

Review

# Current Trends of Polymer Materials' Application in Agriculture

Kamila Lewicka <sup>1</sup>, Izabela Szymanek <sup>1</sup>, Diana Rogacz <sup>1</sup>, Magdalena Wrzalik <sup>2</sup>, Jakub Łagiewka <sup>1</sup> , Anna Nowik-Zajac <sup>1</sup> , Iwona Zawierucha <sup>1</sup> , Sergiu Coseri <sup>3</sup> , Ioan Puiu <sup>4</sup> , Halina Falfushynska <sup>5</sup>  and Piotr Rychter <sup>1,\*</sup> 

- <sup>1</sup> Faculty of Science and Technology, Jan Dlugosz University in Czestochowa, 13/15 Armii Krajowej Av., 42-200 Czestochowa, Poland; k.lewicka@ujd.edu.pl (K.L.); izabela.szymanek@doktorant.ujd.edu.pl (I.S.); d.rogacz@ujd.edu.pl (D.R.); jakub.lagiewka@doktorant.ujd.edu.pl (J.L.); a.zajac@ujd.edu.pl (A.N.-Z.); i.zawierucha@ujd.edu.pl (I.Z.)
- <sup>2</sup> Faculty of Law and Economics, Jan Dlugosz University in Czestochowa, 2/4 Zbierskiego Str., 42-200 Czestochowa, Poland; m.wrzalik@ujd.edu.pl
- <sup>3</sup> "Petru Poni" Institute of Macromolecular Chemistry of Romanian Academy, 41 A, Gr. Ghica Voda Alley, 700487 Iasi, Romania; coseris@icmpp.ro
- <sup>4</sup> Department of Plant Science, Iasi University of Life Sciences, 3 Sadoveanu Alley, 700490 Iasi, Romania; ioan.puiu@uaiasi.ro
- <sup>5</sup> Faculty of Economics, Anhalt University of Applied Sciences, 06406 Bernburg, Germany; galyna.falfushynska@hs-anhalt.de
- \* Correspondence: p.rychter@ujd.edu.pl

**Abstract:** In light of the growing plastic waste problem worldwide, including in agriculture, this study focuses on the usefulness of both conventional, non-degradable plastics and environmentally friendly bioplastics in the agricultural sector. Although conventional plastic products are still essential in modern, even ecological agriculture, the increasing contamination by these materials, especially in a fragmented form, highlights the urgent need to search for alternative, easily biodegradable materials that could replace the non-degradable ones. According to the literature, polymers are widely used in agriculture for the preparation of agrochemicals (mostly fertilizers) with prolonged release. They also play a role as functional polymers against pests, serve as very useful super absorbents of water to improve crop health under drought conditions, and are commonly used as mulching films, membranes, mats, non-woven fabrics, protective nets, seed coatings, agrochemical packaging, or greenhouse coverings. This widespread application leads to the uncontrolled contamination of soil with disintegrated polymeric materials. Therefore, this study highlights the possible applications of bio-based materials as alternatives to conventional polyolefins or other environmentally persistent polymers. Bio-based polymers align with the strategy of innovative agricultural advancements, leading to more productive farming by reducing plastic contamination and adverse ecotoxicological impacts on aquatic and terrestrial organisms. On the other hand, advanced polymer membranes act as catching agents for agrochemicals, protecting against environmental intoxication. The global versatility of polymer applications in agriculture will not permit the elimination of already existing technologies involving polymers in the near future. However, in line with ecological trends in modern agriculture, more "green" polymers should be employed in this sector. Moreover, we highlight that more comprehensive legislative work on these aspects should be undertaken at the European Union level to guarantee environmental and climate protection. From the EU legislation point of view, the implementation of a unified, legally binding system on applications of bio-based, biodegradable, and compostable plastics should be a priority to be addressed. In this respect, the EU already demonstrates an initial action plan. Unfortunately, these are still projected directions for future EU policy, which require in-depth analysis.

