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Embracing Nature's Clockwork: Crafting Plastics for Degradation in Plant Agricultural Systems

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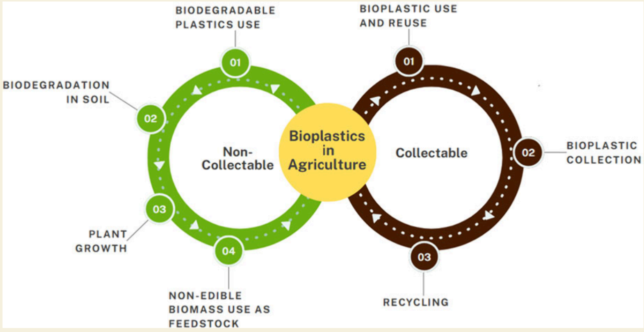
ABSTRACT: In the 21st century, global agriculture confronts the urgent challenge of increasing food production by 70% by 2050 while simultaneously addressing environmental and health concerns. Plastics, integral to agricultural innovation, present sustainability challenges due to their non-biodegradable nature and contribution to pollution. This perspective examines the transition to bioplastics, emphasizing their bio-based origin and their crucial characteristic of being readily biodegradable in the soil. Key bioplastics such as poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), and biomass-derived polymers are discussed, particularly regarding the microplastic generation in soil resulting from their use in specific applications like mulch films, delivery systems, and soil conditioners. Embracing bioplastics signifies a significant step forward in achieving sustainable agriculture and addressing plastic waste. However, it is highlighted that while some bioplastics can be recovered and recycled, special applications where the plastic is in intimate contact with soil pose challenges for recovery. In these cases, that represent more than the 50% of plastics used in agriculture, meticulous design for biodegradation in soil synchronized with agricultural cycles is necessary. This approach ensures minimal environmental impact and promotes a circular approach to plastic use in agriculture.



KEYWORDS: *Sustainable Agriculture, Bioplastics, Agricultural Plastics, Biomass-derived Polymers, Plasticulture, Microplastics*

CHALLENGES AND OPPORTUNITIES IN 21ST CENTURY AGRICULTURE

In the 21st century, agriculture faces formidable challenges in meeting the growing demand for food and minimizing adverse impacts on the environment and human health. The Food and Agriculture Organization of the United Nations (FAO) estimates that the world population will reach 9.7 billion in 2050, requiring a 70% increase in food production compared to 2009 to ensure affordable access to safe and nutritious food.[1] Recognizing these challenges, the United Nations has incorporated into its 2030 agenda the imperative to implement sustainable agricultural practices to eradicate hunger, improve food security, nutrition and sustain ecosystems.[2] Achieving these objectives is essential for a harmonious coexistence between agriculture and the environment.

Over the past 70 years, advancements in agricultural technologies have significantly enhanced the Earth's capacity to meet growing food demands. However, this progress comes at a cost, as agriculture remains a major source of environmental stress (see Figure 1).[3] While there is a pressing need to boost food production, it is crucial to acknowledge that agriculture substantially contributes to issues such as greenhouse gas emissions, energy consumption, land use, groundwater extraction, and deforestation.[4] The interconnection of these factors with global warming has adverse effects on crop yields. Thus, unlocking increased productivity depends on intertwining

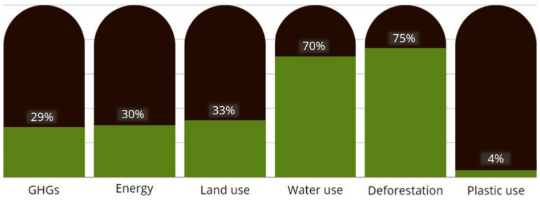


Figure 1. Agriculture's contribution to greenhouse gas emissions (GHGs), energy consumption, land use, groundwater withdrawals, deforestation, and plastic usage.

