

# Microplastics and Agricultural Production: Process, Economic Implications, and Solutions

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## ABSTRACT

Microplastics (MPs) are an emerging agricultural contaminant with wide-ranging biological, environmental, and economic consequences. This review analyzes MPs impacts on soil health, plant health, and crop yields. In addition, this review assesses direct economic costs of MPs attributed to reduced productivity and hence lowered profitability. It was found that costs of remediation often have staggering prices that smaller farms, especially in the developing countries, may not have resources to handle. Moreover, MPs bring indirect effects related to long-term soil degradation, market rejection, and trade disruptions. These challenges may especially affect poorer and developing countries, as oftentimes agriculture holds large percentages in GDP, and is needed for national food security. As such, these countries may face disproportionate risks of increased poverty rates and food insecurity. There are several potential solutions involving plant growth regulators, biochar, conservation agriculture, and other biotechnological methods, however many of these options are offered at unaffordable prices to smaller farming systems. Current knowledge remains limited, particularly in observing long-term effects in field-scale scenarios. Future research should prioritize the integration of agronomic, ecological, and economic perspectives to provide scalable mitigation strategies that could inform effective remediation policies.

## 1. INTRODUCTION

Microplastics (MPs), defined as plastic particles smaller than five millimeters in diameter, have been shown to have detrimental environmental effects, especially in agricultural contexts. These tiny particles are composed of synthetic polymers: mainly polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) (1). Common forms include fragments, fibers, films, foams, and pellets, all typically present in people's everyday lives (2). MPs are extremely durable and degradation resistant, meaning they can survive in the environment for decades. Their small size and physical durability create easy passage into soil, water, animals, and other environmental media (3). MPs are used in a myriad of everyday items, everywhere between cosmetics and cleaning agents to synthetic fibers and tire dust, marking their presence across households around the world. Furthermore, MPs have

April 2026  
Vol 6, No 1.

unique structures characterized by high surface area-to-volume ratios, meaning they are specialized for absorption: heavy metals, pathogenic microorganisms, chemical pollutants) (4).

Broadly speaking, MPs can be classified into two types: primary and secondary (5). Primary MPs are already manufactured small for purposes that require the size to be less than 5 mm. Secondary MPs are more common and form by breakdown of larger plastics. This breakdown could be caused by humans, or natural sources such as UV light, weathering, or various mechanical forces.

MPs can enter the environment in a variety of ways. First, plastics discarded into the environment can break down into MPs through natural factors involving UV light, wind, and mechanical roughness (6). Although wastewater plants can remove approximately 90% of MPs in sludge, a significant number still make it through processing and end up in various water bodies (7). Additionally, industrial activities can produce waste that eventually leaches into the surrounding environment.

Once in the environment, MPs pose serious threats not only to natural ecosystems, but also to agricultural productivity and human health due to their persistence in environments (8). This long-lasting presence threatens further breakdown into harmful chemicals and can also cause other environmental related problems such as disruption to plant and animal health. Additionally, even if MPs end up in landfills, their prolonged lifespan can mean higher chances of leakages into the surrounding ecosystems, possibly even to humans.

Recent studies have shown that human ingestion of MPs can trigger inflammatory responses as the body's immune system recognizes these particles as invasive (9). Consequently, chronic inflammation can have cancer causing potential, further underscoring the possible detriments associated with MP contamination. The substances sorbed on MPs can also leach into tissues, creating disruptions in hormonal regulation, impairing endocrine function, and potentially contributing to long-term health issues such as reproductive disorders, developmental delays, and even certain cancers. Given that humans are at the top of the food chain, we are especially at risk for high MP concentrations due to bioaccumulation and biomagnification (10).

There are many existing studies researching different environmental and physiological effects of MPs. However, much fewer focus on the broader social and economic implications caused by MPs. To address this issue, this article proposes an analytical framework that highlights how biological and economic impacts are connected. Specifically, this article breaks down how yield losses can lead to larger effects to farmers and the global economy. Thus, this framework moves beyond a descriptive review and to a structured approach for understanding how MPs impact the broader agricultural industry.

To achieve that, this review synthesizes 69 studies published between 2010–2025 that are pertinent to MP's effect on plant health and economic implications. The databases used to identify pertinent research include Google Scholar, ResearchGate, and ScienceDirect. Searches were performed using English-language keywords, including combinations of *microplastics*, *nanoplastics*, *plant health*, *soil-plant interactions*, *nutrient uptake*, *plant physiology*, *crop yield losses*, *environmental effects*, *food*

April 2026

Vol 6. No 1.