**Keywords:** agricultural polymers; ecological agriculture; biodegradable polymers; bio-based polymers; controlled release of agrochemicals; mulching films; functional polymers for agriculture; environmentally friendly polymers; polymers for agriculture; agrochemicals with prolonged activity; European Union; EU legal regulations



**Citation:** Lewicka, K.; Szymanek, I.; Rogacz, D.; Wrzalik, M.; Łagiewka, J.; Nowik-Zajac, A.; Zawierucha, I.; Coseri, S.; Puiu, I.; Falfushynska, H.; et al. Current Trends of Polymer Materials' Application in Agriculture. *Sustainability* **2024**, *16*, 8439. <https://doi.org/10.3390/su16198439>

Academic Editors: Angelo Albini, Vito Rizzi and Matthew Jones

Received: 1 July 2024

Revised: 11 September 2024

Accepted: 24 September 2024

Published: 27 September 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Plastic use in agriculture has increased over the last 70 years to an estimated 12.5 million tons annually [1]. Innovations are more crucial than ever in modern, ecological, and sustainable agriculture. This novel idea pertains to utilizing technology in farming and agricultural operations to boost yield, sustainability, and efficiency in food production. It encompasses a wide range of technological fields, including automation, biotechnology, smart irrigation, and precision agriculture. Significant technological improvements have also been made in fields like artificial intelligence, modern greenhouse operations, cattle technology, and indoor vertical farming. For this reason, more and more smart, innovative, and environmentally friendly materials are required to meet the criteria of ecological and sustainable agriculture.

Polymeric materials have been employed in agriculture for several decades and have become an integral part of agricultural practices. They are used in crop protection against pests and diseases in a variety of forms, including films, fibers, and coatings, making them necessary components in modern agricultural operations. Agricultural films (mulching films) protect against weed growth, prevent water loss, improve soil moisture, and enhance plant growth, thereby improving crop yields. Polymeric films are also successfully used to line irrigation channels and reservoirs. Agricultural fibers are employed to create crop covers, weed barriers, and erosion control mats. Polymeric materials like films, bags, and containers are also employed in packaging to protect agricultural products during transportation and storage. Unfortunately, these practices generate a huge amount of non-degradable conventional plastic in the form of micro- and nano-fragments during and after their use, which can accumulate in soil or surface water, causing negative impacts at high concentrations ( $>240$  kg/ha) [2]. For this reason, biodegradable polymers have become more and more attractive from an environmental protection point of view. Bio-based materials made from renewable raw materials are an alternative to conventional, environmentally persistent polymers, such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), providing a sustainable solution for plastic waste reduction in the agriculture area. Obviously, it is impossible to totally eliminate and replace plastic products in agriculture with biodegradable polymers (for example, membranes for removing runoff agrochemicals during and after treatment). However, the commitment to green agriculture without plastics stimulates the technological development of new environmentally friendly designed polymeric materials [3]. The aim of this study is to review the recent usefulness of both conventional (non-degradable) and environmentally friendly (biodegradable) polymers in the broadly understood agriculture.

## 2. European Union Regulations on Polymer Materials from the Perspective of Environmental Protection and Agricultural Policy

Polymers made from renewable raw materials, including biodegradable polymers, are an important group of materials that could solve both raw material problems and problems related to plastic waste disposal [4] in the future. These polymers can make a significant contribution to reducing the environmental burden, not only by reducing the amount of troublesome plastic waste obtained from petrochemical raw materials, but also indirectly by reducing the consumption of fossil raw materials, which are still the key fuel used to obtain classic, non-degradable plastics. Bio-based, biodegradable, and compostable polymers, as an alternative to the currently dominant conventional plastics, are seen as the antidote to the existing problems of environmental protection, depleting fossil raw materials (mainly crude oil), and environmental sustainability [5]. Only in agriculture, 12.5 million tons of plastic waste is generated annually, leading to the accumulation of huge amounts of macro- and microplastics in soils or surrounding environments [1]. Consequently, new routes are constantly being sought to gradually replace the petrochemical raw material base by other sources, through research into technologies for the production of environmentally friendly polymeric materials, as well as efforts in materials engineering and recycling.

This development of research into the use of renewable resources has also been stimulated by the need to find a more systemic approach in the European Union (EU) policy and legislation, which would form the basis for decisions taken by both the public and private sectors and which would result in strategies set out in national public policies, closely linked to the institutional, legal, political, economic, and social system of each country. Undoubtedly, these actions should lead to ensuring market orientation in order to avoid any destabilizing developments, as well as having a positive impact on the functioning of the single market and preventing differences at the national level leading to market fragmentation. In addition, it is important to integrate environmentally friendly solutions into the EU legal system on a long-term basis in order to implement environmental policies that will make the EU economy more environmentally friendly, protect Europe's natural resources, and guarantee the health and well-being of EU citizens [6]. A solution favorable to the concept of sustainable development is expected to be found, aimed at improving and protecting the environment, e.g., through sustainable production and consumption, combating climate change, protecting marine resources, reversing the degradation of terrestrial ecosystems, global cooperation for environmental sustainability [7], sustainable waste management as well as efficient waste-to-energy conversion. As regards the applications of polymers of a natural origin, sustainability is linked to the reduction of fossil fuel consumption and plastic pollution. The EU strategy should also focus on adapting the life-cycle of plastics to a circular economy [8], while minimizing waste and reducing greenhouse gas emissions. A key objective would be to reduce the consumption of short-life products and increase the recycling and recovery of plastics [9].