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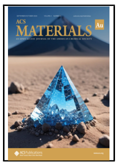

agricultural intensification with ecosystem preservation and fostering technological innovation. Notably, plastics have been pivotal in transforming agriculture, yet it is imperative to ensure that the immediate advantages they offer do not jeopardize long-term sustainability. Striking a balance between agricultural output and environmental preservation, while consistently driving technological advancements, is imperative to effectively tackle the present and future challenges associated with sustainable agriculture.

■ OBJECTIVES OF THIS PERSPECTIVE

This perspective critically examines the transition from conventional plastics to bioplastics as a sustainable alternative in agricultural systems. It emphasizes the bio-based origin and biodegradability of key bioplastics, such as poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), and biomass-derived polymers. The manuscript aims to synthesize recent developments in bioplastic research relevant to agriculture, highlight the importance of bioplastic degradation in soil environments to minimize environmental impact, discuss the challenges posed by microplastic generation in soils and their impact on crop biomass, advocate for tailored bioplastic formulations that optimize biodegradability in soil while maintaining agricultural productivity, and provide recommendations for future research and development to inspire further innovations in sustainable agriculture.

■ PLASTICULTURE

"Plasticulture", a term that describes the extensive use of plastics in agricultural activities, has experienced rapid expansion worldwide, exceeding 15 million tons annually.[5] Its origin dates back to the 1940s with the introduction of greenhouse covers, and since then, its application has been growing steadily. Today, plastics play a crucial role in plant agriculture, ranging from seed coating to the use of mulch films, as well as in various functions such as soil conditioners, controlled release systems for agrochemicals, low tunnels and nets, greenhouse covers, and nursery pots, among others (Figure 2).[6−10]

Presently, the vast majority of these plastics are petroleum-derived and lack *in situ* biodegradability, compromising the sustainability of these practices, especially concerning plastics that cannot be easily recovered after use or come into direct contact with the soil.

Figure 2. Different applications of polymers in agriculture.

A notable example are mulch films, constituting approximately 50% of all plastics used in agriculture and playing a crucial role in crop production.[11] These films offer various agronomic benefits, such as effective weed control, preservation of soil moisture, regulation of both soil and air temperatures surrounding crops and enhancement of nutrient absorption.[10] These advantages result in a significant increase in yield, improved efficiency in water and nutrient management, as well as a reduction in herbicide usage.

The majority of mulch films used are manufactured with low-density polyethylene (LDPE), but they can also be prepared from poly(vinyl chloride), polybutylene, or copolymers of ethylene with vinyl acetate, all non-biodegradable polymers that bring notable environmental and economic drawbacks for conscientious farmers.[9] These polymers persist for many years beyond the intended lifespan of the products for which they were designed, rendering them unsuitable for short-term applications followed by disposal.[12] Additionally, mulch films undergo weakening due to environmental factors during their use and become contaminated with soil residues, microorganisms, and other agrochemical substances.[13] This complicates the physical recycling of these materials, making it impractical and undesirable.

After harvest, it is imperative to remove mulch films to prevent complications with subsequent crops. This involves significant costs for farmers who must allocate labor, equipment, and infrastructure for their collection. Some farmers choose to dispose of their plastic waste in local landfills, while others burn it outdoors, causing environmental and health issues for residents. Some incorporate them into the soil during tillage, posing a significant environmental risk as polyethylene accumulates in the soil, interfering with root growth in the following crop season.[13,14]

An additional case is observed in foliar application products. Agrochemicals are applied through methods such as spraying or soaking, involving direct application to plants and soil. However, these methods carry significant environmental and economic disadvantages. A significant portion of the applied active substances is quickly lost due to leaching, degradation (photolytic, hydrolytic, and/or biological), and volatilization. Only a small fraction, often below the minimum required for effectiveness, reaches the intended location.[15] As a result, maintaining a biological effect demands frequent applications of agrochemicals at high concentrations, resulting in high costs, low efficiency, and serious environmental and health concerns.

