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Review

Plastic Pollution in Agriculture as a Threat to Food Security, the Ecosystem, and the Environment: An Overview

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Abstract: Plastic products in plant production and protection help farmers increase crop production, enhance food quality, and reduce global water use and their environmental footprint. Simultaneously, plastic has emerged as a critical ecological issue in recent years, and its pollution has significantly impacted soil, water, and plants. Thus, this review examines the multifaceted problems of plastic pollution in agriculture as a risk to food security, the ecosystem, and the environment. The study's objective was to review and present the most recent information on using different plastic products in agriculture, the sources of plastic pollution, the advantages and drawbacks of using plastic products, and the strategies for mitigating plastic pollution in agriculture. Furthermore, after examining current plastic applications, benefits, adverse effects, and risks to soil, plants, and the environment, we addressed the requirements for technological advancements, regulations, and social processes that could contribute to mitigating plastic pollution in our ecosystems. We identified different pathways toward more sustainable use of plastics in agriculture and discussed future research directions.

Keywords: microplastic; nanoplastic; single-use plastic; online food delivery service; climate change

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Citation: Lakhiar, I.A.; Yan, H.; Zhang, J.; Wang, G.; Deng, S.; Bao, R.; Zhang, C.; Syed, T.N.; Wang, B.; Zhou, R.; et al. Plastic Pollution in Agriculture as a Threat to Food Security, the Ecosystem, and the Environment: An Overview. *Agronomy* **2024**, *14*, 548. https://doi.org/10.3390/agronomy14030548

Academic Editor: Andrea Baglieri

Received: 1 February 2024
Revised: 24 February 2024
Accepted: 5 March 2024
Published: 7 March 2024

1. Introduction

The world's population is predicted to increase from 7 billion in 2010 to 10 billion in 2050. The world is on course to require a 50% increase in annual crop production in 2050 compared to 2010. Population growth will need a yearly crop production growth rate that is faster than that experienced over the last decades. On the other hand, the population is increasing pressure to reduce the finite resources used to produce food globally [1–3]. The COVID-19 virus made progress even steeper by creating unexpected negative global situations. During the pandemic, the economy, agricultural sector, human health, and food security were the top areas affected globally [4,5]. The COVID-19 crisis had the unexpected impact of transferring food supply to the home due to social distancing restrictions [6].

In addition, food insecurity is an issue that is challenging to resolve globally. Because it cannot be characterized or limited by geography or defined by a single grouping, it has a significant impact on public health concerns linked to shared, costly, and preventable chronic conditions like diabetes, heart disease, and mental health issues. Globally, agriculture has several positive effects on societies: supplying food, generating employment, supplying raw materials for several industries, and fostering robust economies through international trade. Its development positively correlates with food security and is one of the most powerful tools for ending extreme poverty and boosting the economy [7]. The development of the agricultural sector is dependent and susceptible to local changes in the weather. It relies heavily on soil, water, and other natural resources that climate parameters may affect because it is spread globally, with varying climate zones and elevations. Therefore, uncertain climate change scenarios can negatively impact agricultural production and cause severe concerns for global food security [8–10]. Researchers have concluded that the world should learn to live with climate change for sustainable food production by adopting alternative food-growing methods [11]. Also, several research studies have been validated and provide evidence for adopting modern farming methods to cope with the effects of climate change. Modern farming practices can promote soil health, minimize water use, maximize water productivity, and provide maximum output with minimum input with lower pollution [12,13].

In addition, plastics play an ever-increasing role in achieving sustainability goals and are considered an essential component in modern agriculture globally [14,15]. Generally, plastics are used in several field activities in agriculture, including for mulching and drip irrigation, and as seedling trays, pesticide containers, livestock feed bags, and others [16]. All these plastic products have undoubtedly helped to increase crop yield. Simultaneously, plastics have emerged as a critical environmental issue in recent years, and their pollution significantly impacts soil, water, and plants [17]. They are beneficial for a short time as their usage significantly increases water productivity but threatens long-term food security [14,18–20].

The study's objective was to present information on using different plastic products in agriculture, the sources of plastic pollution, and a balanced assessment of the advantages and drawbacks of using plastic products in agriculture. In addition, Section 2 provides an overview of plastic production and single-use plastic pollution and a strategy for reducing the use of single-use plastics. Sections 3 and 4 discuss the use of plastic products in agriculture and the different pathways of plastic pollution and adhesive effects in agriculture. Section 5 deals with how we can sustainably mitigate plastic pollution in agriculture and microbial mitigation of plastic pollution. Section 6 discusses what we know and what remains to be learned about agricultural plastic pollution. Finally, the paper ends with the study's conclusion in Section 7.

2. Overview of Plastic Production

Plastic is a word that initially meant "material that can be easily shaped, formed, molded by providing heat and pressure". It only recently became a name for a category of materials called synthetic polymers. The polymer means "of many parts" and is a long chain of repeating smaller or larger molecules (monomers) bonded in subunits. Generally, natural polymers and synthetic polymers are used for making plastics. Synthetic polymers differ from natural polymers (such as silk, cellulose, muscle fiber, rubber, hair, and DNA). They are manufactured using raw materials such as oil, coal, and natural gas [21]. There are two other types of plastics that do not fall into the above category of materials (natural or synthetic) and are known as biodegradable plastics and bioplastic materials. Biodegradable plastic is made from petroleum- or biomass-based resources. Bioplastic products are manufactured using biomass-based materials only. Both plastic materials are substitutes for synthetic plastic [22,23]. The first fully synthetic plastic (containing no molecules found in nature) was invented by Leo Baekeland in 1907. He first mixed phenol and formaldehyde and formed a new artificial plastic material. The created material was a good insulator. The material was cheap, durable, heat resistant, and ideal for mechanical mass production [24–26].

Geyer [27] reported that Celluloid and Bakelite materials are primarily of historical interest. Most items made from both materials are considered good collector items. However, the first modern invented plastic was polyvinyl chloride (PVC). It is still manufactured and used to make many products globally. The most commonly manufactured types of synthetic plastic materials are thermoplastic and thermoset plastic. The thermoplastic type is divided into several types based on the chemical formation. The types are polyvinyl chloride polyethylene, polyethylene terephthalate, high-density polyethylene, low-density polyethylene, polypropylene, polyamide, and polystyrene. The different types of thermoset plastic are silicone, polyurethanes, melamine, unsaturated polyester, phenolic, epoxy, and acrylic resins. Compared to thermoset plastics thermoplastics are best known for their properties, such as easy to melt and harden, etc. Also, they are the most widely used type of plastic material [28].

In addition, plastic materials are classified into seven (1–7) categories known as resin codes. These resin codes were initially developed to categorize plastics into different types to ensure consistency during plastic manufacturing and recycling. The resin identification codes 1–7 mean that the plastic material is made from one of seven specific types of plastics: resin code 1 = polyethylene terephthalate, code 2 = high-density polyethylene, code 3 = polyvinyl chloride, code 4 = low-density polyethylene, code 5 = polypropylene, code 6 = polystyrene, and code 7 = plastic that does not fall into the above categories (such as EVA (Ethylene Vinyl Acetate) copolymer) or is not recyclable in regular collections.

2.1. Micro and Nano-Plastic Particles

Plastic debris can be of different sizes, shapes, colors, and densities, and all plastic debris play a vital role in its degradation and bioavailability. Micro- (MPs) and nano-plastic particles (NPs) have emerged as a global problem due to a worldwide rise in the plastic pollution rate, adversely affecting the overall environment and biota on the Earth. MPs and NPs are solid and insoluble plastic particles [29,30]. Plastic particles are classified based on their particle size: (1) 5 mm–1 mm as large MPs, (2) 1 mm–1 µm as tiny MPs, and (3) <1 µm as NPs. MPs have different sizes and shapes (fiber, microbead, film foam pellet, fragment, and filament) [31,32].

In addition, MPs can be divided into two types based on their sources of origin: (1) primary and (2) secondary particles [33]. While the primary MPs are manufactured intentionally by industries for commercial purposes, secondary MPs occur due to weathering and degradation of large plastic residues in open field conditions due to several climate actions such as solar exposure, waves, mechanical shear, thermal oxidation, and others [34]. Studies have reported that the continuous degradation of primary and secondary plastic particles could cause significant variations and alterations in their physical properties, such as their shape and color, morphology of the surface, crystallinity, size, and density. These variations and changes might impact their chemical and physical properties and other life forms in nature [35,36]. MPs have been found in several areas in nature, from soil, water, air, marine organisms, salt, beer, and others. Recently, some studies have reported their presence in plastic bottles used for drinking water [37,38]. Wright and Kelly [39] said that MPs, upon exposure to open fields, can accumulate and be transported into different body parts of living bodies, such as human and animal tissues. After entering living bodies, the MPs can alter the immune system or cause several clinical disorders and complications. Additionally, the breaking up of MPs into different smaller sizes, shapes, and components—or the development of nanotechnologies, which involves the engineering of nano- or micron-sized polymeric materials—can lead to the formation of even more challenges in the future.

Studies have reported that a large amount of attention was only being given to MP pollution in the environment; however, several researchers have recently begun to consider the fragmentation of plastic particles down to a tiny scale, below 1 µm; these are known as NPs [40]. NPs are generated during the fragmentation and weathering of MP debris. They can also originate from engineered materials manufactured in industries. Exposure of MP plastic debris to solar radiation catalyzes the rate of the photo-oxidation process and makes them more brittle. However, the abrasion process and wave action can further degrade the larger plastic fragmentations into micro-size and nano-size particles [41,42]. Gigault et al. [43] noted that converting MPs into NPs largely depends on the buoyancy and sedimentation of the plastic waste. The attributes linked to NP formation showed that they have colloidal behavior in nature. This colloidal behavior is attributed to and regulates contaminants, chemical partitioning, and sorption mechanisms to control their environmental fate and toxicological chemistry. NPs have large surface-to-volume ratios compared to MPs, making them more prone to adsorption, diffusion across air, soil, and water plumes, and being taken up by microorganisms, wildlife, and plants. Thus, they can pose a significant threat to human health by entering their bodies via the human food supply chain [44,45].