One of the purposes of the EU's existence is to protect the environment and the climate [6]. From the point of view of EU legislation on the use of bio-based, biodegradable, and compostable plastics, it is important that legal work is still being undertaken to attempt to further regulate these aspects. In order to achieve this, the EU presents an initial action plan covering the main policies and measures necessary to bring about future developments in EU environmental and climate law. By means of the Communications, it only presents preliminary action plans for the time being. Unfortunately, these are still projected directions for future EU policy, aiming, *inter alia*, to close loopholes in this area and to ensure market orientation in order to avoid any destabilizing changes. As the European Commission (EC) points out, these policies should foster a better understanding of the challenges and benefits of their application, while basing these assumptions on the European Green Deal (EGD) [10] action plan for a circular economy [8,11] and the European strategy for plastics in a circular economy [12]. In addition, the EU Action Plan contributes to the Pollution Elimination Strategy [13], which aims to reduce the amount of plastic waste in the sea by 50% and the amount of microplastics released into the environment by 30% by 2030, as well as the EU Soil Strategy [14], which focuses on preventing soil pollution at the source.

The desired effect would be to create regulations that would allow conventional plastics to be replaced in whole or in part by producing them from bio-based raw materials that could decompose at the end of their life-cycle by converting all their organic components (polymers and organic additives) mainly into carbon dioxide and water, new microbial biomass, mineral salts, and, in the absence of oxygen, methane [15]. The Commission stresses that in addition to the properties of the plastic material, the essence must be seen in the suitable conditions of the receiving environment, as well as being dependent on the relevant time. Therefore, the biodegradation of plastics should be considered not only in terms of the properties of the material, but primarily in terms of a "system-property" in which material-related and environmental factors are equally important.

In the light of these considerations, the first principle when designing new plastics (*inter alia* in the agricultural sector) or developing policy measures should be to treat biodegradation as a "system-property" that takes into account material properties, specific environmental conditions, and risks. Second, the use of plastics that are biodegradable in an open environment should be limited to materials where full biodegradability has

been proven to be within a certain time frame to avoid environmental damage, and to specific applications where the reduced use or reuse is not a viable option and the full disposal, collection, and recycling of plastic products is not feasible. In addition, another challenge faced by ecological agriculture is the additives used to produce biodegradable or compostable plastics, which should also be safely biodegradable and not harmful to the environment. It is then important to put in place regulations that create consistent and scientifically based testing standards and certification systems, an appropriate system of extended product liability, but also a proper product-labeling system that includes labeling and instructions for the correct use and disposal of these products and, in the case of plastics labeled as “biodegradable”, specify the environment for which they are intended and the required timeframe for their biodegradation, expressed in weeks, months, or years.

### *2.1. The European Green Deal, a New EU Environmental and Climate Strategy*

The European Green Deal is a new strategy for growth, which aims to transform the EU into a prosperous society with a modern, resource-efficient, and competitive economy that will achieve zero net greenhouse gas emissions in 2050 and will separate economic growth from the use of natural resources. It also aims to protect, preserve, and enhance the EU’s natural capital and to protect the health and well-being of its citizens by, inter alia, improving the quality of agri-food products and thereby developing ecological agriculture without environmental risks and negative impacts. At the same time, this transition must take place in a fair and socially inclusive manner. A number of initiatives are planned as part of the EGD strategy. Among the most important is a circular economy, which aims to ensure that raw materials are recycled and reused in the economy instead of, for example, being landfilled. To this end, the Commission will develop requirements to ensure that by 2030, all packaging on the EU market will be re-usable or recyclable in a cost-effective manner, or propose an EU model for the separate collection of waste [10].