Recent research suggests the use of nanotechnology as a promising avenue that provides innovative alternatives to traditional methods of agrochemical application.[16] Nanotechnology involves the use of nanostructured or nanoscale materials as vehicles for the sustained delivery of agrochemical substances.[15,16] Intelligent systems for the controlled release of fertilizers, herbicides, and pesticides allow sustained release, minimizing chemical losses, and efficiently managing resources to enhance crop performance. This technology reduces the need for frequent applications of agrochemicals and enhances safety in substance handling. Ultimately, the benefits include increased efficiency, higher yields, reduced environmental and health impacts, as well as greater profitability.[16]

Furthermore, controlled release systems have expanded their applications in agriculture, offering a novel approach to optimize production. These systems facilitate the targeted delivery of various chemicals to modulate and regulate plant metabolism, aiding in pest management as well.[17,18] For example, quaternized poly(2-(dimethylamino)ethyl methacrylate)-*block*-poly(N,N-dimethylacrylamide) double hydrophilic block copolymers were proposed as nonviral delivery vehicles for double-stranded RNA (dsRNA), enabling RNA interference (RNAi) to combat pest attacks. Encapsulation ensures the protection of dsRNA against nucleases, thus keeping biological activity and avoiding degradation before reaching or internalizing the cells of the insect. This eliminates the need for toxic pesticides for farmers and prevents affecting nontarget organisms. Furthermore, RNAi technology allows for the precise introduction of specific RNA molecules into plant cells without altering the plant's genetic makeup, enabling the modulation of gene expression in pests. This efficient approach allows for plant modification in a nontransgenic manner, alleviating concerns regarding the hereditary transfer of genetic alterations to subsequent generations.[19]

In each of these examples, plants and soil engage with plastics, either by directly applying them to the soil or through direct spraying of particles. The majority of these materials consist of nondegradable polymers. Given the challenges in retrieval, it is crucial for these substances to be designed for absorption and break down into nonharmful components that can be naturally processed by plants, soil, and microorganisms. This design approach not only prevents the generation of hazardous waste but also mitigates potential dangers associated with their transfer through the trophic chain.[20] Additionally, it is crucial that these materials degrade in the soil within relatively short time periods, synchronized with agricultural cycles, to avoid interfering with subsequent crops and prevent the accumulation of permanent residues in the soil.

IMPACT OF POLYMERS ON AGRICULTURE

As mentioned before, the use of plastic has contributed to improving yields and reducing food waste, but the lack of effective systems and processes for the reuse, recycling, biodegradation, and proper disposal of agricultural plastics has led to negative consequences. Evidence indicates that plastics contaminate our environment, affecting biodiversity and soil health, which could threaten productivity and long-term food security.[21−23] The problem is exacerbated when considering that projections indicate a 50% increase in the demand for agricultural plastics by 2030.[24]

The decomposition of plastics used in agriculture poses a significant threat to both food production and human health. Subjected to biotic and abiotic processes, these materials undergo disintegration, persistently fragmenting and dispersing, rendering their elimination increasingly challenging and facilitating the widespread dispersion of micro- and nanoplastics throughout soil, air, and water bodies.[25−27]

These particles not only have the potential to transport other contaminants but also represent a threat in themselves, as the monomers and additives can cause endocrine problems, exhibit mutagenicity, or be carcinogenic.[28,29] Recent research has indicated that the presence of microplastics in soil can be detrimental to plant development, both directly and indirectly. Directly, microplastics inhibit seed germination and root growth by clogging seed pores and adhering to root surfaces, interfering with water and nutrient uptake. Indirectly, they alter soil structure, reduce microbial activity, and disrupt nutrient cycling, negatively affecting the quantity, diversity, mobility, and reproductive capacity of soil biota.[30] Additionally, microplastics alter the physicochemical properties of the soil, including its water-holding capacity and density, potentially limiting root growth, nutrient uptake, and future crop yields.[25]

Moreover, micro- and nanoplastics can impact the accumulation of heavy metals in plants by altering the soil microbial community and causing injury to plants. In a study, two concentrations (100 and 1000 mg/kg) of polystyrene micro- and nanoplastics were used to explore the effects and mechanisms of micro- and nanoplastics on the uptake of Cu, Zn, Pb, and Cd in lettuce (*Lactuca sativa L.*). The microparticles increased the uptake of heavy metals in lettuce by increasing the relative abundance of key metal-activating bacteria in rhizosphere.