*security, economic implication, toxicity, agricultural supply chain, and mitigation strategies.* As a result, the review largely reflects recent findings available in English-language publications.

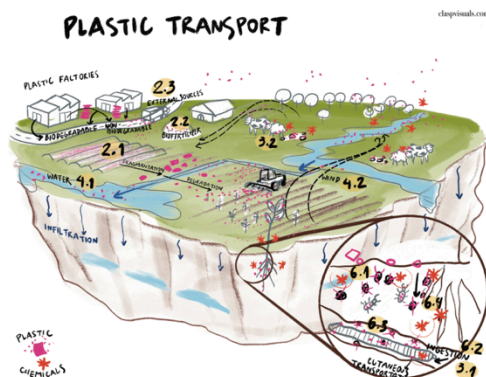
This article contributes to existing academic discussion as well as decision making in businesses and governance. The analysis discusses potential solutions and potential policy interventions, which offer suggestions on actionable plans for farmers and other stakeholders seeking to mitigate associated risks of MPs.

Accordingly, the article is organized into three main parts. First, this article presents an overview of the presence of MPs in agriculture, including uptake pathways, toxicities, and environmental effects. Next, there is an assessment of direct and indirect economic effects due to reductions in crop yield. Lastly, there is a brief review of potential solutions and policy recommendations that can be implemented to reduce the threat of MPs in agroecosystems.

## 2. ENVIRONMENTAL AND BIOLOGICAL EFFECT ON PLANT HEALTH

### 2.1 Entry Pathways of Microplastics into Agriculture

MP particles can enter and spread across the realm of agriculture in a variety of different pathways, each of which has potential to cause long lasting detriments to soil health, crop productivity and food safety overall, as seen in Figure 1. The primary pathways of MPs contamination include plastic mulch films, organic fertilizers, irrigation, and surface runoff and flooding, as further discussed below.



**Figure 1:** Schematic representation of plastic transport in agricultural ecosystems. This diagram shows how plastics move through agricultural systems. Sources include biodegradable and non-biodegradable plastics, plastic-containing fertilizers, and other external inputs (2.1–2.3). Once in the environment, plastics break down and spread through wind (4.2), water runoff (4.1), and can seep into the soil. From there, they can be taken up by plants (3.2), eaten by animals (3.1), or accumulate in soil organisms (6.1–6.3), leading to deeper soil transport and movement through the food chain (11).

#### *Plastic Mulch Films*

April 2026  
Vol 6, No 1.

Plastic mulch films (normally polyethylene) are applied extensively in agricultural contexts for weed suppression, soil temperature regulation, and moisture retention (12). However, these films are subject to degradation through ultraviolet (UV) radiation, mechanical action and microbial breakdown which consequently release MPs into the surrounding soil environments (13). Released particles remain in these ecosystems year after year, causing long-term stress to the soil and surrounding environments.

### ***Organic Fertilizers***

Organic fertilizers such as animal manure, composts, or sewage sludge can also introduce foreign MP particles into the farming and agricultural context. Livestock will commonly ingest feed that contains MPs causing their manure to also contain these particles (14). Composts are often from human sources where MPs can end up in these mixtures through a variety of urban processes. Sewage sludge represents the solid waste from wastewater treatment plants which commonly contains MPs from the incoming wastewater. All three sources are commonly used organic fertilizers, granting MPs easy access into agricultural environments.

### ***Contaminated Irrigation***

Many regions will use treated or untreated wastewater for crop irrigation especially those lacking large freshwater sources (15). Wastewater is a recognized reservoir for MPs and even if treated, a large majority can still exist and escape treatment. Even seemingly clean water can contain MPs from atmospheric and upstream contamination (16). With each irrigation cycle, contaminated water permits increasing deposition of MP particles onto agricultural crops.

### ***Surface Runoff and Flooding***

Mechanical wearing of tires has been proven as one of the largest sources of MPs to the environment (17). In addition, other urban sources can contribute to the presence of MPs in the natural world. Entry of these MP particles into the agricultural context can happen from surface runoff or flooding or regions containing these MPs, eventually ending up in agricultural farms or contaminating water used for irrigation (18).

