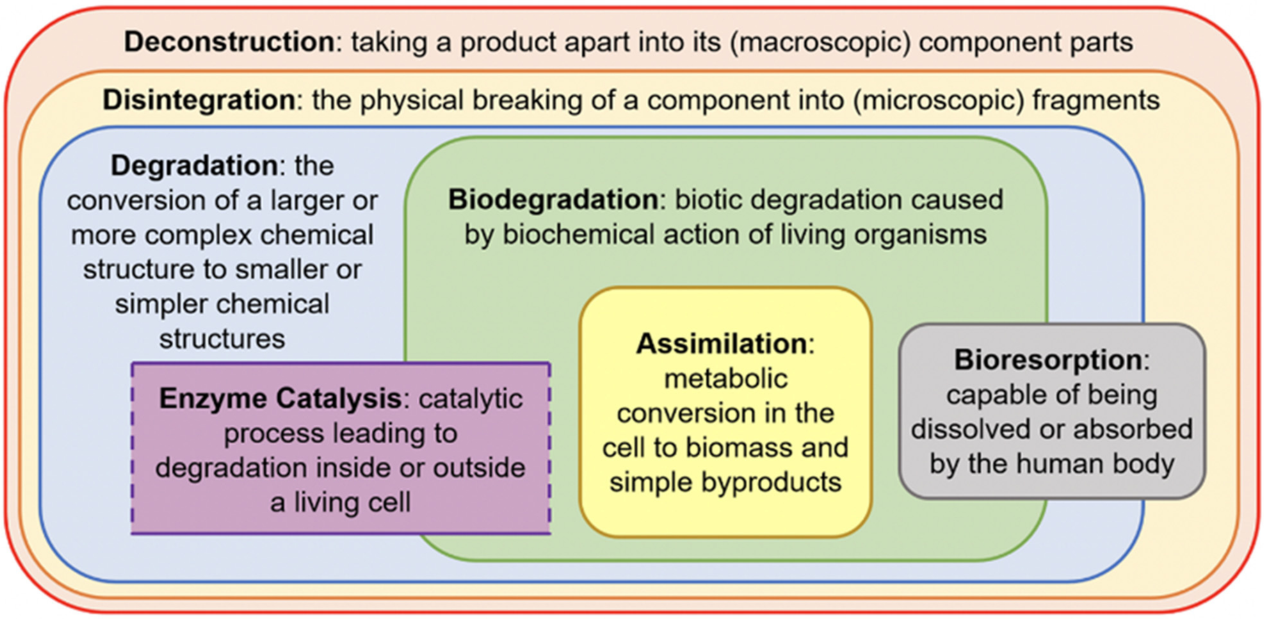

FIGURE 14
Cascade of transformations involved in deconstruction and degradation. Reprinted under a Creative Commons license from Egan and Salmon (2021).

these materials before and during breakdown is largely unknown. Studies indicate that field-weathered BDMs have stronger negative effects on plant development than pristine ones (Serrano-Ruiz et al., 2023). The issue parallels plastic microbeads in personal care products—initially valued for convenience but later recognized as environmental pollutants. Precaution is warranted, as biodegradable polymers may degrade unpredictably outside controlled conditions (Sintim and Flury, 2017). Both fossil- and bio-derived plastic mulches impact the environment through their life cycles. Life cycle assessments (LCA) compare environmental impacts, showing that while PE film has a better environmental profile than alternatives, it accelerates soil organic carbon decomposition and greenhouse gas emissions (Dong et al., 2022). However, there are issues with traditional LCA approaches because they are skewed toward costs associated with stages earlier in the plastics life cycle such as production and shipping costs (e.g., weight of the material) rather than weighing in longer term impacts such as fragmentation (Gontard et al., 2022). Recycling is preferable but often impractical due to soil contamination, making managed landfilling potentially more environmentally sound. Some studies suggest compostable plastics exhibit better environmental outcomes in landfills than in composting facilities due to incomplete degradation under composting conditions (Vendries et al., 2020; Chamas et al., 2020).

While often spoken of as a binary characteristic, the potential for any substance (both natural or synthetic) to biodegrade is a product of two critical factors: (1) the physical and chemical properties of the substance, and (2) the environmental conditions in which the substance is found (Sommer, 2024). Egan and Salmon (2021) describe the "biological cascade" of both physical and chemical changes that are necessary to achieve complete biodegradation, which is the breakdown of organic molecules into carbon, water and salts, and conversion to biomass (Figure 14). Many materials may physically disintegrate but never biodegrade due to either environmental conditions or chemical structure or both. Common plastics in agriculture such as polyethylene and PVC are examples.