Ng et al. [46] reported that MP and NP particles are tiny. Therefore, it is possible that many organisms can ingest them quickly. However, our understanding of their ecological impact on the terrestrial environment is limited, and we must develop a greater understanding of any potentially harmful or adverse impacts of MPs and NPs on our agroecosystems and surrounding environments.

2.2. Plastic Use and Waste Generation in Our Ecosystem

The conception of plastic, its subsequent and continued growth, and mass production have resulted in the current throw-away culture (use and dispose of as waste). However, when plastic was initially introduced, it was thought that its imperviousness to moisture and its extreme versatility made it a dream material for many industries. These attributes made plastic an advantageous material. At the same time, it also negatively impacts the Earth's ecosystem. Currently, plastic products dominate packaging, construction, transportation, electrical and electronic equipment, agriculture, household items, sports goods, and medical supplies and equipment [47,48]. Sbarberi et al. [49] reported that for these reasons, the demand for plastic follows a positive trend worldwide; its usage is increasing, and its global production reached 391 Mt in 2021. However, in 2017, its global production was 348 Mt compared to 1.5 Mt in 1950 [26,48]. The recent data on global plastic production provided by Statista [50] reported that in 2023, the global plastic market was valued at USD 712 billion. The global plastic production market is projected to grow in the coming years to reach a value of more than USD 1050 billion by 2033.

Moreover, in the last decade, the rate of manufacture of several plastic products has significantly increased compared to other materials. At the same time, we have seen a worrying shift toward using single-use plastic (SUP) products. The SUP products are those plastic items thrown away after a single or short use. SUP products are causing significant plastic pollution globally.

The continuous innovation of polymeric technology and plastic manufacture helps to explain why, since 1950, plastic production has increased by an average of almost 10% annually globally [51]. A report by the United Nations [52] stated that plastic production and usage positively and negatively impact the world's ecosystem. Its negative impacts are higher if we compare its positive and negative effects on our ecosystem. Many researchers consider plastic pollution to be one of the most significant environmental challenges of the 21st century. It can cause a wide range of damage to our ecosystem and human health.

The plastic's properties (chemical and physical) make it a material that is challenging to dispose of or degrade in the natural environment. Some plastic types may take thousands—even tens of thousands—of years to degrade in landfills under natural conditions. Degraded plastic pollution is an even bigger environmental issue, as plastic particles break into microscopic particles and pollute our ecosystems (see Figure 1). Plastic pollution can also significantly alter habitats and natural processes. It can reduce the ecosystem's ability to adapt to climate change, affecting millions of people's livelihoods and food production capabilities.

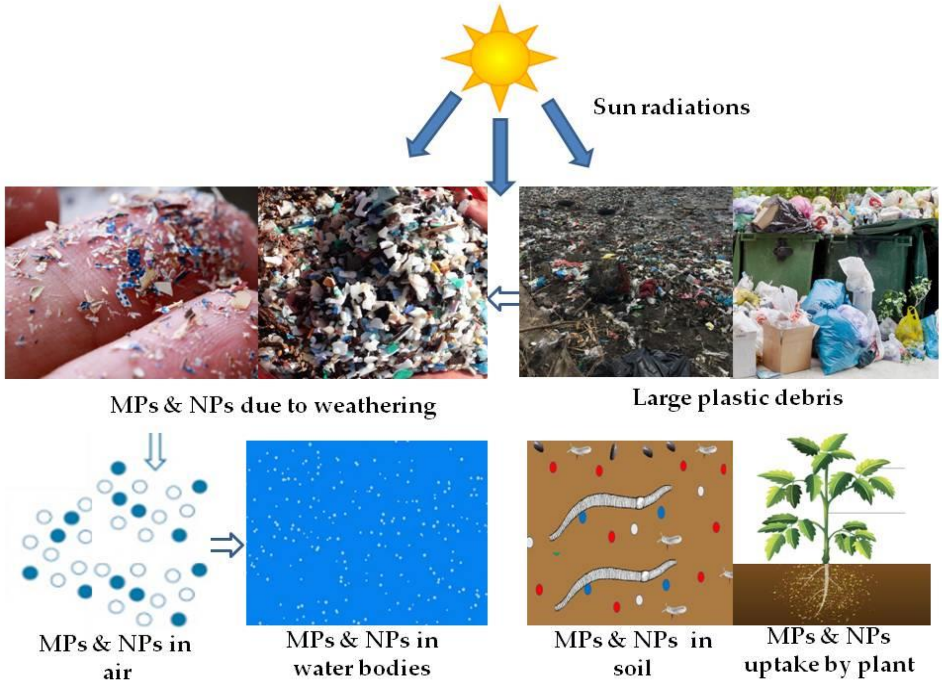

Figure 1. How plastic waste enters the ecosystem.

Plastic use will continue to increase at a faster rate and could lead to a 50% increase in plastic debris leakage into our ecosystem by 2040 (30 Mt per year). The current trends of population growth and higher incomes could lead to a 70% increase in annual plastic use and waste generation in 2040 compared to 2020. The above prediction is based on the current scenarios, such as production rate, low recycling rate, and lack of plastic degradation, which have created sizeable problems, and plastic pollution is accumulating significantly at alarming rates in our ecosystems [53]. The current sheer magnitude of our society's use and consumption of plastic products results in a significant carbon footprint associated with plastic manufacturing, a lot of garbage being produced, ongoing pollution, and harm to ecosystems and species. Several research studies have predicted that accumulated plastic leakage and waste in our ecosystem could increase in the coming years, exacerbating climate change and health impacts on living bodies. Greenhouse gas emissions (GHG) from the plastic lifecycle are projected to more than double to 4.3 Gt CO_2e. However, its adverse impacts on other lifecycle or environmental parameters, such as ozone formation and degradation, acidification, and human toxicity, will double in the coming years [53]. The United Nations [52] estimated that by 2050, greenhouse gas emissions from the manufacturing, use, and disposal of plastics will contribute 15% of the total allowable emissions, which will help keep global warming at the 1.5 °C (34.7 °F) set by the Paris Climate Agreement. Furthermore, plastic pollution is anticipated to threaten over 800 marine and coastal species via entanglement, ingestion, and other dangers.

Now, the world must act to find sustainable substitutes to tackle plastic pollution, protect our ecosystem, and fight climate change. Plastics have significantly impacted our daily lives, including technology, medicine and treatments, and domestic appliances, and their wastes are generated during both production processes in the industry and after the product reaches its end. Therefore, we must control its release into our ecosystem by adequately managing plastic waste from the above sources. In industries, plastic product production and development contains several goods that typically involve various processes, from polymerization, part formation, monomer production, and product assembly, to the final product transportation step. There are many possibilities where waste may be generated during any of these steps, and the waste generated during this stage is called pre-consumer or production waste. Plastic waste is also generated when the consumer uses a plastic-containing product. This waste is called post-consumer or end-of-life waste. Pre-consumer waste is generally easier to recycle than post-consumer waste as it is less contaminated and mixed with other materials.

2.3. Single-Use Plastic Pollution through Online Food Delivery (OFD) and a Strategy to Reduce Its Usage

OFD apps have put food a click away and are preferred as they save the hassle associated with cooking. The OFD industry has opened up new opportunities for restaurant owners and consumers by having food delivered to their homes without meeting physically (see Figure 2 [54]). On the other hand, its popularity can increase the risk of enormous plastic waste generation because each order often comes with at least 3–4 disposable plastic containers. These plastic consumption habits result in 500 billion single-use plastic (SUP) cups ending up in landfills annually [55]. According to Vasarhelyi [56], one million SUP plastic bottles or cups are bought every minute, and up to five trillion plastic bags are used globally annually.

Figure 2. Online food delivery value chain (from placing an order to the final disposal).

In addition, the COVID-19 pandemic promoted an unprecedented change in consumption habits that involved using SUP products. The COVID-19 pandemic boosted worldwide demand for OFD [57,58]. Beyrouthy [59] reported that grocery and meal delivery segments of the OFD industry earned revenues that were more than double those of pre-pandemic levels. Hu et al. [60] reported that in Japan, the OFD industry increased by 25% from 2016 to 2020, and it is set to increase by a further 17% from 2021 to 2025. South Korea's OFD industry sales have grown by an average of 85% over the past four years, achieving USD 14.3 billion in sales in 2020 [61]. Bush [62] stated that in 2019, Canadians spent CAD 4.7 billion on online food orders, and is estimated will be worth over CAD 98 billion by 2027. Lin et al. [63] reported that during the COVID-19 pandemic, the OFD industry in China experienced 20% annual growth, leading to revenue growth from USD 3.2 billion in 2015 to USD 51.5 billion in 2020. Nowadays, China has the world's most prominent takeaway food market, and its scale is more than a quarter of China's catering industry [64]. However the OFD industries in Bangkok [65], Pakistan [66], Brazil [67], India [68], Indonesia [69], New Zealand [70], South Africa [71], Saudi Arabia, the United Arab Emirates, Bahrain, Kuwait, Qatar [72], Bangladesh [73], Vietnam [74], Turkey, Spain [75], and Russia [76] saw significant popularity during the COVID-19 period. Additionally, these figures indicate a substantial potential for future growth in the OFD industry. However, this fast-growing trend does not show that although the sector is improving, its effects on society, agriculture, and climate are not very optimistic. This behavior will significantly increase the burden on waste disposal, generating significant waste that litters cities, chokes rivers, causes soil pollution, and threatens wildlife [70].