## **2.2 Damages to Soil Environment**

MPs in the soil can have many negative effects; these include damage to the microbial community, soil fauna (animals that inhabit the soil), and various soil properties.

To the microbial community, MPs pose as serious threats as they can alter the abundance, composition and total activity of these soil communities (19). MP accumulation will often shift the soil climate to favor more of the plastic degrading microbes at the expense of plant beneficial ones. The presence of MPs can also negatively affect the enzymatic activity in microbes which is crucial to maintain a healthy soil environment (20). Furthermore, disruptions in microbial activity can lead to the soil's reduced ability to handle stress, weaken plant-microbe interactions, and impair the natural cycling of essential nutrients such as nitrogen and phosphorus.

Beyond microbes, MPs can also inhibit growth and reproduction in various soil fauna such as earthworms, nematodes, and other soil inhabitants (21). The soil fauna, organisms living in the soil, are highly important to plant life as they work in the decomposition of organic matter, nutrient cycles, and overall health (22). MPs are harmful to these organisms as their presence in the soil can induce physical blockage in digestive tracts, introduce toxic pollutants such as plasticizers and heavy metals, and inhibit reproduction (23). These damages reduce overall wellbeing of soil fauna which consequently leads to decreased plant health.

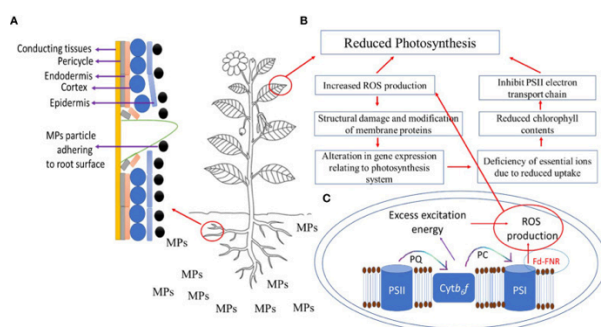
Furthermore, MPs in the soil can cause changes to soil properties including its physical structure and porosity. In terms of structure, certain types of plastic fibers can cause soil particles to irregularly bind to each other, leading to compaction or excessive fragmentation (24). These structural imbalances cause reduced soil aeration and water infiltration rates, thereby increasing the difficulty by which plants obtain oxygen and moisture. Moreover, MPs have been proven to clog soil pores, decreasing the porosity of the soil and further challenging the plant's ability to uptake oxygen, water, and other important nutrients (25).

### 2.3 Biological Effects

After MPs infiltrate the soil, they can proceed to enter the plant in many ways and once in the plant can cause physiological damage to the photosynthesis, reproduction, and vascular systems.

#### *Impacts on Photosynthesis*

MPs can impede the cellular process of photosynthesis in numerous ways (Figure 2). Inside the chloroplast—where photosynthesis happens—MPs have been proven to inhibit the activity of photosystem II (PSII) which is a key compound involved in the process of photosynthesis (26).



**Figure 2:** Mechanisms by which MPs impair plant physiology and photosynthesis. A) MPs adhered to the root surface can penetrate root tissues, disrupting cellular structures including the epidermis, cortex, endodermis, pericycle and conducting tissues. B) Once MPs reach internal plant tissue, they cause increased ROS (reactive oxygen species) that leads to not only reduced photosynthesis, but also structural damage, modification of membrane proteins, and alteration to relevant photosynthesis genetic expression. MP buildup can create a deficiency of essential ions which decreases chlorophyll contents, inhibits the electron transport chain and ultimately leads to reduced photosynthesis. C) MP-induced overproduction of

ROS creates excess excitation energy which disrupts the electron transport chain, leading to impaired energy flow in photosynthesis (27).

Studies have shown MPs, formed by polylactic acid (PLA), are culprits of reduced chlorophyll content, the specific pigment plants use in photosynthesis (28). These results were observed in maize leaves—a staple crop in many countries across the world—pointing towards the impacts of MPs on global food production (29). Similar results were also seen in photosynthetic algae, where three different species of algae experienced decreased chlorophyll levels (30). Given that photosynthetic algae are close relatives to plants, these results further point to the damaging effects of MPs on chlorophyll concentrations.