Frequent trade-offs between non-biodegradable plastics and potentially biodegradable alternatives have been mentioned above. Due to the very likely disintegration (but not necessarily biodegradation) of most polymers used in agricultural applications, a preference for biodegradable rather than non-biodegradable polymers is logical. Yet important questions remain about the impact of biodegradable polymers relative to their non-biodegradable counterparts. There is evidence (mentioned in the previous text) of toxicity associated with both biodegradable and non-biodegradable polymers possibly due to the hazards of the materials themselves and likely due to the additives and treatments applied to them. The precise causes of toxicity associated with MNPs from both biodegradable and non-biodegradable polymers is rarely understood, and therefore further toxicity testing is warranted to begin to design for lower impact polymers and materials. Comparative toxicity testing and a thorough understanding of the chemical content of tested materials is critical to providing such actionable information. Further, changes to the way toxicity studies are reported and conducted would enable meta-analysis and clearer conclusions to be drawn from existing data (Thornton Hampton et al., 2022).

In short, while biodegradability is an important feature for materials used in environmentally dispersive applications—such as terrestrial and aquatic agriculture—it does not, on its own, eliminate the risk of toxicity. Therefore, thorough testing of both biodegradable and non-biodegradable polymers is necessary before large-scale use, in order to prevent regrettable substitutions.

Recycling

The lack of available recycling facilities that accept common farm-use plastics, or that would accept bio-based options, has made it extremely difficult for farmers to manage excess, damaged, or seasonal plastic waste. For many farms under 99 acres in Oregon, it is common practice to leave drip tape in the ground year-round, replacing it only when it is damaged, rather than seasonally (Ahmadaali et al., 2016). The flexibility of the material allows the drip lines to withstand low temperatures, making them impervious to frost or freezing, even when small volumes of water remain inside.

Farmers frequently remove PVC-based accessories, such as ball valves and other rigid components, due to PVC's vulnerability to breakage in cold conditions. In contrast, drip lines are retained for extended periods because of their durability and resistance to freezing temperatures. Some companies provide looped recycling services, supplying high-density polyethylene (HDPE) crates to farms while also accepting damaged brand-specific crates for recycling. One such company has adopted a first-right-of-refusal policy, which allows existing customers to purchase recycled crates for non-edible item handling. This cost-efficient approach promotes waste reduction and sustainability, enabling farms to enhance operational efficiency through the reuse of recycled materials.

Statewide, plastic materials constitute a small fraction of Oregon's overall material recovery efforts. In 2022, plastics accounted for just 2% of the total recovered materials, with the majority being metals (28.5%), yard debris (25.2%), and cardboard (19.1%) (Hefferan, 2024)[3]. This indicates that while agricultural plastics contribute to waste, they represent a minor portion of the state's recycling stream. To address the broader challenges of plastic waste management, Oregon enacted the Plastic Pollution and Recycling Modernization Act (RMA) in 2021, set to take effect on July 1, 2025. This legislation aims to overhaul the state's recycling system by introducing producer responsibility programs, standardizing recycling practices, and ensuring that collected plastics are processed in environmentally responsible ways. These measures are expected to enhance the efficiency of recycling programs and reduce the environmental footprint of plastic waste, including that generated by agricultural activities (Environment Oregon, 2023). Notwithstanding this effort, said act will focus on packaging for consumer products rather than those specific materials in farm production that this paper addresses.

While post-use plastic recovery from farms is a desirable aspiration, it is important to not draw too many material management parallels from the region's solid waste management practices that are typically organized to recover residential and business generated waste. On farm generated plastic waste comes with a very different waste profile as described herein, much of it is embedded with soil and is in various stages of physical deterioration. Both conditions in turn affect the material's secondary uses. Policies that take into consideration these unique characteristics, as well as field trials and appropriate recovery infrastructure need to be part of the dialogue both regionally and nationally. Examples such as the European Union's Plastic Strategy and China's ban on different uses and types of plastic are important models. Yet, they represent national and multinational agreement. Such agreement is lacking in the USA and represents a significant deficit for unified plastic materials management in the USA. Opportunities may exist in the form of regional cooperative agreement, and advocacy for parallel legislation modeled after the RMA in Oregon tailored for on farm applications.

3 Resource Recycling. https://resource-recycling.com/plastics/author/marissa/ (Accessed March, 2025).

Conclusion

While the use of plastics in agriculture and aquaculture was once hailed as a revolutionary advancement, it has now resulted in a cycle of waste that provides few viable options for sustainable recycling or responsible disposal. In summary, although plastics have played a crucial role in enhancing the productivity and efficiency of agriculture and aquaculture, the environmental and health hazards associated with agri- and aquacultural plastic use, waste, and resultant microplastics (MPs) are not fully understood, particularly in U.S, including productive regions of the country such as the Pacific Northwest. Microplastics present a unique and dynamic challenge to agricultural and aquaculture systems. Microplastics (MPs) and nanoplastics (NPs) have significant and detrimental effects on soil ecosystems, including alterations to soil pH, impacts on organic matter content, and reductions in biodiversity among microbial communities. Studies have even indicated that MNPs present in soil can be taken up by a variety of crops, accumulate in their roots, and negatively affect plant growth. Efforts are greatly needed to reduce the pollution of agricultural sites from the use of mulch films, compost, and biosolids, as well as other practices such as the use of encapsulated pesticides and fertilizers.