The OFD industry has witnessed massive growth in the last few years, and ordering a meal is a convenient option but its impacts on our ecosystem are unsuitable. Janairo [77] and Sha [78] reported that OFD services are a significant burden against the United Nation's developed sustainable goals that address good health, climate action, decent work, and economic growth. This study further stated that high volumes of OFD consumption exacerbate plastic waste and increase the contamination of natural environments such as oceans, freshwater systems, and terrestrial areas. A study [79] on the environmental impacts of takeout food containers revealed that SUP products are the worst packaging material for takeout food, with many adverse effects on the environment. Plastic containers made from polypropylene and polystyrene foam accounted for approximately 75% of the total food delivery packaging waste by weight [80]. Additionally, each OFD order generated an equivalent of 111.80 g of CO_2 emission on average. Most (86%) of the CO_2 equivalent of the express food delivery came from the SUP food packages [81]. However, the UN environment program report [82] mentioned that approximately 36% of all SUPs produced are used for packaging food and beverages. The GHG emissions associated with making, using, and disposing of conventional fossil fuel-based plastics are forecast to grow by 19% of the global carbon budget by 2040.

Their significant usage and disposal have become a global concern, and the over-utilization has pushed governments to implement a mix of policy measures or ban single-use plastic products. However, after being used, the items are disposed of in waste dumping sites and landfills, where they may end up in rivers, oceans, soil, and the atmosphere [83–87].

SUPs have created many environmental issues, and there are also various upstream consequences of a consumption-oriented society that will not be removed even if plastic waste is significantly decreased [88–90]. The Competitive Enterprise Institute [91] reported that studies have shown that the vast majority of plastic waste is due to poor global disposal practices. Therefore, to some extent, disposable plastic can be removed from the environment through proper recovery and recycling. Putting plastic trash in its correct context is the first step toward better scientific communication about its environmental impact. Furthermore, to assist the public in making linkages between product consumption, energy use, and upstream environmental implications, scientific communication needs to go beyond the "Reduce, Reuse, and Recycle" mantra [92].

Martin [93] stated that both governments and consumer bodies should put pressure on manufacturing industries to adopt sustainable manufacturing practices to reduce emission levels as fossil fuels are depleted and global warming increases. Customers can also do their part by refusing SUP packaging and opting for reusable alternatives whenever possible. Kochańska et al. [94] stated that bioplastics could be the best alternative material for packing takeaway food. Bioplastics can be produced using food waste, a significant stimulus for transformations in producing petroleum-derived plastics [95].

3. Plastic Products in Agriculture as a Sustainable Food Production and Irrigation Water-Saving Approach

The key characteristics responsible for the success of plastic products are affordability, low weight, ease of use, low management, and exceptional durability. No alternative material currently possesses this wide range of valuable traits or qualities. The growing trend of global plastic production and manufacturing may be attributed to the increasing demand across numerous sectors such as agriculture. Plastic products have revolutionized the performance of the agricultural sector throughout the world in the era of climate change. Considering the extensive use of plastic products in agriculture, the term "plasticulture", which means using plastic products in agriculture, has been coined. Plastic products in agriculture were initially introduced and employed in the USA. The purpose was to improve crop yield quantity and quality, as well as the conservation and efficient use of water. Plastic products in agriculture (see Figure 3) have progressively replaced the traditional materials used previously, such as glass and paper [96]. The recognized benefits of plastic products in agriculture include water-saving irrigation solutions for crop cultivation, especially in arid regions, increased efficiency of water and nutrient supply and use, controlled weed growth, earlier crop harvesting, and more sustainable use of applied pesticides [97,98].

Figure 3. Plastic products and their uses in agriculture. (**A**) Thin plastic sheet for covering crops; (**B**) Plastic-sheet-covered glasshouse; (**C**) Plastic plant hanging rope; (**D**) Plastic floating trays; (**E**) Plastic seedling trays; (**F**) Plastic mulching sheets; (**G**) Plastic sheet for use as a water reservoir; (**H**) Plastic trolley for loading; (**I**) Plastic sprayer machines; (**J**) Plastic pest glue sticky trap; (**K**) Plastic growth bags; (**L**) Plastic spraying nozzles; (**M**) Plastic drip irrigation line and tags; (**N**) Plastic sprinkler irrigation setup; (**O**) Plastic irrigation line; (**P**) Plastic bottles for fertilizer/pesticide packing; (**Q**) Plastic bags for seed packing; (**R**) Plastic bags for grain storage; (**S**) Plastic net for fruit support and (**T**) Plastic covers for fruit decoration.

In addition, plastics have multiple applications in agriculture, and their use has increased globally over the last decades to a projected 12.5 million tons annually [15]. In agriculture, plastic products are used for soil fumigation management, irrigation applications (drip and sprinkler irrigation systems), packaging and decoration of agricultural products, sheltering and protection of harvests from precipitation, and others (see Figure 3) [99,100]. Hofmann et al. [14] reported that agricultural plastic products have many environmental and societal benefits. For example, plastic mulch film provides multiple agronomic benefits, including weed and pest control, soil moisture conservation, a means to control soil and air temperatures, and enhanced nutrient uptake. Sun et al. [101] stated that in China, plastic mulch is significantly improving the progress of the country's agricultural sector by enhancing food production using fewer inputs. Without plastic mulch, China would need an extra 3.9 million hectares of arable land to cultivate the same crops. In conclusion, it can be said that plastic products have provided several opportunities for farmers to get maximum yield using minimum inputs [102,103].

3.1. Plastic Water-Saving Agricultural Systems and Reservoirs

One of the most critical aspects that come into play during the agricultural process is irrigation efficiency, as irrigation is used to keep the cropland in good condition and to ensure its sustainability over time by providing high water productivity and significant crop yield. The availability of high-efficiency irrigation systems, water storage reservoirs, drainage and supply networks, and other supporting materials (such as pipes and fittings) are important parameters for an efficient irrigation system. Simononson [104] reported that the efficiency and durability of any irrigation system depend largely on the type of materials used in its construction. In particular, irrigation pipes and fittings are vital in ensuring optimal functionality. Generally, metal, aluminum, and plastic products are used in irrigation. The main drawbacks of metal and aluminum products are cost efficiency, corrosion due to poor quality water (saline or acidic water), difficulty in installation and maintenance, and prone to theft when used in open fields compared to plastic products [105]. Therefore, various types of plastic products are utilized to make irrigation channels, plastic fittings, and pipes for high-efficiency irrigation systems [106,107], water storage reservoirs [108,109], and water drainage and supply networks [110,111]. Compared to metal and aluminum products, plastic products provide durability, resistance to corrosion, and flexibility, making them suitable for constructing efficient and long-lasting irrigation systems; they are also exceptionally economical. In the past couple of years, the use of plastic products in irrigation water management has increased tremendously. Now, water can be stored easily and kept leak-free for longer by covering it with plastic materials. The water can then be supplied to water circulation and irrigation systems via plastic pipes. Plastic irrigation systems and reservoirs have contributed significantly to agricultural water management and proper land utilization.

3.2. Plastic Mulching for Covering Soil Surface Layers

Mulching is a technique where a layer of different types of materials is used to cover the soil surface to prevent it from degrading over time by protecting it from freezing, improving soil fertility, preserving moisture, reducing weed growth, and increasing water use efficiency [112–114]. Luo et al. [115] reported that soil mulching enhances the moisture storage capacity of the soil (32–89 mm) and water use efficiency of the crop (0.2–19.5 kg ha^{-1} mm^{-1}). It can also maintain the temperature variations in the soil at 0.98–10.0 °C. Different materials, both organic and synthetic, are used for mulching. Organic mulch is made from biodegradable materials such as wood chips, dry leaves, grass clippings, and wheat or rice straws while synthetic mulching materials are produced from non-biodegradable materials such as plastics. The plastic mulching sheet is an alternative to organic mulching [116,117]. Lamont [118] stated that introducing polyethylene plastic film as the mulch for vegetable crop production has significantly enhanced crop production globally. Studies have reported that different types and colors of plastic mulches with various formulations have been utilized in the farming community. The most used colors are white, black, brown, green, red, blue, and silver. These colors are formulated with their role in light absorption and crop physiology. Many researchers have discussed the impact of different colored plastic films in their studies by growing various crops [119–121]. A study by Matsoukis and Gasparatos [122] reported that the purpose of using different colors of plastic mulches is to alter and control the micro-climate parameters (such as temperature and relative humidity) at the plant and soil levels. Covering the soil surface and plants with plastic film can provide multiple benefits for crop production, including maintaining humidity levels because it reduces evaporation. Also, it can maintain suitable and improved thermal conditions for plant roots, prevent contact between the plant and the soil surface, and prevent weeds from growing [123,124].