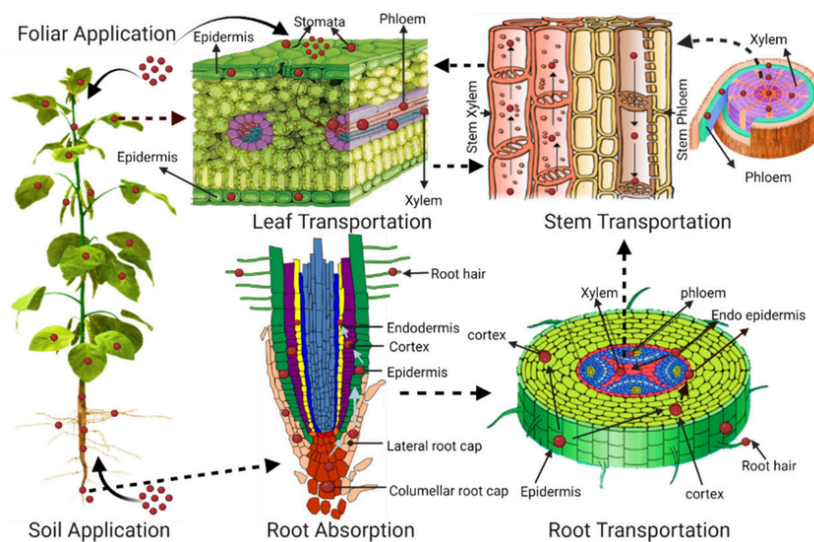
### ***Impacts on Plant Reproduction***

MP accumulation in plants can also lead to declines in germination rates and reproductive potential. Germination is the process in which a plant embryo within a seed begins to grow and develop into a seedling. Previous studies have shown significant reductions in germination rates when seeds were exposed to MPs. Specifically, three different concentrations (50, 500, and 4800 nm) of MPs were applied and consequently resulted in magnified reductions as the concentrations increased (32). Quantitatively, germination rates dropped from 78% in the control to 17% when exposed to the 4800 nm concentration. Continued presence of MPs over several days can also result in progressive clogging of pores and chemical toxicity that inhibit internal germination.

The deposition of MPs on plant surfaces carries significant consequences for reproductive potential and output in agriculture. MPs were mainly observed to inhibit reproductive potential through blockage tissue in relevant organs. This blockage resulted in decreased seed production and stymied the ability of pollen tubules to find ovaries in sexual reproduction (33). Moreover, MPs can act as vectors for heavy metals and other harmful pollutants that can stress plant tissues and possibly cause long term reproductive damage. Given that many staple crops rely on healthy reproductive cycles for evolutionary success, even minor disruptions can scale up to have global impacts.

### ***Impacts on Vascular System***

The vascular system is critical in plant physiology as it functions to transport water and vital nutrients to all parts of the plant (35). MPs have been proven to be absorbed via leaves or root and end up in the vascular system after permeation through various membranes, as shown in Figure 3 (27). Accumulation in the vascular system can eventually end up inducing blockage that inhibits the passage of water and other nutrients.



**Figure 3:** Pathways of uptake of MPs to plants and their internal transport through vascular systems. MPs and NPs are transported through different ways via the vascular system and can circulate to different tissues. These particles easily permeate through endodermic tissue, making access to the vascular system likely and expected (34).

### 3. ECONOMIC IMPLICATIONS

The disruptions caused by MPs, collectively stressing both the soil and plant health, can contribute to declines in crop yield and quality. A synthesized comparison of inferred yield loss for a variety of crop types associated with MP-induced physiological impairments is summarized in Table 1. To farmers, this impact means reduced number of crops per square unit and reduced quality of crops. At scale, the infiltration of MPs into agricultural systems poses a threat to food security, especially in regions where environmental conditions are already challenging.

Experimental MP Dose in Soil (w/w)	Typical Physiological Impairments	Yield or Biomass Impact
0.1% Polystyrene MPs	Photosynthesis: ↓~10-12%	Biomass: ↓~8-10%; (Wheat experimental observation) (36)
1% Polystyrene MPs	Photosynthesis: ↓~15-25%; Chlorophyll: ↓~10-15%; Root length/biomass: ↓~10-20%	Biomass / grain proxy: ↓~12-20%; (Wheat experimental observation) (36)