Furthermore, the infiltration of microplastics into the soil-plant system poses a significant threat to food safety. There is a growing concern that these microplastics can enter the human food chain, raising potential risks to public health.[31] These tiny plastic particles have been detected in various human tissues, including heart,[32] lungs,[33] blood,[34] human placenta[35] and breast milk.[36] Its presence can induce tissue rejection and inflammation, similar to the impact of particles smaller than 2.5 mm on the human respiratory system. Urgently addressing these challenges is crucial to ensuring both environmental sustainability and the well-being of ecosystems and individuals.

While the general definition of microplastics is primarily based on their size, which includes plastic particles smaller than 5 mm, it is important to acknowledge that microplastics encompass a wide range of plastic materials with diverse characteristics. They can vary in terms of composition, size, shape, and surface properties, all of which influence their interactions with agricultural systems.[37] For example, it has been suggested that microplastics with shapes differing significantly from soil particles, like fibers and films, can exert stronger effects on soil compared to spherical microparticles like beads and particles.[38,39]

Addressing these challenges is critical for environmental sustainability and ecosystem health. Understanding microplastic diversity and their varied interactions within biological systems is crucial for effective mitigation strategies. Current knowledge gaps in microplastic exposure levels through air, food, and water underscore the need for further research to safeguard ecosystems and human well-being.

BIOPLASTICS

The concept of "bioplastic" encompasses two essential principles: the biological origin of raw materials and the ability to biodegrade at the end of the product's life cycle.[40] The shift toward using biological sources is considered an urgent necessity to reduce dependence on fossil fuels and address the challenges of climate change. Simultaneously, the increasing importance of polymer biodegradability is evident in the battle against the accumulation of plastic waste and the resulting environmental pollution. This landscape has prompted various industries to develop products based on sustainable polymeric materials, specifically designed for plant agricultural applications.

Among the available options, several polyesters stand out, with notable examples such as poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHA), which not only provide biodegradability but also originate from biological sources. Additionally, alternatives such as polymers derived from various biomass sources are being explored, thus expanding possibilities in the development of sustainable solutions in the field of bioplastics.

Poly(lactic acid) (PLA)

PLA is a thermoplastic polyester derived from lactic acid (LA). Lactic acid exists in two forms, L-LA and D-LA, due to the presence of an asymmetric carbon atom in its molecule. The ratio and distribution of L- and D-LA in the polymer chains influence the thermal and mechanical properties of PLA. Depending on the type of LA used, PLA can produce either a semicrystalline polymer (PLLA) in the case of poly(L-lactic acid) or an amorphous polymer (PDLLA) in the case of poly(DL-lactic acid).[41] This polymer stands out as an eco-friendly choice due to its biological origin and features like recyclability and industrial compostability, making it an appealing substitute for petroleum-derived plastics.

Despite its advantages, the biodegradability of PLA presents specific challenges in agricultural applications, such as mulching and controlled release systems for agrochemicals. In this context, conditions and timelines may not be ideal for effective degradation in the soil, potentially leading to the generation of micro and nanoplastics.[42] Although efforts have been made to enhance PLA biodegradability through combinations with plant-derived derivatives, or through enzyme-embedded composites, concerns persist regarding the possible generation of micro and nanoparticles during the degradation process.[42−44]

Despite PLA proving successful in various applications, including agricultural mulches like in Ecovio,[45] or products like pots and agricultural mulches marketed by NatureWorks,[46] it is crucial to address the environmental implications associated with its degradation. The biodegradability of PLA products may not align with the specific conditions and timelines required for agricultural applications, particularly when seeking biodegradation in soil without the need for elevated temperatures or specialized industrial composting conditions.