In the field of ecological agriculture [16], activities, including legislation, are undertaken to reduce the use of chemical pesticides and their associated risks and to reduce the use of fertilizers and antibiotics. The Commission will take action to reduce the use of pesticides and their associated risks to 50% by 2030. To this end, on 22 June 2022, the Commission adopted a proposal [17] to review the Directive on the sustainable use of plant protection products and will promote the greater use of alternative means of protecting crops from pests and diseases. In November 2023, however, the Parliament rejected the proposal for a regulation on the sustainable use of plant protection products, and in February 2024, the Commission withdrew the proposal in the face of supportive action.

### *2.2. A European Strategy for Plastics in a Circular Economy*

The plastics industry is very important for the European economy and putting more emphasis on its sustainability can create new opportunities for innovation, competitiveness, and job creation, in line with the objectives of the renewed EU industrial policy strategy [18,19]. Since 2015, the Commission [20] has made it clear that plastics are of crucial importance and has committed that it “will prepare a strategy addressing the challenges posed by plastics throughout the value chain and taking into account their entire life-cycle”. In 2017, the Commission confirmed that it would focus on the issue of plastics production and use, and that it would aim for all plastic packaging to be recyclable by 2030 [19].

In order to implement a closed loop throughout the life cycle of plastics, it is important to find a solution to deal with the problem of generating more and more plastic waste and releasing it into the environment. According to the EC, one of the main sources of plastic entering the environment is single-use plastic articles. It is worth noting that the EU has already taken action by introducing requirements for Member States to adopt measures to reduce the use of plastic carrier bags [21] and to reduce marine waste [22], as well as to prevent the environmental impact of certain plastic products [23].

### 2.3. EU Soil Strategy 2030—The Benefits of Healthy Soils for People, Food, Nature, and Climate

Soil protection is one of the elements of the European Green Deal; the proposals and objectives for soil protection can be found in a number of strategies, such as the EU Biodiversity Strategy 2030, the Pollution Remediation Action Plan, the EU Climate Change Adaptation Strategy, and the EU Soil Strategy 2030. The EU Soil Strategy 2030 itself sets out a long-term vision that all EU soils will be “in good health” by 2050. Unfortunately, there is still a perceived lack of a comprehensive and coherent soil protection policy framework across the EU. In addition, the 2006 European Thematic Strategy on Soil Protection has become outdated as it is not adapted to the current EU policy context and the evidence-based scientific knowledge available [24]. There is also a risk that, if no action is taken on soil protection, the EU will fail to meet the European Green Deal and the UN Sustainable Development Goals, i.e., to achieve the planned climate neutrality and soil degradation neutrality targets. Furthermore, scientific data show that organic carbon stocks in the top layers of arable soils are declining, and the extent of wetlands and peatlands in the EU is steadily decreasing, with around half of the EU’s peatlands now drained and two-thirds of European wetlands lost irretrievably since the beginning of the 20th century [25,26]. For this reason, the European Parliament has taken action to protect soils, focusing attention on defining a framework and specific measures for the protection, restoration, and sustainable use of soils. Unfortunately, comprehensive and harmonized soil health data from soil monitoring are currently lacking. This is because only some Member States have introduced soil monitoring systems, and even these are fragmented, unrepresentative and unharmonized. Therefore, the proposal for a Directive provides a soil monitoring framework for all soils across the EU, while clarifying a common definition of what is meant by healthy soil. The Directive manifests the current European Commission’s characteristic view that the first and fundamental environmental problem in the EU is the lack of reliable data. In spite of existing legislation [27–31] which addresses the problem of soil protection in a partial way, there is still no legal regulation that addresses the fundamental environmental problem in the EU, which is the lack of reliable data.

EU efforts will focus first on preventing pollution at the source. As part of this, it will take action to reduce the deliberate use of plastic microplastics and the unintentional release of microplastics. In addition, it will develop a policy framework for bioplastics as well as biodegradable and compostable plastics. The Commission stresses the need to adopt biodegradability criteria for certain polymers, such as coated substances and agricultural mulch films, acting, in this regard, in line with the EU Fertilizer Products Regulation (taking into account the revision of the legal status in this respect). The Regulation explicitly stipulates that by 2026, coated substances and formulation additives must meet certain biodegradability criteria. Furthermore, it specifies a requirement to assess the biodegradability of agricultural mulch films in natural soil conditions and aquatic environments across the EU. In addition, the proposed restriction on intentionally added microplastics under the REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) [32] regards polymers, including biodegradable polymers, as announced in the Chemicals Strategy for Sustainability [33]. The Commission is considering extending the registration obligation to certain potentially hazardous polymers [34].