0.4% LowDensity Polyethylene or polyester MPs	Root biomass: ↓~5-10%; Shoot height: ↓~5-8%	Biomass: ↓~5-15% in some soil textures; near-neutral in others; (Winter wheat experimental observation) (37)
0.1-10% mixed aged Polystyrene, Polyethylene, Polylactic Acid MPs	Chlorophyll: ↓~5-25%	Biomass / marketable yield: ↓~5-25% with increasing MP dose; (Lettuce experimental observation) (38)
0.005-0.025% Polystyrene MPs	Root length and biomass no discernible difference	Stem biomass ↓~12.8-25.9%; (Rice field trial observation) (39)
0.1-1% various MPs	Photosynthesis & chlorophyll: ↓~7-15%; Root traits & nutrient uptake: ↓~5-20%	Yield / biomass: ↓~5-20%; (Inferred based on meta-analysis for multiple crops typically) (40)

**Table 1:** Inferred Plant Yield Reduction from MP-induced Physiological Impairments

The total economic burden caused by MPs emerges as a culmination of its direct economic effects (4.1), indirect and downstream economic effects (4.2), and long-term consequences of inaction (4.3). Together, these layers reveal a compounding threat that extends from individual farmers to global food security and economic stability.

### 3.1 Direct Economic Effects

The presence of MPs in an agricultural context not only has biological and environmental effects but also has serious economic implications. Agriculture holds a prominent role in the global economy, holding around 4-6% in global GDP (41). While this may not seem like a particularly large number, the sector is crucial to food security and poverty rates. Food security directly depends on agricultural production, meaning any disruptions could have a large impact. In many countries, including Ethiopia, Sierra Leone, and Chad, agriculture represents approximately 40-60% of GDP (42). This means these countries could experience devastating economic losses in terms of GDP if their crops were to face productivity reductions due to MPs.

Moreover, in lower income countries, food represents large portions of income and sometimes may represent all or even more than earned income. This can easily lead to vicious cycles, where the presence of MPs causes economic losses, which depletes funding and resources that could be used to address the issue. Consequently, some areas could find themselves in negative feedback loops driven by MP-contamination. Negative changes to agricultural productivity and development can create a myriad of economic problems down the road.

However, agricultural development is also known as a powerful tool to reduce poverty rates. Out of any economic sector, growth in the agricultural sector has been shown to be 2-3 times more effective than any other sector in reducing poverty rates. This is because the food system produces millions of jobs whether on farms or throughout the supply chain. In Sub-Saharan Africa, economic growth from agriculture is 11 times more effective in mitigating severe poverty than any other sector (43).

Broadly speaking, MPs in agriculture can exacerbate income inequality, especially among poorer countries. Citizens of poorer countries spend higher portions of income on food. Studies have found that consumers in Nigeria, Kenya, and Burma spent over 50% of total expenditures on food, with more in the 30% and 40% range (44). For reference, higher income countries such as the United States, United Kingdom and Canada were found to have less than 10% spent on food. This is because poorer countries have less to spend, and since food spending is largely constant independent of income, larger shares are devoted to food when income is lower. Consequently, if MPs cause declines in crop yield, prices will rise, meaning many consumers will have to spend even more on food. While this may be insignificant to countries such as the US, UK or Canada, citizens of poorer countries may experience increased poverty rates as food spending must increase.

Unlike other known stressors such as harmful insects or natural disasters, MPs are a relatively novel threat meaning the full range of their damages remains not fully understood. For American farmers, as well as those globally, reductions in crop yield exacerbated by presence of MPs can have immediate and severe effects that can cascade towards larger economic problems.

It is important to break down how decreased crop yields translate into economic losses for farms. In the US, most field crop producers only earn modest profits after accounting for input costs. An assumed prolonged decline in yield due to MP contamination, even at the lower bound of projected estimates (4-10% per season), could quickly snowball into greater effects and turn marginally profitable years into sustained losses. The income loss is not merely theoretical, though; each percentage drop in yield lowers the physical crop output. Unless market prices rise enough to compensate, farmers almost always will incur higher costs and take home less.

Moreover, typical safety nets for agricultural risk, such as crop insurance or government programs, rarely address MP-related yield reductions. This gap leaves agricultural producers especially vulnerable. A single poor yield year can result in greater issues than just output numbers. Farmers must spend more to bring yield rates up, often at the expense of crucial investments or cut back on labor and technology use. In fact, severe cases may result in drastic increases in borrowing, and with more farmers deepening in debt, the chances increase for bankruptcy and may cause large decreases and shortages throughout the entire industry.