3.3. Plastic Products for Greenhouse and Low Tunnel Covering for Controlled Environment Farming

Usually, plants are grown using open soil-based farming methods, but climate change, urbanization, and food insecurity concerns have led to a change from open soil-based farming methods to modern farming methods (such as greenhouse or low tunnel farming). Moreover, greenhouse or low tunnel farming involves an artificially covered structure with glass or plastic cladding frames covered using thin-walled steel or aluminum that presents crops with an optimal artificially controlled growth environment [125,126]. Its adaptability offers an excellent solution for growing high-quality crops and sustainable year-round food production, particularly in regions with adverse climate conditions [127–130]. Furthermore, there are different types of materials used for glazing the greenhouse. However, the standard materials are thin plastic films, rigid plastic panels (fiberglass-reinforced plastic, rigid panels, polycarbonates, polyvinyl chloride, and polymethyl methacrylate acrylics), and glass (e.g., annealed, tempered, and laminated) [131]. These covering materials are used to maintain the environmental parameters (such as temperature, humidity, and light intensity) inside the greenhouse at a level suitable for the successful cultivation of crops [132,133]. Compared to plastic material, glass glazing is expensive to purchase and install. Also, its operating and maintenance costs are higher than those of plastic glazing. Kim et al. [134] stated that plastic-covered greenhouse glazing material is inexpensive and easy to install. The plastic film-covered greenhouse is the most favorable for managing the heating effect, especially during the cold season. The heating effect is produced by exploiting the incoming solar radiation, known as the greenhouse effect, depending on the radiometric properties of the covering materials, transparent in the solar radiation wavelength and quite opaque in the long wave infrared radiation wavelength [135–137]. In addition, plastic material (such as Polyethylene film) is very light in weight and does not require a permanent structural support system. In addition, the environment inside the greenhouse is managed using multiple plastic-made components, including water supply and drainage systems, shade materials, air distribution tubes, energy curtains, etc. Plastic products are now commonly utilized for greenhouse vegetable crop training, insect monitoring, postharvest handling, storage, and marketing [138]. Greenhouse materials (such as plastic sheets) that possess ideal optical properties allow crops to absorb ultraviolet A (UV-A) radiations, concentrating humidity and CO_2, reducing heat loss, and preserving a heated environment that extends the plant-growing season. However, the most apparent reason for opting for a greenhouse is to extend the growing season by controlling the climate within the artificial structure [139–144].

3.4. Plastic Products for Sustainable Development of Livestock and Aquaculture Sectors

The worldwide development of the livestock and aquaculture sectors has improved by adopting several plastic-made products in production processes such as genetics, nutrition, hygiene, facilities, and types of equipment. In the livestock and aquaculture sectors, plastic products perform multiple tasks and are becoming more important, particularly for enhancing the quantity and quality of products (milk, meat, eggs, etc.). In addition, plastic products are mainly used in livestock farm operations for animal shelters, storage of animal feed (plastic silage bags/films for covering silo pits), manufacturing of animal feeding and watering devices, animal tags, milking machines, tubings, milk cans of multiple sizes, semen straws, artificial insemination sheaths, plastic cages for poultry, plastic egg carriers, plastic slats, plastic water drinkers and feeders, and plastic transportation boxes, while in aquaculture operations, plastic products are mainly utilized in portable hatcheries, silos, live fishing transport systems, feeders, packaging materials, poly house ponds, nylon fishnets, pen cultures in water-locked areas, plastic pipe frames and nylon net cages, etc. [145,146].

3.5. Plastic Products for Performing Several Other Agricultural Activities

There are many other areas where plastic products are used for multiple agricultural activities. Some of them are (1) covering orchards and vineyards with plastic films or nets to offer protection against birds, hail, and wind [51]; (2) used in the packaging industry for fruit packaging and decoration of boxes, used to make tags and crates for collecting crops, handling and transporting crops with the goal of increasing the shelf life of organic products by preserving the physicochemical properties of the fruit and shielding it from damage; (3) making plastic hanging ropes for providing plant support in greenhouses; (4) used in distribution and retail activities with the goal of maintaining the agricultural products' quality [147]; (5) used for making plastic seedling trays, nursery trays, and nursery pots for growing plants [14]; (6) making agrichemical containers for pesticides; (7) making plastic traps and plastic insect sticky traps for integrated pest management [148], and (8) designing soilless farming systems (aeroponics, hydroponics and vertical farming) [149].

4. Sources of Plastic Pollution in Agriculture and Its Adhesive Effects on Agriculture

Research studies have reported that plastic pollution has significant adverse effects on the sustainable development of the agricultural sector, especially soil, water, and plants. Plastic particles of dissimilar types, sizes, and forms are widely spread in soil (surface, subsurface, and profiles) and water bodies. Therefore, it is currently considered one of the major global issues in agriculture and is receiving increasing attention from scientists and society [150,151]. Plastic products in agriculture have risen noticeably in recent years compared to past years. At the same time, the generation and disposal of plastic waste from agriculture also leads to increased plastic contamination in agricultural farmlands. Studies have reported that primary and secondary sources are the two main pathways through which plastic contaminants can enter agriculture. Both sources can be further defined as (1) primary sources include leakage or entry of plastic pollution from agricultural activities (such as mulching, irrigation, and fertigation) and (2) secondary sources include leakage or entry of plastic pollution from non-agricultural activities (such as plastic particles blowing in the air in urban areas and landfills) [152–157]. Climate variables such as high temperature, solar radiation, precipitation, and wind are among the factors responsible for physical weathering, aging, and quality deterioration of plastics in soils [158–161]. Figures 4 and 5 show the different sources of plastic pollution in agriculture and water.

Studies published by Xu et al. [162] and Lwanga et al. [163] showed that the transport of soil particles and the co-transport of plastic debris has been intensively studied by several researchers globally. These transport and co-transport routes generally transport plastic particles in groundwater aquifers. Additionally, the properties of the plastics themselves (e.g., type, size, and shape), the properties of the soils (physicochemical and hydraulic conditions and biogenic activity), and the soil–plastic-particle interactions determine their transport ratio in the soil system and groundwater aquifers. Rehm et al. [164] stated that soil erosion is anticipated to be an essential diffuse pathway for plastic debris to get to freshwater bodies. At the same time, plastic fragment sizes and shapes are considered sensitive parameters causing soil erosion. However, due to their persistence in the environment, plastic fragments will inevitably accumulate in the soil over time, disintegrate into different particle sizes (MPs and NPs), and release additives. These MP and NP particles can negatively impact soil health and can be transferred horizontally and vertically across and within soil profiles. Moreover, the vertical transfer of MP and NP particles happens due to leaching, the activities of soil and microbial organisms, and agricultural practices such as mulching, irrigation, and greenhouse farming [165,166].

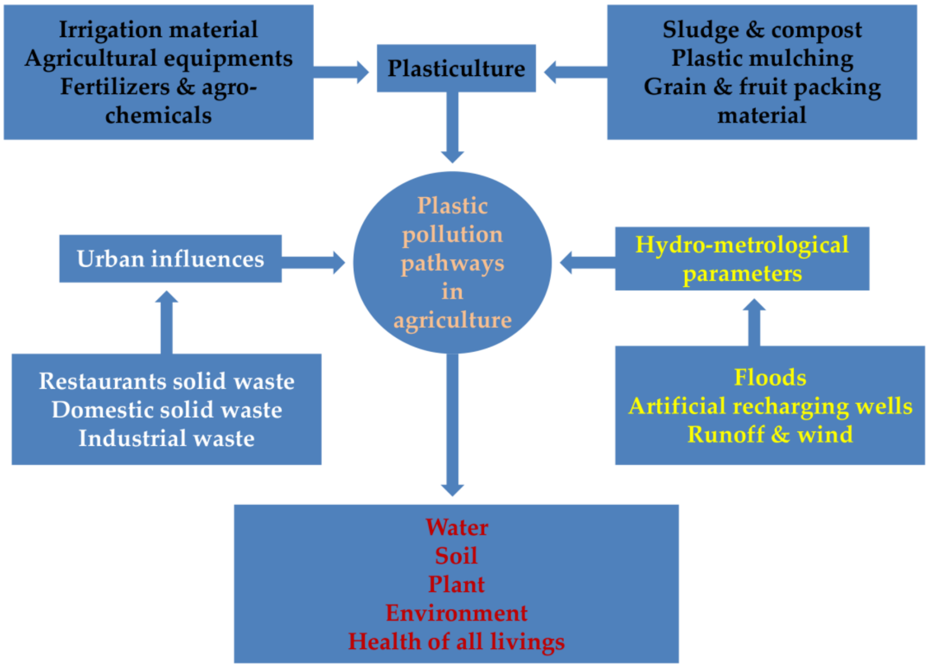

Figure 4. Sources of plastic pollution in agriculture.

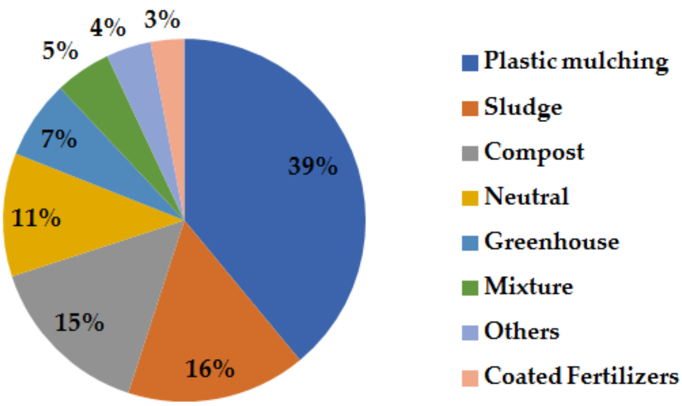

Figure 5. Sources and share of agricultural plastic pollution (redrawn from [159]).

Lin et al. [167] reported that MPs and NPs are seen from high to low latitudes across terrestrial ecosystems such as urban and industrial areas, agricultural lands, and remote mountains. Recent studies of plastic-contaminated soils have demonstrated that pollution by MPs and NPs can alter the coupling between carbon and nutrient cycling by significantly increasing CO_2 fluxes and nutrients in dissolved organic matter. The above results have triggered increasing concern about how and to what extent MPs and NPs could impair numerous ecosystem processes mediated by soil organisms, such as organic matter decomposition and nutrient cycling. In addition, Table 1 summarizes some of the published research studies reporting the adverse effects of plastic contaminants on water, soil, and plants. Further discussion on the unfavorable impact of plastic contaminants on water, soil, and plants is given in the subsequent sections.