Recently, a comprehensive study was conducted to assess the impact of biodegradable microplastics on agricultural ecosystems.[47] Researchers carried out a controlled experiment focused on PLA microplastics, aiming to analyze the effects of these biodegradable plastics on soil properties, bacterial communities, and corn growth.

The results revealed that PLA microplastics had significantly negative consequences on plant development. These microplastics can pose a threat to microbial conditions and overall soil health in the short term, adversely affecting soil properties and plant growth. Additionally, notable changes were observed in the structure and function of soil microbial communities, raising concerns about the long-term health of these ecosystems.

The presence of PLA microplastics above 1 wt % showed a significant reduction in both the aboveground and root biomass of corn, indicating a phytotoxic effect.[47] Another research also highlighted a similar impact on the total biomass of rice when exposed to concentrations of 10 wt % of PLA microparticles.[48] These findings suggest that beyond certain thresholds, both conventional and biodegradable microplastics can have substantial negative consequences on plant growth and development.

Similarly, the application of PLA particles to transport agrochemicals has been the subject of multiple investigations, but a careful assessment of their environmental fate is required.[49−51] While PLA represents a competitive option with favorable properties, its continued expansion demands a conscientious evaluation of its environmental impact. It becomes imperative to conduct additional research to gain a deeper understanding of the ecological risks associated with the use of biodegradable plastics, such as PLA, in soil ecosystems, ensuring sustainable agricultural practices in the long run. Consequently, it is essential to urgently monitor the quantity and frequency of biodegradable plastics used in agricultural activities along with conventional plastics.

Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates (PHA) stand out in the realm of sustainable bioplastics, recognized for their role in replacing petrochemical plastics. The versatility of these bioplastics in various applications makes them relevant in the quest for sustainable alternatives. They contribute to sustainable development goals by addressing environmental concerns such as dependence on fossil fuels and issues related to the impact of plastics on health and food safety, thereby supporting the global sustainability initiative of the United Nations.

PHAs are linear polyesters naturally produced and stored in granules by various microorganisms, including bacteria and archaea.[52] They function as energy reservoirs and form under conditions of essential nutrient scarcity, such as oxygen, nitrogen, and phosphate deficiency, when there is an excess of carbon sources in the environment.[53,54] In this context, the fermentation of available sugars, lipids, alkanes, alkenes, and alkanoic acids, initiates the synthesis of PHAs, which accumulate in their cells in an amorphous form within the granules.

The final composition of PHAs can vary depending on the type of bacterial species and the carbon source used, offering flexibility to adjust the physical and biodegradable properties of the polymers according to specific needs. Additionally, PHAs are classified based on the number of carbons present in a monomer, dividing them into three groups: short-chain PHA ($\leq$5 carbons), medium-chain PHA (6 to 14 carbons), and long-chain PHA (more than 15 carbons).[54] This broad spectrum of PHAs offers distinctive properties; PHAs with short side chains exhibit characteristics similar to polypropylene, while those with longer side chains present elastomeric properties. In the commercial realm, some notable PHAs include poly(3-hydroxybutyrate) (PHB), poly(3-hydroxybutyrate-*co*-4-hydroxybutyrate) (P3HB4HB), poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV), and poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate) (PHBH).[55]

In agriculture, PHAs are used as mulch to enhance soil structure, retain water, and prevent contamination, thereby benefiting crop yields. Companies such as Biomer,[56] Danimer Scientific,[57] and GreenBio[58] have ventured into the commercial production of PHAs, particularly in agricultural applications such as mulch and bags for germination and seedling growth. Additionally, the use of these polymers has been reported in the manufacturing of slow-release particles for chemicals like fertilizers, pesticides, and herbicides.[59−62]

PHAs offer environmental advantages compared to conventional plastics, standing out for their exceptional biodegradability in soil and marine environments, properties that position them as an environmentally sustainable alternative. Unlike conventional plastics that can persist for centuries, PHAs are capable of degrading in both aerobic and anaerobic environments, yielding harmless end products such as biomass, CO_2, and water in as little as 20 to 45 days in the presence of moisture and suitable microorganisms, and depending on various factors, such as polymer crystallinity, surface morphology, side chain length, and environmental conditions.[63]