For an individual farmer, the effects of stresses caused by MPs can be staggering, especially when alternative options can be too expensive. Large commercial sized farms can more easily write off a bad year, as profit margins are much larger and can take harsher losses than individual farmers. In addition,

large scale production may invest in soil monitoring and filtration in attempts to alleviate MP related maladies.

Developing countries face even harsher economic consequences given that yield losses can exacerbate situations where food is already scarce. Families could face food shortages and MPs can pose a serious threat to food security. This adds yet another reason to drive up prices in developing countries, effectively leaving households less income to spend on health or education. Consequently, households face increased risk of falling into poverty, creating negative cycles of food security and economic instability.

The accumulative nature of MPs presents another issue because of their persistence in the environment. The costs needed for remediation, as for now, remain very high, whether by chemical, biological, or mechanical means. Funds dedicated to cleaning up pollution are even more limited in developing countries, adding to the economic hardship.

Thus, the challenge posed by MPs to agricultural yields and farmer economics is urgent and multi-layered. Although quantifying total monetary losses remains difficult due to the variability of local conditions, converging studies all point toward a scenario where declining yields threaten broader economic and food system stability.

The decreases in crop yield associated with plant impairments by MPs have been correlated to losses in economic value in terms of US dollars. An economic study (45) found that rice, wheat, maize, tomato, and pea plants could contribute to up to 12.72 billion dollars in yearly losses. For comparison, other studies examined how crops grown in Brazil were affected by insect pests and found that yearly economic losses totaled 12 billion US dollars (46). In addition, crops in India were shown to experience an 11 billion US dollar yearly decrease due to weeds (47). These numbers are significant because they show that economic losses due to MPs are rising and in fact may be more damaging than some other factors. It shows that MP contamination is a topic that is becoming increasingly prevalent, as shown in the economic losses. Moreover, research on MPs has only been around for a few years, meaning economic effects could be even more staggering than what is already found.

Furthermore, MPs could have even more associated costs if money is spent for cleanup purposes. Unlike most contaminants, once MPs are in plant organs or the soil, it can be extremely hard to filter out. Due to their ubiquitous nature, it is equally as hard to prevent MPs from entering agriculture. For instance, filtering MPs out of drinking water could have costs up to thousands of dollars, meaning large-scale filtration of irrigation systems could be overwhelming to many farmers (48). In addition, soil remediation in the form of fungi or bacteria can have staggering costs, with prices ranging from a couple hundred dollars to a couple thousand dollars (49). The use of alternative plastics designed for safer breakdown are usually more expensive, and costs many farmers are not willing to spend on.

From a different angle, costs spent on remediation and cleanup is money and resources that could be allocated towards other aspects in the agricultural industry. For instance, resources could be allocated into

technological research, empowering advancements in the field of smart agriculture. Development of novel agricultural technologies can promote growth and prosperity, while also moving society forward.

In sum, MPs cause direct economic pressures on agriculture by lowering crop productivity, diminishing profitability, and introducing possible costly remediation challenges. While these immediate impacts already demonstrate a significant burden on farmers and agricultural systems, the presence of MPs in agriculture carry indirect costs and broader implications in the economy.

### **3.2 Indirect Economic Effects**

After agricultural products leave farms, MP contamination can have more downstream effects. First, food processors would have to pay more for raw imports, meaning increased prices across the entire market for both supply chain firms and consumers down the line. Furthermore, if there is enough awareness about the harms MPs can bring to humans, it is possible that products known to be MP-free could gain a competitive edge, especially to consumers who already engage in buying healthy, organic food. In addition, costs might rise if MPs are recognized as a systemic agricultural threat, meaning farms could face insurance or risk management costs in attempts to eliminate detrimental effects from MPs.

In turn, these effects could create a multiplier effect. Essentially, a loss at the farm level could magnify through the supply chain, creating larger effects when these problems carry throughout the economy. This suggests that even small amounts of contamination from MPs can snowball into a greater effect. As a result, it makes mitigation strategies even harder, knowing there is no way to truly eradicate contamination of MPs in agriculture, especially at a commercial scale.