Table 1. Adverse effects of plastic contaminants on water, soil, and plants.

Object	Factor	P-Type	P-Size	P-Shape	P-C (% (*w*/*w*))	Outcome
PPN and drought effect under AMF [168]	SLS/*Allium cepa*	PE	1.70 µm	Microfiber fragments	0.4	PP affected the plant–soil system
Effect of PMFR [169]	SRA/Wheat	LDPE and Bio	4–10 mm and 50 µm to 1 mm	Rectangular	1	LDPE and Bio affected plant–soil system
PPN threat to plant–soil system [170]	SCL/Wheat	PVC and PE	125 µm	NM	0, 1, 5, 10, and 20	PP harmed the plant–soil system
PPN effect on soil and plants [171]	SLS/Onion	PA, PE, HDPE, PP, PS, and PET	15–20, 5000 µm, and 2–3 mm	Beads, fibers, fragments, spheres, and cylinders	0.2 (PE) and 2.0 (other)	PP affected the plant–soil system
Soil and plant response under different PPN [172]	FLS/Maize	LDPE	150–180 µm	NM	0 and 0.2 (Mw: 2000, 5000 and 100,000)	Different Mw of PE-particles had adverse effects on the soil–plant system.
PPN and cadmium [173]	NM/Lettuce	PE	3.5 mm	Microfiber	0, 0.1, and 0.2	PP and cadmium caused a dose-dependent effect on the plant–soil system
PPN impact and cadmium uptake [174]	CL/Rice	Bio, PPC, and PLA	200 ± 20 µm	NM	200 mg/kg	Different PP types and concentrations have diverse effects on the plant–soil system.
Spread of antibiotic resistance [175]	NM/Lettuce	PS	100 µm and 100 nm	NM	100 and 1000 mg/kg	PP has significant effects on the plant–soil system.
PPN effect on growth traits [176]	NM/Buckwheat	PLA-MPs	N/M	NM	0, 5, 10, 20, 40, and 80 mg L^{-1}	Positive and negative results were observed
PPN effect on invasive plants [177]	SS/*Amaranthus palmeri*	PE and PP	150 µm	Pellets	0.1, 0.5, and 1%	Negative effects were observed
Changes in CM-SM [178]	NM/Rice	PA and PE	100 nm	Fragments	2 g/kg	PP is a big threat to plant–soil systems.
Bio PPN effect on soil and plants [179]	NM/Pakchoi	PBAT and PE	100–180 µm	NM	0, 0.02, 0.2, and 2	PBAT MPs may be more harmful to soil–plant systems than PE
Food quality and security with PPN [180]	Foliar route/Rice	aSMPs	1, 10, 50, 100, 500 µm	NM	30 µg d^{-1}	Positive and negative results were observed
PPN effect on floating water body plants [181]	*Duckweed Lemna minor*	PO	4–12 µm	Microbeads	10 mg in 100 mL	PP has negative impacts on floating plants in freshwater ecosystems

Table 1. *Cont.*

Object	Factor	P-Type	P-Size	P-Shape	P-C (% (*w*/*w*))	Outcome
Environmental impacts of PP [182]	FSL/Lettuce	PP	500 µm	NM	0, 0.25, 0.5, and 1	MM has negatively impacted the soil ecosystem and physical properties
PPN in WW [183]	WW	AC, PO, and PE	10–5000 µm	Films and Fragments	113 P g^{-1} (DW)	WW is a potential source of PP for agroecosystems.
PPN in WW [184]	WW	NM	10–5000 µm	NM	370–950 P kg^{-1} (WW)	Even after treatment, WW holds PP.
PPN in river [185]	FW	PET	NM	Fiber	0–71.04 n/kg (DW)	WW plants are the most likely source of PP in FW bodies.
PPN in the Japanese River [186]	FW	PE and PET	<5, 5–25, and >25 mm	Fragments and fibers	0–273.3 (P/m^3) and 0–42.34 (mg/m^3)	PP was found in different sites in the study area
PPN in river [187]	FW	PE, PET, PS, and SI	0.3–1 mm	Fiber, film, pellet, and foam	9.3 ± 1.27–18 ± 1.41 P/L.	PP was found in different sites in the study area
PPN in surface water [188]	FW	HDPE, PP, and ST	>1000, 25–1000, and 5–25 mm	Fiber, film, pellet, and foam	166.50 items·kg^{-1} and 7.62 items·m^{-3}	PP was seen in surface water.

Note: Acrylonitrile (AC); Aged submicron plastic (aSMPs); Arbuscular mycorrhizal fungi (AMF); Biodegradable (Bio); Biodegradable poly(butylene adipate-co-terephthalate) (PBAT); Carbohydrate metabolism and soil microorganisms (CM-SM); Clay loam (CL); Dry weight, (DW); Farmland soil (FSL); Freshwater (FW); High-density polyethylene (HDPE); Low-density polyethylene (LDPE); Mask-microplastics (MM); Molecular weight (Mw); Not mentioned (NM); Particles (P); Plastic concentration (P-C); Plastic mulch residues (PMFR); Plastic pollution (PPN); Polyamide (PA); Polyester (PE); Polyethylene (PO); Polyethylene terephthalate (PET); Polylactic acid (PLA); Polylactic acid MPs (PLA-MPs); Polypropylene (PP); Polypropylene carbonate (PPC); Polystyrene (PS); Polyvinyl chloride (PVC); Saline soil (SS); Sandy loam (SLS); Sandy soil (SAS); Silicon (SI); Silty clay loam (SCL); Styrene (ST); Wastewater (WW); weight per weight (*w*/*w*).

4.1. Status and Impact of Plastic Pollution in Irrigation Water

The production of plastic waste and its poor management cause many issues and threats to human health and the sustainability of ecosystems. In developing countries, plastic waste disposal and environmental emissions have caused plastic materials to build up in water systems, leading to the pollution of water and the surrounding ecosystems [189]. A study published by Thompson et al. [190] was the first study that reported the presence of microscopic plastic particles in the ocean. Later, there was an increased focus on the repercussions of plastic waste buildup in the natural environment, particularly in marine and coastal ecosystems and other environmental sectors like freshwater bodies and agriculture. A study by Andrady [191] reported that land and ocean-based sources are critical sources of plastic pollution in coastal and marine ecosystems through in situ and ex situ pathways. Additionally, primary land-based plastic pollution sources are from freshwater input, residential and domestic activities, tourism, and other economic actions, including harbor operations. Eriksen et al. [192] reported that five trillion plastic debris weighing more than 260,000 tons float on the world's ocean surface due to improper waste disposal. Several previous studies assessed the availability of plastic debris in different oceans across the world. They found <0.1 particles/m^2 in the Atlantic Ocean [193], 0.27 particles/m^3 in the Western English Channel [194], 0.116 particles/m^2 in the Northwestern Mediterranean Basin [195], 0.334 particles/m^2 in the North Pacific Gyre [196], 0.017 particles/m^2 in the North Pacific Offshore Subsurface [197], and 3.4 items 100 m^{-3} in Mangrove Creeks, Goiana Estuary [198].

Micro and nanoscopic plastics refer to tiny fragments of plastic that cannot dissolve in water [199]. Ziajahromi et al. [200] found that microplastics are released into water bodies through plastic waste discharge from industrial and domestic wastewater. Their presence in freshwater bodies such as ponds, lakes, and rivers has been reported by many studies [201], which reported that freshwater bodies can play a vital role in moving plastic debris into our ecosystems [202], especially those freshwater bodies located near plastic manufacturing industries. Continuous manufacturing or utilization of plastic products in these industries can directly impact the surrounding environments. Therefore, there are many possibilities for the significant presence of MPs and NPs within these water bodies [203]. A study found that Taihu Lake had a relatively high concentration of MPs and NPs (3.4–25.8 items/L). Using contaminated water from lakes for crop irrigation may lead to the accumulation of dangerous metals in agricultural soils, resulting in decreased crop yield and impaired human health [204]. Leal Filho et al. [205] documented that most Asian rivers are unsustainable and highly polluted due to solid waste and high concentrations of MPs and NPs. This study further informed us that there is a significant gap in regulations and standards of plastic and solid waste management. The major factors that are causing freshwater plastic pollution are lack of proper waste management, people's attitudes toward dumping plastics in rivers and waterways, the proximity of cities to rivers, the presence of dams and litter traps, floods, and direct rainfall discharge into freshwater bodies [206]. Additionally, rapid urbanization has contributed to most of the plastic pollution in freshwater bodies due to mismanaged solid waste and sewage systems [207,208]. The mismanagement of solid waste can be attributed to its diffusion in open areas, as it often results in runoff or spreads into the air from streets, eventually finding its way into nearby water systems. Sewage systems contain several MP and NP particles (ranging from worn-out car tires, personal care products, laundry fibers, and household dust), and their supply network systems are the primary source of MP and NP pollution into nearby water systems [209]. Compared with other published studies, a study by Blettler et al. [210] found a vast number of MPs and NPs in freshwater ecosystems. Several studies have been conducted to determine the presence of plastic debris in different lakes in the world, including the Alpine Lake [211], the Great Lake [212], Lake Victoria [213], the Danube [214], Thames [215], Tamar [216], Los Angeles [217], and Rhine and Main rivers [218]. These studies reported that plastic pollution in lake waters endangered the lake ecosystem, and we should improve environmental policies and educational strategies globally to maintain the lakes' sustainability. A study by Hu et al. [219] reported that small waterbodies are freshwater habitats for many species that are most vulnerable to MP and NP contaminations. In this study, authors found MPs and NPs in 25 small waterbodies. The selected waterbodies were linked with the Yangtze River Delta, China. This study found an abundant presence of small plastic debris at different locations in the waterbodies, including the water surface, sediments, and tadpoles. However, the plastic particles ranged in size, from 0.48–21.52 items L^{-1}, 35.76–3185.33 items/kg^{-1}, and 0–2.73 items individual^{-1}, respectively.