Additionally, plastics can act as vectors for pollutants and pathogens, depending on their deposition. Plastics not only affect agricultural organisms but pollute the entire terrestrial food web, hence the need for policies and altenative pathways. The increasing dependence on plastics in the U.S. Pacific Northwest and other food producing regions in the U.S., raises concerns about food contamination and pollution in both terrestrial and aquatic environments. This region uniquely recognizes the need to transform and modernize its waste management systems, including those of agricultural and aquacultural plastics. For example, a report by the Center for Sustainable Infrastructure outlines a path to create tens of thousands of environmentally-focused jobs across the region by 2040 through waste management and recycling infrastructure advancements. This transformation aims to balance environmental sustainability with economic growth, potentially offsetting some costs associated with plastic pollution (Roth and Mazza, 2020).

Efforts to understand and mitigate the environmental impacts of agricultural plastic waste are gaining international momentum, exemplified by the European Union's (EU) MINAGRIS project, which investigates the sources, environmental fate, and soil impacts of micro and nano plastics (MNP) in agriculture in 11 countries (MINAGRIS, 2023). Both the EU and Japan classify agricultural plastics waste as industrial waste, placing responsibility for proper collection and disposal on producers or farmers under EPR systems (European CAP Network, 2023; Ministry of the Environment Japan, 2022). Future international collaboration, guided by the eventual Global Plastics Treaty (Stöfen-O'Brien, 2022; Brander et al., 2024; Dignac et al., 2025), could focus on coordinated waste classification standards, investment in biodegradable or circular plastic alternatives, and cross-border research platforms to assess soil contamination and remediation. Such alignment would support global sustainability goals while enabling coordinated responses to the rising challenge of plastics pollution in agriculture (He et al., 2018; Sa'adu and Farsang, 2023b). Addressing these challenges requires a holistic strategy that can include improved management practices, the creation of truly sustainable plastic alternatives, and efficient recycling systems to reduce the environmental effects of plastic usage in food production systems. It is imperative to note that recycling is not an all-encompassing solution. It can be a step toward addressing some of the challenges we have to grapple with regarding plastics in the food industry. Ultimately there is a need to limit the use of plastics in agriculture, especially as this category of plastics contributes up to 5% of global plastic production, with predictions of large increases if business as usual continues. The continued reliance on plastics without clear strategies for circularity or reduced production underscores the urgent need for research and policy interventions in a manner that the benefits of plasticulture do not compromise long-term environmental health and sustainability at a planetary scale.

Author contributions

SB: Writing – review & editing, Software, Investigation, Conceptualization, Writing – original draft, Supervision, Funding acquisition, Visualization. GL: Investigation, Writing – original draft, Visualization, Conceptualization, Writing – review & editing. MM: Writing – review & editing, Conceptualization, Writing – original draft, Investigation. SS: Conceptualization, Investigation, Writing – review & editing, Visualization, Writing – original draft. MH: Visualization, Writing – original draft, Conceptualization, Investigation, Writing – review & editing. LK: Formal analysis, Investigation, Writing – review & editing, Visualization, Writing – original draft, Conceptualization. KA: Writing – review & editing, Investigation, Writing – original draft. EG: Visualization, Writing – review & editing, Writing – original draft, Conceptualization, Investigation. KB: Writing – review & editing, Writing – original draft. RP: Conceptualization, Writing – review & editing, Writing – original draft. NC: Visualization, Writing – review & editing, Conceptualization, Writing – original draft. HT: Writing – original draft, Writing – review & editing, Conceptualization, Visualization. LS: Writing – original draft, Conceptualization, Visualization, Writing – review & editing. SH: Conceptualization, Funding acquisition, Writing – review & editing, Writing – original draft. GT: Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by Oregon State University Research Advancement Academy provided support to SB for the Farm to Table Workshop held in September 2024 that resulted in the generation of this manuscript.

Acknowledgments

We would like to thank all of the attendees at the September 2024 Plastics from Farm to Table workshop held in Portland, OR, USA, who contributed valuable ideas and discussions that led to the writing of this manuscript.

Conflict of interest

NC and HT were employed by Zero Waste Washington. LS was employed by Libby Sommer LLC.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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