From a macroeconomic scope, nations worldwide could experience reductions in trade supply of their staple crops. Reductions in staple crop food supply could mean a strained export pool, ultimately resulting in harms to foreign trade (50). In terms of food security, countries that heavily rely on imports could face consequences of decreased exports from trade partners. According to the USDA's Economic Research Service, even small reductions in staple crops such as rice and wheat can lead to spikes in world prices (livestock ingested MPs through sources outside of eating contaminated plants, their manure is commonly used as a "natural" fertilizer, meaning another contamination source of MPs in agriculture. Second, the consumption of livestock and poultry could mean that MPs are transferred from these animals to humans, which was proved in a 2024 study conducted by Jeong et al (53). Bioaccumulation is where a toxic chemical (including MPs) is absorbed or ingested at a faster rate than it is broken down or excreted. Inconveniently, MPs have shown to be incredibly hard to digest, and excretion of MPs is much too slow to stop the process of bioaccumulation (54). The substance accumulates in the organism's tissue and through biomagnification—where the concentrations of toxins increase as it travels up the food chain—can pose significant threats to human health.

### **3.3 Long Term Costs of Inaction**

While immediate economic impacts are significant, failing to address or consider long term implications could have potentially far greater consequences. Because MPs accumulate in soils, remediation becomes progressively more expensive the longer it is delayed. Persistence and accumulation can also decrease the long-term land value, as soil structure degrades and the soil slowly experiences declines in fertility. Furthermore, it is possible that governments could implement policies that require stricter practices and can incur further costs in the future. Thus, proactive mitigation today could reduce the risk of exponential cost escalation in the future.

#### **4. POTENTIAL SOLUTIONS AND POLICY INTERVENTIONS**

As seen in prior sections, MPs are a significant threat to agroecosystems, inflicting both physiological and economic stress through reduced crop quality and yield amount. This means that addressing this problem requires an approach that combines multiple practices and techniques. Developing countries, who are already more susceptible to damages because of greater reliance on agriculture, face additional barriers that come in the form of staggering costs of implementation. As a result, solutions must be accessible, sustainable, and effective for widespread mitigation.

First, one of the more straightforward strategies is the adoption of biodegradable and environmentally friendly alternatives to conventional plastics. Plastic mulches are widely used in agriculture to conserve moisture and suppress weed growth. However, they introduce plastics that could be broken down over time into the soil, contributing substantially to MP pollution. Biodegradable mulches, on the other hand, can have the benefits of decomposition without introducing MPs. Early studies suggest that these alternatives can reduce MP concentrations in soil and, in some cases, enhance soil fertility by contributing organic matter. Some studies suggest that these alternatives can reduce MP concentrations in soil and, in some cases, enhance soil fertility by contributing organic matter. However, there are also others that show these mulches inhibit plant growth in certain conditions, highlighting the need for more research (55).

Another preventative strategy to limit MP entry into agricultural systems is through the filtration of irrigation water. Many filters and barriers can be used to capture MPs before they reach fields, protecting both the soil and the crops. Although these systems are not fully developed and implementation may require a hefty cost, they do offer a proactive approach to manage containment, particularly for farms that rely on surface water—often major carriers of MPs.

At the plant level, the application of plant growth regulators (PGRs) provides a promising technology for mitigation. Melatonin has been shown to reduce internal circulation of nanoplastics through regulating related genes in the roots and shoots, while simultaneously enhancing antioxidant systems to combat reactive oxygen species (56). Brassinosteroids (BRs) have demonstrated the ability to improve growth and stress tolerance in plants (57, 58, 59). Recently, a study found that BR-application resulted in a decrease in nanoplastics because of BR's regulatory effects on genes related to the activity of aquaporins (60). Moreover, the same study showed BR was found to enhance growth and offset negative effects from nanoplastics by accelerating amino acid and fatty acid metabolism and synthesis. Glutathione (GSH) plays an important role in the antioxidant defense system, as it helps to manage hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>)

April 2026

Vol 6, No 1.

accumulation and lipoxygenase activities (61), both contributors to oxidative stress (62). Exogenous application of GSH was found to alleviate the damages such as reducing chlorophyll and photosynthesis, thereby increasing growth and yield.

Biochar is a charcoal-like substance that can be added to soil to improve its structure, water retention, and ability to hold nutrients (63). Biochar also holds potential to mitigate some of the maladies caused by MPs, as studies have shown that biochar can increase microbial activity, water restoration/retention, and adsorption of MPs and heavy metals to its surface (27, 64, 65). In rice, biochar has already been proven to improve height of plants and increase yield (66). Furthermore, biochar has been proven to enhance numerous soil properties, such as enzyme activity, health of relevant soil organisms, and microbial community (67, 68, 69). There is now an abundance of studies showing the positive benefits that biochar provides for plants, and even more recently about how biochar could help ameliorate some of the other risks. Biochar application improves plant growth under MP stress by directly regulating plant growth and indirectly regulating soil fertility and productivity.