Moreover, due to human population growth and a lack of fresh water, wastewater from domestic and industrial sources is being reused as sewage sludge for agriculture. Wastewater, which includes household waste, flows through the sewerage system to wastewater treatment plants and is sometimes treated or untreated before being discharged into water bodies or agricultural lands. Many research studies consider wastewater collection points for several metals and contaminants. Jeong et al. [220] and Kye et al. [221] stated that reusing wastewater for agriculture is a crucial source of plastic pollution in the agricultural sector. When wastewater sludge is used for irrigation, MPs, NPs, or other metals in the wastewater directly leach into the soil, potentially affecting soil health and contaminating crops and groundwater [222]. Li et al. [223] analyzed the presence of plastic particles in China's wastewater. This study found about 1.60–56.4 $\times$ 10^3 MPs and NPs per kg particles in sewage sludge. This study concluded that there are many possibilities as to how 1.56 $\times$ 10^{14} MPs and NPs per kg particles had accumulated in the soil, including using wastewater in agricultural fields. A study by van den Berg et al. [224] found that soils irrigated with sewage sludge hold 256% higher MPs and NPs per kg than non-irrigated soils. Biosolids produced from wastewater treatment plants are commonly used as fertilizers for crops, yet their application on agricultural lands can introduce MPs and NPs (particularly microfibers) to the soil environment [225]. Hassan et al. [226] addressed the presence of plastic waste in domestic wastewater. This study concluded that it is crucial to implement technologies that can enable sustainable sludge disposal because of the high levels of plastic debris. Otherwise, its continuous use for irrigation can create several problems for our ecosystem. Based on the above discussion, it can be stated that the discovery of plastic particles in fresh water and wastewater has increased worries about the effectiveness of the water treatment sector and the use of wastewater for irrigation, as its direct use can negatively affect crops and the public due to exposure to potentially harmful particles [227].

4.2. Status and Impact of Plastic Pollution in Soil

The foremost roles of soil are sustaining and maintaining biodiversity, moderating nutrient cycling, providing a growing environment for plants, and helping to produce food. Soil also plays a role in atmospheric CO_2 absorption and sinking. Therefore, it is essential to have up-to-date knowledge of the impact and status of plastic pollutant deposits in soils globally [228]. Plastic pollutants are one of the most widespread contaminants in soils in many areas worldwide and are increasing each day. Plastic harms human health, plant growth, nematodes, earthworms, and soil properties [229–231]. When plastic particles are deposited, some stay in the soil and run off with excess water, eventually ending up near water bodies [232]. At the same time, some might be transported vertically into the subsoil layers over time and eventually join the groundwater aquifers [233].

A study by Johansen et al. [234] stated that the content of MPs and NPs in soil depends on several factors, from fertilization to agricultural inputs such as mulching, irrigation, and peeling of paint from farm machinery, as well as deposition from the air. The highest MP and NP concentrations in soil are 0.224 g plastic/kg dry-weight soil or 5.3 $\times$ 10^5 particles/kg dry-weight soil. The above figures are obtained from the results of 30 different research studies. However, the highest MP and NP concentrations found in soils near industrial and urban areas were 67.5 g plastic/kg dry-weight soil or 2.6 $\times$ 10^7 particles/kg dry-weight soil. Crop yield can decrease when the residual plastic film in the soil exceeds 550 kg ha^{-1} particles [235,236]. Other studies have indicated that a threshold range of plastic particles from 50 to 600 kg ha^{-1} can significantly reduce crop yield [237–239]. Based on the above recommendations, Zhao et al. [240] conducted a three-year experiment to determine the effects of plastic residues from landfills on maize crop productivity using three plastic sizes (0.4 × 0.4 cm^2 (small), 4 × 4 cm^2 (medium), and 10 × 10 cm^2 (large)). The experimental data showed that medium-sized plastic residues significantly decreased crop yield compared to the control treatment. This study reported that all plastic types and sizes would gradually be degraded, and soil health could get progressively worse. Plastic debris could ultimately negatively affect the sustainability of agricultural output. It can alter the soil's chemical and physical properties, including bulk density, water-holding capacity, soil structure, and migration of plastic particles into groundwater aquifers [241–246]. The availability of plastic particles in the soil can change soil organic carbon in the short term, leading to an overestimation of soil organic carbon during the quantification process. It can also alter other soil nutrient properties by raising soil chemical properties, organic nitrogen, and ammonium nitrogen [247]. Hodson et al. [248] stated that plastic debris can absorb heavy metals. Also, researchers have shown that a geochemical reaction between metals and plastic particles may occur when heavy metals are released into the soil. Recent research has revealed that plastic can be a vector for environmental contaminants. When plastic is discharged into the environment, it comes into contact with organic contaminants that originate from various human sources, including landfill leachate, urban runoff, and wastewater. Specific organic contaminants, including pesticides, herbicides, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons, are crucial elements that affect the health of the soil ecosystem [249,250]. A number of creatures depend on the soil system for their habitat. It is also conceivable that many animals may be unable to digest plastic bits that they have unknowingly consumed from the soil, hindering food from passing through their digestive systems [251,252]. However, soil fauna, especially earthworms, can digest plastic particles by crushing fragile fragments. Numerous researchers have noted that earthworms can consume enormous amounts of plastic debris from the soil, which can damage their digestive systems and lower their chances of survival [253]. According to Rillig and Bonkowski [254], flagellates and ciliates, which are native filter feeders, may be especially vulnerable to the adverse effects of consuming plastic particles. Due to adhesion, excretion, and death, earthworms can carry small plastic particles over a significant distance when they migrate. According to research, earthworms play a substantial role in the movement of plastic particles through the soil; these creatures mainly carry tiny plastic microbeads downhill [255]. In addition, oribatid mites can carry plastic particles up to 9 cm in soil and alter soil moisture and structure [256]. According to [257–259], microbes are integral to soil ecosystems. They are critical to biogeochemical cycles, which include the mineralization of organic matter, the biodegradation of organic contaminants, and the cycling of nutrients. Fu et al. [260] reported that there were fewer plastic particles in greenhouse soils than in open fields, with fragmented and fibrous plastic particles making up most of the particles. Nevertheless, over 80% of the plastic particles were smaller than 1 mm, suggesting they could enter the food chain and endanger human health.

A Meta-analysis (based on the results of 781 paired observations from 73 publications exploring the overall effects of plastic pollution on soil phosphorus) conducted by Zhou et al. [235] suggested that plastic particles potentially threaten soil fertility and plant productivity and have adverse effects on soil phosphorus. Previously, Brown et al. [261] reported that plastic particles directly or indirectly affect plant growth and phosphorus concentration. Furthermore, plastic particles in soil may carry toxic materials that suppress soil microbial activity. For instance, additions that contain plastic particles, such as plasticizers, flame retardants, antioxidants, and photo stabilizers, may inhibit soil microbial activity. A decline in soil microbial biomass, phosphorus, and phosphatase activity would directly result from the detrimental impacts of plastic particles on microbial activity [262–265].

4.3. Status and Impact of Plastic Pollution in Plants

The availability of plastic debris in the soil ecosystem is alarming, as it can accumulate in plants cultivated in contaminated soils and affect consumers by directly entering the food supply chain. Plastic pollution in agriculture adversely affects the soil ecosystem and plant growth. People are interested in learning more about how plastic particles affect plant growth and biomass quality and whether plants may absorb plastic particles from the soil ecosystem and accumulate them in plant root systems [266]. Plastic particles have significant adverse impacts and can alter the growth of cultivated plants. Carbon allocation and biomass production are two indicators of this shift in plant growth because plastic particles can infiltrate plant roots and impede water and nutrient absorption, causing genotoxicity and physiological toxicity and directly influencing plant development and phosphorus concentration [267,268]. Plastic pollution disrupts the soil ecosystem and harms plant survival and growth by changing the chemistry of the soil. Unhealthy compounds may be able to accumulate on soil surfaces due to the presence of plastic particles, which would be difficult to accomplish in a soil ecosystem. It can also create a barrier between the plants and sunlight (preventing photosynthesis), impede rainwater penetration into the soil, affect oxygen circulation, and reduce the soil's ability to retain moisture. Large plastic pieces such as bags, bottles, and fragments on the soil surface can destroy plants through compaction. Plastic accumulation can create a layer of debris, reducing pore space and limiting air, water, and root movement. Plastic debris can restrict root growth and deep penetration, cause soil erosion, and expose plant roots. It has previously been discovered that various crops, including broccoli, apples, pears, lettuce, and carrots, contain plastic particles. As a result, there is a significant chance that humans may consume plastic particles from plant-based materials [269,270]. Plastic consumption harms the human body by interfering with the neurological, gastrointestinal, excretory, and respiratory systems [271–273].

According to studies, plastic particles can be absorbed by plant roots and relocated to aerial sections of the plant [274]. This plastic absorption can reduce crop yield and grain biomass [275,276]. Regarding phytotoxicity, plastic particles stimulate oxidative damage and other metabolic changes in plant tissues [277,278]. They also significantly impact mineral composition, seed germination, root and shoot growth, and growth [275,276]. According to Lozano and Rillig [279], certain plant species, particularly invasive ones, may spread more efficiently due to soil modifications brought on by plastic debris. However, soils exposed to plastic fibers may result in lower crop yields and a rise in the application of herbicides.