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Despite positive results related to their rapid biodegradation in soil, concerns may still arise regarding their use in agricultural applications where plastics are not collected. In a recent article, Nayab et al.,[64] explored the effects of intentionally prepared PHA microparticles on the performance of corn plants and soil quality. They found that, similarly to non-biodegradable polymer particles like PE or PVC, PHA microparticles (sizes below 1000 μm and at a concentration of 5 wt % in soil) reduced seed germination rates. Additionally, these particles stimulated microbial biomass and enzymatic activity by providing additional carbon resources, altering soil quality and ecosystem multifunctionality. The rapid microbial growth in PHA-treated soils led to nitrogen immobilization and nutrient competition between plants and microorganisms, resulting in a 65% decrease in the plant health index compared to the control group.

However, it is important to consider that contrary to PE or PLA, PHA bulk materials demonstrate a lower propensity for microplastic and nanoplastic accumulation, as highlighted in the review by Colwell et al. (2023).[65] This difference stems from PHAs' reduced susceptibility to embrittlement and fragmentation, attributed to their rapid enzyme-catalyzed depolymerization on exposed surfaces. This process yields soluble products, facilitating their transformation into end products. While microplastics and nanoplastics may arise during biotic hydrolysis due to heterogeneous consumption, they constitute a minor portion of the plastic's overall mass throughout its lifespan. Consequently, a more detailed investigation into the impact of PHA degradation products on soil ecosystems is imperative before drawing conclusive assessments.

Concurrently, the broad adoption of PHAs encounters substantial economic challenges, primarily stemming from their high production costs. The microbial fermentation process utilized to derive PHAs often proves more expensive than both conventional petrochemical methods employed for synthetic plastics and biomass-derived biological materials, thereby constraining widespread adoption.[66] Although PHA production entails lower energy consumption compared to traditional plastic manufacturing, the persistently high production costs pose a significant obstacle. Despite PHAs currently having a considerably higher market price than traditional plastics, around 5 euros per kg compared to 0.8−1.5 euros per kg (average values taken from www.AliBaba.com), global production capacity is expected to continue increasing. With projections of further cost reductions and increased adoption, there is the possibility that PHAs may become a more valuable and cost-competitive material in the future.[67]

In summary, PHAs stand out as fundamental biopolymers due to their high biodegradation efficiency in various environments, making a significant contribution to addressing plastic pollution issues and laying the groundwork for a circular economy. Nevertheless, additional studies are essential to unveil both the immediate and prolonged consequences of their application in plant agriculture, particularly when the aim is to facilitate their biodegradation in the soil after use.

Biomass for Bioplastics

This discussion focuses on the direct utilization of vegetal biomass and its constituent polymers for bioplastics development, distinct from the use of biomass for the synthesis of polyesters like PLA or PHA.

Vegetal biomass, encompassing elements like leaves, straw, and stems, as well as byproducts from the food industry such as peels, skins, seeds, and pomace, emerges as an ideal raw material for the manufacturing of various industrial products, including bioplastics.[52] These materials capitalize on their status as waste not intended for human consumption. Beyond being carriers of essential polymers such as cellulose, pectin, hemicellulose, lignin, starch, and proteins, these residues also contain compounds with antimicrobial, antioxidant, and phytoactive properties, adding additional value to their potential applications in the industry.[68]

The utilization of vegetal biomass for bioplastic production not only taps into abundant resources not destined for human consumption but also entails significant environmental benefits. Vegetal residues undergo photosynthesis during their growth, a process that consumes carbon dioxide. Consequently, bioplastics derived from these residues achieve a nearly zero carbon impact. In essence, bioplastics function as carbon sinks, actively extracting CO_2 from the atmosphere and securely storing it throughout their entire lifecycle.[68] Developing materials for cultivating food plants using the residues obtained after harvest presents a prime illustration of a circular economy.