Beyond technical and agronomic strategies, regulatory and policy interventions are critical to reducing MP stress at a systemic level. Stricter controls on the use of biosolids and agricultural plastics can help ameliorate one of the main sources of contamination. Policymakers can also incentivize sustainable practices such as biodegradable mulch adoption or biochar application through subsidies, grants, or support programs, especially because of the heavy price tags associated with those practices.

Finally, farmer education and awareness are essential to translating these strategies into meaningful action. By equipping farmers with knowledge and practical tools, awareness initiatives amplify the effectiveness of technological and policy interventions, ensuring that MP mitigation measures can be implemented broadly and sustainably. Even simple practices such as being mindful about plastic use, or choosing alternatives, when possible, can have large impacts. These simple actions, if practiced by many people over extended periods of time, can end up being just as, if not more effective than the proposed solutions above. In this way, daily mindfulness complements larger interventions, reinforcing a culture of sustainability that can endure over time.

## **5. CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH**

This article has demonstrated that MPs possess the ability to enter agricultural systems through various pathways including irrigation, biosolids, fertilizers, atmospheric deposition, and direct farming practices. Once present, they disrupt microbial communities, impair soil structure, inhibit plant physiology, and ultimately reduce crop yields. These biological and environmental stresses lead to direct economic implications which include decreased productivity, costs for possible remediation technology, reduced profits, and heightened risks of food insecurity. Indirectly, MP-induced reductions in crop yield threaten market competitiveness, trade relations and can disrupt the soil quality in the long term. However, there are many possible solutions for mitigation. These range from biotechnological approaches such as biodegradable mulch films and biochar to policy interventions and farmer education programs. The

bottom line, however, is that being mindful about plastic use on a daily basis is the most important, as it requires no cost yet can have meaningful impacts at a large scale.

Even with the growing number of studies on MPs, there are still major gaps in what we know. A lot of the current work has been done in lab settings under controlled conditions, which do not always match what happens in real farm soils over time. Much of the current research has been conducted solely in lab settings with most variables controlled. However, results cannot be directly applied to real-world scenarios, as many more factors are uncontrollable. Moreover, yield loss estimates vary depending on variables such as crop type, plastic type, and location of where the study is conducted. Thus, it is hard to standardize how a certain MP, or how MPs in general affect agriculture. MPs research also has only been a relevant subject of matter in recent years, meaning there is a lack of studies highlighting long-term effects. In terms of quantifying the actual economic losses, few studies give clear insight into specific loss amounts, with even less describing an effective approach to obtain reliable numbers. Finally, while there are several proposed solutions, most have not been tested for whether they are affordable, scalable, or practical for everyday farmers, especially in developing countries.

Looking ahead, increasing the amount of real-world field studies should be a priority. Research is especially needed on the topic of how MPs persist in soils and affect crops over multiple generations, not just short-term lab experiments measuring short-term effects. Additionally, MPs research in this field should prioritize developing economic models that connect yield losses with farm profits, food prices and broader supply chain impacts. Environmental scientists, agronomists, and economists must work together to find connections between biological effects of MPs and financial outcomes. This article acts as an example of an analytical framework that shows an interdisciplinary approach to be used in the future.

In terms of approaching potential solutions, future work should test mitigation methods like biochar, plant growth regulators, or microbial degradation in farming systems of different sizes and income levels. Lastly, more attention should be placed on how MP contamination affects smaller, individual farmers and food-insecure regions, since they are likely to face the heaviest burden. With this research, policy makers would have a clear framework into how MPs have impacts greater than biological, allowing them to develop regulations and policies regarding the use and distribution of MPs.

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April 2026  
Vol 6. No 1.

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## **ABOUT THE AUTHOR**

David Liu is a high schooler passionate about environmental science, economics and biology. In hopes to combine these areas of interest, David researched the implications of microplastics on agriculture and the economy. As a student at Phillips Exeter Academy, David is heavily involved in Exeter's Economics, Biology and Environmental Action clubs. With this paper, David hopes to share his passions and spread awareness about a growing topic.