Furthermore, the growth of edible parts of various crops has been inhibited by plastic exposure: this includes the roots of carrot and maize [280–282], lettuce (weight, leaf area, and height) [283], Chinese cabbage (weight) [284], and wheat grains [285]. Various sizes and concentrations of plastic particles have been shown in several studies to have distinct effects on plant nutrient absorption and translocation. Nanometric particles were transferred to shoots, while plastic particles smaller than 1 μm were discovered in root stele. The accumulation of various plastic particles in the roots and leaves of Arabidopsis, carrots, lettuce, maize, mung beans, rice, and wheat plants has been documented in previous research. Certain plant species can absorb plastic particles at any point in their growth, even in the very early stages, less than seven days after sowing [286]. Additionally, it was discovered that certain plastic particles could influence the stomatal restriction of photosynthesis by causing stomatal closure and thereby lowering water availability. This occurs because plastic particles in soils can change the water cycle, significantly impacting water uptake by roots. It also occurs because blockage of cell walls and aquaporins in roots prevent water absorption [287]. By employing plastic particles with various sizes as an influencing parameter, previous studies discovered a decrease in photosynthetic gas exchange variables in maize, lettuce, and rice leaves. It was found that various plastic particles changed the concentrations of reactive oxygen species and antioxidant enzymes (catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD)) in the roots and leaves of various crops [288–291]. According to a study by Hartmann et al. [292], more research is required to fully understand the mechanisms underlying the variable plastic particle-induced toxicity in plants, as most of the available data describing the impacts of diverse plastic types, sizes, and concentrations are still descriptive. Furthermore, most trials are conducted under controlled conditions, which may reduce the effects of outside factors such as interactions with the microbiota, other chemical compounds, and ambient fluctuations. Therefore, to truly understand the impact of plastic pollution in natural habitats, these factors must be carefully examined, with a primary focus on how they affect plants used to produce food.

5. How Can We Sustainably Mitigate Plastic Pollution in Agriculture?

The invention of plastic products revolutionized the development of the agricultural sector by significantly improving performance and enhancing crop production. At the same time, it also brought several visible and invisible problems to the agricultural sector [293]. In the process of production and the operation of agricultural activities, a large amount of plastic waste is ineffectively treated, collected, or managed, and the rate of reuse and recycling of plastic waste generated in the agricultural sector is low (<10%) [294].

Throughout our literature review, we found that at a global scale, several governments, nongovernment organizations, and companies are making great efforts to discover feasible solutions and multiple strategies to cope with plastic pollution in agriculture. The complete elimination of plastic products from agriculture may not be possible. However, there are effective strategies for lessening its impacts using different approaches involving innovation, material design, changes in usage practices, education, and behavior change among stakeholders in agriculture, and policy and regulation collaboration among policymakers, environmentalists, researchers, industries, and farmer's organizations to find a balance between economic interests and environmental sustainability. By adopting the above strategies, the agricultural sector can reduce reliance on traditional plastic and minimize the environmental impact associated with its use. Generally, plastic waste mitigation strategies vary across locations globally. Many stakeholders consider that the adverse effects can be prevented using the "R" model (Refuse, Reduce, Redesign, Reuse, Recycle, and Recover) [295–297]. It can also be mitigated using the following recommendations: (1) eliminate the most polluting plastic products; (2) replace conventional plastic with natural or biodegradable alternatives; (3) promote reuse methodology; (4) improve waste management; and (5) introduce producer responsibility on collecting and processing agricultural plastics. According to Steven and Octiano [298], Mashood et al. [299], and Vox et al. [300], biobased and biodegradable plastics are currently considered the solutions for achieving this sustainable expansion of the plastic sector and providing a vital substitute for petrochemical or conventional plastics in the near future. Compared to synthetic plastics, biodegradable plastics aim to create a more sustainable and environmentally friendly world with a lower environmental effect.

Furthermore, renewable resources like corn, sugarcane, or vegetable oils are used to make biobased polymers. These materials have several uses in agriculture, including for making trays, plant pots, and packaging. Biobased plastics may be recycled or composted and have a lower carbon footprint. Jute, coconut coir, and hemp are natural fibers that can replace plastic materials. These fibers can be utilized to create packaging, blankets to stop erosion, and plant pots. According to Campanale et al. [301], biodegradable plastic mulches (BDMs) can be an environmentally friendly substitute for polyethylene (PE) mulch films in agriculture. BDMs are tilled into the soil, where they can biodegrade with soil, whereas PE films need to be removed after use. A substitute for agricultural development that prevents the buildup of MPs and NPs in soils might be bioplastics, particularly biobased and biodegradable ones [302,303]. Blanke [297] reported that many publications have addressed using substitute biodegradable polymers for the cultivation of several crops, primarily for short growing cycles on bare soils, although they are inappropriate for use as long-term coverings over uneven terrain. Their primary ecological and practical benefit is that they can be buried in the ground and left in the field for microorganisms to break down. However, a drawback of biodegradable films is that they are vulnerable to weathering and chemicals applied to crops and soil microbes, much like plastic films. As a result, there is a chance that the soil will not be fully covered throughout the crop cycle. Kasirajan and Ngouajio [304], and Greer and Dole [305] reported that photo-biodegradable polyethylene films made of organic starch had been developed and used in agriculture. They can increase the temperature, preserve soil moisture, raise yield better than plastic films, and degrade after use. Photodegradable plastic mulches have proven effective but unreliable and expensive; their degradation is also slower in areas with less solar radiation. Photodegradable plastics or Oxo-degradable plastics also harm the environment because they produce MPs and NPs. Other biodegradable options include mulching with a thick layer of compost, cover crops (living or rolled/mowed), straw, or even wood chips, depending on the crop.

In addition, farmers use several non-conventional water sources, including domestic and municipal wastewater, to irrigate their cultivated crops, especially when conventional water resources are scarce [306]. The improper use of untreated water sources, especially wastewater, in agriculture can lead to the accumulation of heavy metals, other toxic elements, and plastic pollutants in soil and plants [307,308]. Therefore, wastewater must be treated before unloading into spillways or for irrigation practices by removing plastic particles from municipal wastewater. As wastewater streams concentrate on plastic debris, they also offer an opportunity to reduce the plastic pollution entering the agricultural sector. According to Lau et al. [309], an estimated 78% of plastic waste can be removed if all feasible reduction pathways are followed. These include lowering consumption, increasing reuse, collecting and recycling waste, and accelerating innovation and design in producing plastics and plastic products. Additionally, finding the most suitable alternative material to plastic remains challenging. Adopting sustainable farming methods such as regenerative agriculture, efficient waste management, and recycling programs can help mitigate the problem of plastic pollution in agriculture.

Microbial Mitigation of Plastic Pollution

The sections above showed that the accumulation of plastic waste and its environmental impact on the ecosystem and human health are of huge concern. Therefore, several mitigation strategies are adopted to cope with plastic pollution, including photodegradation, thermo-oxidative degradation, and biodegradation [310,311]. Compared to others, microbial mitigation of plastic polymers offers sustainable routes to plastic production and waste management [312]. Natural plastic decomposition is a common phenomenon in which living organisms, especially microbes, transform complex organic matter into a simple organic substance. The microorganism obtains nutrients from the plastic via the enzymatic degradation process. Plastic waste serves as the source of energy and carbon required for their growth and development. It is a vital part of recycling materials by the natural ecosystem [313]. Plastic materials can be degraded under either anaerobic or aerobic conditions. Aerobic bacteria utilize O_2 as an electron acceptor and break down the complex organic chemicals into simpler forms, often producing CO_2 and water as the end products [314]. Aerobic and anaerobic decomposition act as a significant environmental component for the natural remediation of contaminants at many harmful waste sites. In anaerobic decomposition, the microbial mechanism degrades the organic pollutants without the involvement of O_2. Certain anaerobic bacteria use carbon dioxide, manganese, sulfate, iron, nitrate, and organic chemicals as electron acceptors during the degradation process to form simple products [315]. In addition, microorganisms adhere to the surfaces of plastics and discharge chemicals (enzyme blend) that can break the chemical bonds between plastic polymers (see Figure 6). Small subunits of the plastics are taken up by the microorganisms and are then metabolized to CO_2 and other by-products by another set of enzymes. Energy is discharged from this reaction and utilized by the organism for other functions, including amassing biomass [316].

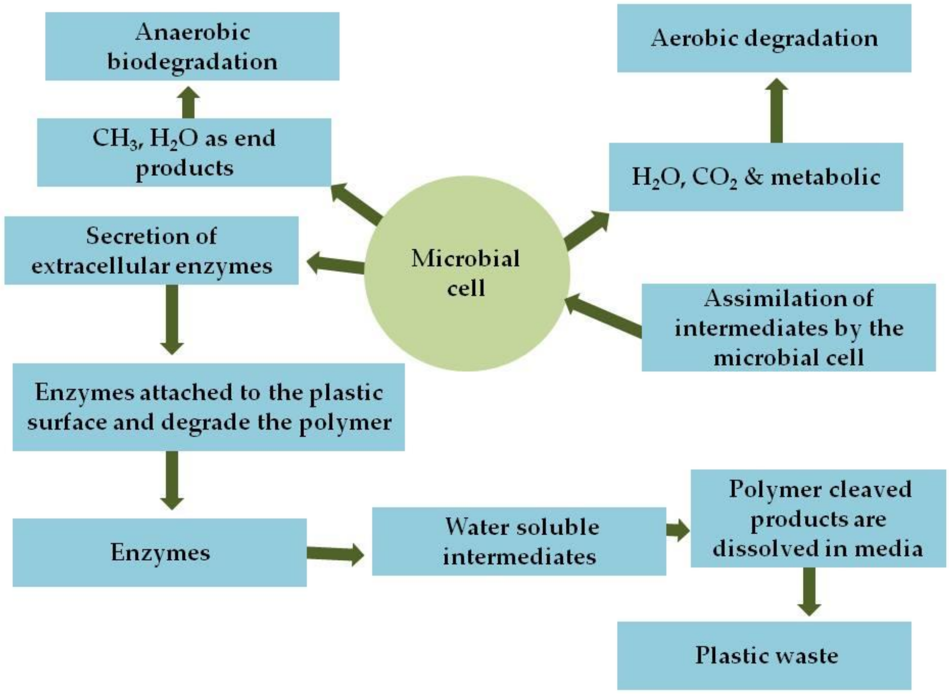

Figure 6. Microbial mitigation of plastic polymers (redrawn from [311]).