An additional and significant advantage of vegetal residues lies in their ability to yield biodegradable bioplastics, which is crucial for agricultural applications. However, the complexity of natural environments, with variables such as moisture, microorganisms, oxygen, sunlight, and temperature, makes it extremely challenging, if not impossible, to control and guarantee the times involved in the degradation of these plastics. This challenge is especially significant, considering that biomass-derived polymers often biodegrade at notably high rates compared to traditional plastics, completely breaking down in soil within a few weeks or months.[69,70] This rapid degradation raises concerns about the potential loss of the desired function of the bioplastic before it can fulfill its intended purpose.

The adaptation of the molecular architecture of polymers emerges as an essential strategy to regulate biodegradation times and modify their properties, especially when intended for application in agricultural environments that demand moisture resistance, the primary trigger for biodegradation processes.[71] This key approach allows for adjusting the degradation rate and the resulting products.

Polysaccharides, due to their versatility with numerous reactive functional groups such as hydroxyl, amino, and carboxyl, are highly adaptable to chemical reactions that introduce new groups into their structure.[72] Any modification or additive introduced in the manufacturing process carries the potential to impact the degradability of materials, alter the nature of decomposition products, and ultimately shape the environmental destiny of the product. This phenomenon is evident, for instance, in cellulose derivatization, where the degradability is intricately linked to the degree of −OH substitution.[73]

Taking hydrogels used for soil conditioning as another example, the nuances of their composition and manufacturing processes significantly influence their environmental behavior. These materials, upon integration into the soil, can absorb substantial amounts of water when available and release it as needed by the plants. Their use facilitates more efficient irrigation management, and increases water retention, and soil porosity, providing plants with moisture and an environment conducive to root development.[70,74] Although commercial variants have proven effective in water retention, they often rely on petroleum-derived polyacrylate or polyacrylamide polymers and lack biodegradability.[75] Alternatives described in the literature frequently explore natural polysaccharides as

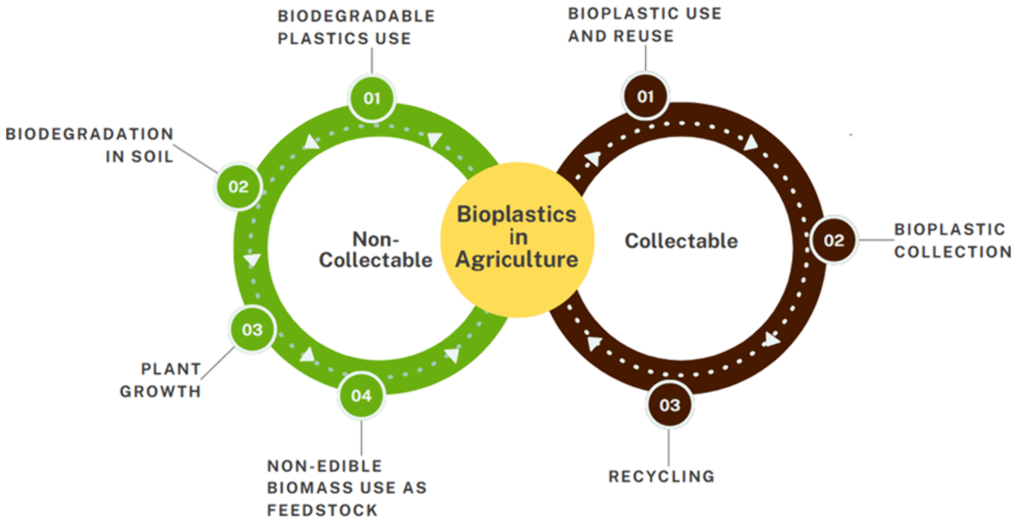

Figure 3. Perspective on the utilization of bioplastics in agriculture. Bioplastics when collected entirely postuse, should undergo recycling or reuse. Noncollectable plastics must exhibit complete biodegradability in the soil.

substitutes.[76] However, a significant portion relies on the use of acrylates and acrylamide monomers for cross-linking and achieving higher swelling percentages, raising concerns about the potential for incomplete degradation of hydrogels, leading to the generation of micro or nanoplastics, a factor that has not been studied.