A study by Rutkowska et al. [317] reported that microorganisms such as bacteria, fungi, and algae could degrade polymer materials through their metabolic activity, the so-called "biodegradation", without the involvement of heat energy under aerobic or anaerobic conditions. There are various reports on polytene degradation by microbes, for example, *Pseudomonas* sp. and *Bacillus cereus* [318]; *Streptomyces*, *Phanerochaete chrysosporium*, *S. setonii* 75Vi2, Viridosporus T7A, and *S. badius* 252 [319]; *Pseudomonas*, *A. nidulance*, *B. subtilis*, *P. vulgaris*, *S. aureus*, *A. niger*, *S.lactis*, *A. glaucus*, *A. flavus*, *Penicillium*, and *M. luteus* [320]; *Aspergillus* sp. and *Aspergillus versicolor* [321]; *P. aeruginosa*, *P. putida*, and *P. syringae* [322] and *B. megaterium*, *Brevibacillus*, *B. cereus, and B. subtilis* [323].

6. What Do We Know and What Remains to Be Learned about Plastic Pollution in Agriculture?

Plastic pollution in the ecosystem is a primary societal concern. Plastic debris is made of polymers and additives that evolve over time. Plastics are present at the macro-scale in the form of MPs and NPs, formed by the natural erosion of larger plastic particles through physical, chemical, or biological processes. The scientific community is tracking these plastic types and sizes in different environments to understand how micro- and nano-plastics affect different organisms. According to Gehyer et al. [324], plastics make up around 79% of the waste that ends up in landfills in the terrestrial environment.

Additionally, the soil is a substantial sink for plastic pollutants such as MPs and NPs, and numerous routes allow MPs and NPs to infiltrate the soil environment [325,326]. Therefore, the issue of plastic waste appears to be a growing problem globally. Previously, plastic waste was understood to harm marine life. However, scientists have recently begun to realize the impact of MP and NP pollution on terrestrial ecosystems such as crops, livestock, humans, and the environment. Recent discussions have focused on the possible effects of MPs and NPs on plants and the problem of crop food safety. Subsequent research has shown that NPs can be absorbed by plant roots and then move to the aboveground aerial tissues. Research has demonstrated that MPs and NPs can cause physiological changes in plants, including alteration of gene expression and root exudate patterns, as well as a decrease in growth, photosynthesis, and antioxidant activity. Most published studies have focused on the dispersion, possible toxicity, and transfer of MPs and NPs to aquatic environments and human food sources. However, investigating the possible detrimental impacts of MPs and NPs on terrestrial plants and crop productivity is also desperately needed. Moreover, the overall impact of plastic particles on plant growth and soil physico-chemical properties is complex and depends on factors such as the type of plastic, the size of the plastic particle, the concentration of plastics in the soil, and the plant type (species). However, plastics can have both positive and negative effects on plant growth; therefore, more research is needed (1) to understand the environmental impact of plastic pollution, (2) to protect human health and food security, (3) to identify the different plastic types and concentrations that are most harmful to plants, and (4) to develop sustainable agricultural practices. Plastics are of different types and have different sizes and concentrations, each with a different effect. Therefore, the following questions could be answered using field experiments: (1) Do different types, sizes, and concentrations of plastics in soils with varying textures affect plants and soil? (2) How does the addition of biochar influence the bioavailability of plastics in soil, and what are the optimal types and concentrations of biochar needed to improve plant growth and resilience to plastic stress in different soil textures? (3) How do different types, sizes, and concentrations of plastics affect plant growth and development under different climate parameters (e.g., temperature, humidity, CO_2 concentration)? (4) How do different types, sizes, and concentrations of plastics affect plant growth and development under different irrigation regimes and irrigation water quality (e.g., deficit irrigation, full irrigation, and over-irrigation)? and (5) How do plant and soil parameters respond under different types of soilless cultivation systems such as aeroponics and hydroponics? Some specific examples of the different types, sizes, and concentrations of plastics analyzed in previous studies are given in Table 2.

Table 2. Specific examples of different types, sizes, and concentrations of plastics analyzed in previous studies.

Plastic-Type	Size	Shape	Concentrations	Plant/Factor	Method
PS, BC, and WS [327]	95–300 µm	NM	0 and 1% (*w*/*w*)	Lettuce	LS
PVC [328]	<0.9 mm	FI	0, 0.1, and 1%	Soil	LS
PES [279]	30 µm	FI	NM (Present and Not present)	Seven species	SLS
PS and CUO [329]	50 nm	SP	1, 10, and 50 mg/kg	Lettuce	LS
BCDM and PVC [330]	0.1–1.0 µm	SP	0 and 100 mg L^{-1}	Lettuce	HP
PS [331]	75.10 ± 0.53 nm	SP	0.05, 0.1, 0.25, 0.5, and 1.0 mg/g	Garlic	LS
PE, PA, and PLA [332]	13 a 500 µm	MN	0, 0.1, and 1%	Cucumber	LS
PS [333]	100 and 1000 nm	NM	0, 0.01, 0.1, 1, 10, and 20 mg L^{-1}	Pakchoi	HP
PET [334]	0.5 µm and 1.0 µm	NM	0.5% and 1.0% (*w*/*w*)	Spinach	-
PS [335]	80 nm	SP	0, 0.5, 5, and 10 mg/L	Spinach	HP
LDPE and PVC [336]	-	FR and FB	0, 0.5, 1.0, 1.5, and 3.0% (*w*/*w*)	Lettuce	SCLS
PET and PVC [337]	40–50 µm	SP	0 and 0.5%	Tomato	SCL
PS [338]	26 nm	NM	0, 10, 100, and 250 mg/L	SR	SMC
PET and PP [339]	98.6–89.9 and 26.5–25.7 µm	NM	0, 0.5, 1.5, and 5%	Pakchoi	SLS
LDPE [340]	13 µm	NM	0, 10, 100, and 1000 mg/L	Tobacco	HP
PS [341]	3 µm	NM	0, 5, 10, 30, 50, and 100 mg·L^{-1}	HV	HP
PTFE and PS [342]	10 µm	NM	0.04, 0.1, or 0.2 g L^{-1}	Rice	HP
PS [343]	100 nm and 5 µm	NM	0, 10, 20, 50, 100, and 200 mg·L^{-1}	Wheat	HP

Note: Biochar (BC); Biochar-derived dissolved matter (BCDM); oxide (CUO); Fibers (FB); Film (FI); Fragments (FR); *Hydrilla verticillata* (HV); Hydroponics (HP); Local soil (LS); Low-density polyethylene (LDPE); Not mentioned (NM); (PES); Polyethylene terephthalate (PET); Polylactic acid (PLA); Polypropylene (PP); Polystyrene (PS); Polytetrafluoroethylene (PTFE); Polyvinyl chloride (PVC); Sandy clay loam soil (SCLS); Sandy loamy soil (SLS); Silty clayey soil (SCL); Solid media culture (SMC); Spherical (SP); *Stevia rebaudiana* (SR).

7. Conclusions

Plastic pollution is a significant problem for the ecosystem and is identified, alongside climate change, as a rising issue affecting biological diversity on Earth. Plastics in agriculture play an ever-increasing role in achieving sustainable goals. The use of plastics in agriculture has improved overall efficiency but led to many visible and invisible problems. Plastics threaten the overall sustainability of agricultural soils, plants, irrigation water, and the environment due to their accumulation and mismanaged recycling activities.

Additionally, recent plastic flux calculations have indicated that plastic concentrations in agricultural settings may exceed previous estimates in the future, and we cannot fully comprehend the existence and abundance of plastics in agricultural settings. Agricultural soils are one of the primary receptors of plastics and are known to contain larger quantities of plastic particles than oceans, especially in urban areas. Several studies have reported that plastics cannot be entirely avoided in agriculture, but their wastes can be managed by following recommendations such as the Refuse, Reduce, Redesign, Reuse, Recycle, and Recover model that can reduce the flow of plastic pollutants in agricultural settings. As we know, plastic particles/waste in agricultural soils and irrigation water come from multiple sources. Although the task is enormous, it is attainable and can be achieved using existing technologies and policies recommended by local stakeholders or policymakers. In addition, developed countries should focus on decreasing plastic consumption in different sectors, controlling single-use plastics, and improving product design and recycling mechanisms.

Author Contributions: Conceptualization, writing—original draft preparation, I.A.L. and T.N.S.; methodology, J.Z.; validation, G.W., S.D. and R.B.; formal analysis, C.Z.; investigation, B.W., R.Z. and X.W.; formatting and revision, S.D., R.B. and B.W.; writing—review and editing, J.Z., G.W. and C.Z.; supervision, H.Y.; funding acquisition, H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the National Key R&D Program (2021YFC3201103), the Natural Science Foundation of China (U2243228, 41830863, 1509107), the Key R&D Project of Jiangsu Province (BE2022351), Yinshanbeilu Grassland Eco-hydrology National Observation and Research Station, Institute of Water Resources and Hydropower Research, Beijing 100038, China (YSS2022011).

Data Availability Statement: No data were used or generated.

Conflicts of Interest: The authors declare no conflicts of interest.

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