In the case of mulch films, numerous publications report their development from biomass-derived polymers and even through the direct transformation of biomass into bioplastics.[69,77] The literature review underscores the importance of this latter approach, where biomass, through appropriate techniques, can be redissolved and molded without the need for extensive depolymerization.[52,78] This technique has the potential to generate bioplastics with comparable properties to petroleum-derived plastics, featuring moisture resistance and soil biodegradability. However, commercially available products with these characteristics are not yet found, emphasizing the need for a greater focus on this type of resource and its transformation into bioplastics.

Furthermore, biomass-derived mulch films offer an additional advantage by serving as natural fertilizers and allowing the integration of biostimulant substances.[69,79] Another benefit is the possibility of developing sprayable agricultural mulches.[77] These are solutions containing biomass-derived polymers, plasticizers, and relevant fillers. They are sprayed onto the soil, undergoing gelation or cross-linking to form a protective layer that may yield benefits comparable to or surpassing those of traditional PE mulch films. Despite facing challenges in regulating soil temperature and moisture, likely contributing to their absence from the market, these films offer on-site biodegradability.[79]

In the realm of controlled release of agrochemicals, natural polymers, encompassing polysaccharides,[80,81] proteins,[82] and lignin,[83] play a crucial role. These polymers possess ideal properties for such applications, marked by attributes like wide availability, cost-effectiveness, nontoxicity, biodegradability, and biocompatibility. Their versatility is evident in diverse chemical structures, including linear, branched, cross-linked, neutral, or positively/negatively charged configurations. Undoubtedly, biomass-derived polymers hold a promising future in promoting sustainable practices within plant agriculture.

CONCLUSIONS AND FUTURE OUTLOOK

We embarked on this perspective with a crucial acknowledgment: the imperative to augment food production a 70% by 2050 to accommodate the burgeoning global populace. Within this imperative, we delved into the realm of plastics and their potential in plant agriculture. The introduction of biobased and plant-derived polymers has emerged as a promising approach to pursue this goal sustainably. At the core of our discussions was the necessity for material designs that utilize renewable resources without compromising food production. A critical aspect of this effort involves ensuring that these materials do not disrupt both short and long-term agricultural sustainability. Of particular concern is the widespread presence of micro and nanoplastics, which pose significant risks to soil and plant health. This emphasizes the urgent necessity for conscientious, ecologically sound solutions.

In this regard, various inedible plant wastes generated throughout the entire food production chain have been highlighted as valuable sources for the development of new materials. However, focusing solely on valorizing these wastes is not enough to achieve sustainability. Single-use applications are especially risky, considering that biomass requires more time to regenerate than the lifespan often given to these materials.

The sustainable management of agricultural plastic waste requires prioritizing collection, reuse, and recycling.[84] However, in cases where plastics cannot be recovered or their recovery is challenging due to integration with the soil and possible fragmentation, it is preferable to develop *in situ* biodegradable alternatives (Figure 3). Here, awareness of the limited regeneration of biological resources and careful consideration of material life cycles are essential to ensure environmentally friendly and socially responsible agricultural practices.

Bioplastics offer three fundamental advantages: (1) the potential to be derived from renewable sources such as biomass, (2) the ability to align with the crop's life cycle, and (3) *in situ* biodegradation, eliminating the need for removal from the soil after use. The efficient transformation of renewable resources into useful polymers that do not generate nanoplastics and do not interfere with food production poses a fundamental challenge. Future research should address performance improvement of materials directly derived from biomass leveraging not only biotechnology, but also additives, possible functionalizations, and new supramolecular architectures to optimize the efficiency of transforming renewable feedstock into high-performance materials. Moreover, there is a pressing need for the design of plastics capable of facile transformation into nontoxic soluble products through enzymatic processes. This facilitates their bioassimilation by microorganisms without undergoing fragmentation and forming micro and nanoplastics during their end-life, addressing critical environmental concerns.

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Notes

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