In conclusion, the initiatives taken by the EU to date to prepare Member States for the implementation of a broader climate and energy policy, which involves the EU’s transition to a climate-neutral economy and a change in the current approach to soil management, continue to contribute to the development of successive strategy packages and other initiatives that establish measurable objectives with a clear timetable for achieving the set targets for shaping EU legislation that aims to sustainably use and protect agriculturally used soils. The essence is for EU member states to review implemented agricultural models and to begin managing soils in such a way as to achieve a higher level of effectiveness in reducing erosion, improving the drought resistance of soils and enhancing soil biodiversity in the long term. Undoubtedly, soil protection and the restoration of soil quality have become some of the objectives of the new European Union policy set out in the European

Green Deal [35]. Protecting biodiversity, producing high-quality food, reducing the use of pesticides, caring for soil quality, remediating contaminated soils, increasing carbon sequestration in soils, and protecting wetlands, mainly peatlands [36], are only parts of the sustainable use of agricultural soils in the European Union's policy until 2050.

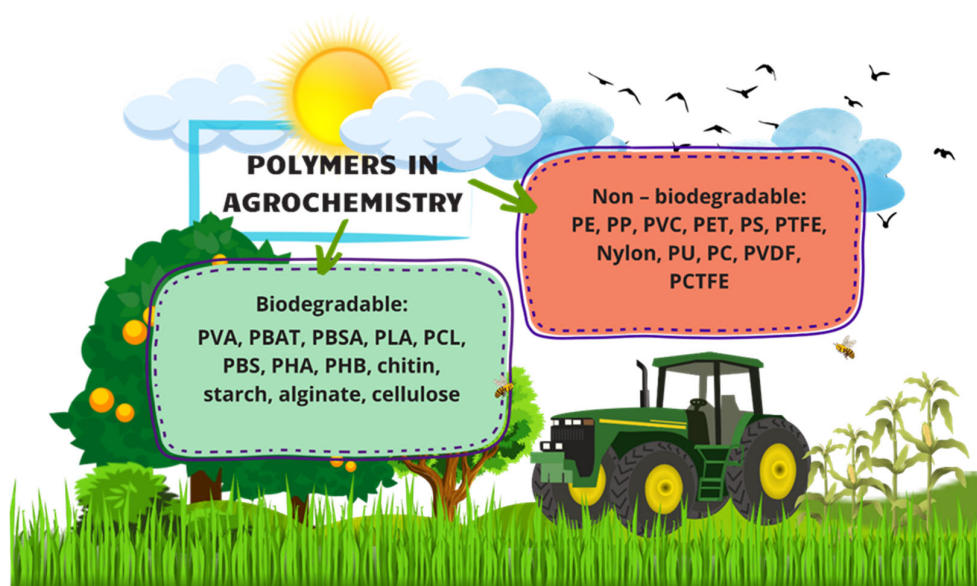
### 3. Polymers and Composites for Agriculture

#### 3.1. Non-Biodegradable Polymers in Agriculture

There is no doubt that polymers, due to their unique properties, are very useful in a wide range of applications and have gained significant attention in recent years. Depending of the final use of polymers, the structure of these macromolecules' chain can be altered to obtain materials with a wide range of properties, such as stiffness, flexibility, elasticity, and degradability. This versatility allows the development of polymers for use in many industrial branches including construction, automotive, electronics, packaging, or agriculture. Unfortunately, although these materials are very useful in our daily life, their widespread use (especially polyolefins) has led to concerns over their impact on the environment because they are not biodegradable and can persist in the environment for hundreds of years. Consequently, the accumulation of plastic waste including microplastics has been noticed in landfills and water reservoirs (especially seawater) in recent years. For these reason, there is an urgent need to develop more sustainable, environmental friendly polymers that can be recycled or biodegraded. The degradation of polymers depends both on environmental conditions and material properties. Temperature, light, oxidation, moisture, the hydrolysis process, microorganisms, and stress conditions are the main environmental factors determining ageing and the degradation/(bio)degradation rate of polymers. Polymer properties like stiffness, elasticity, shape, structure, composition, compatibility, molecular weight, tacticity, crystallinity, morphology, hydrophobicity, number and type of heteroatoms, and the type of chemical bound in the main chain are main factors affecting the degradation rate of polymers. Obviously, biopolymers, bioplastics, or biodegradable polymers like the most popular polyesters are much more susceptible for (bio)degradation when compared to classic polyolefins. This is caused by the fact that ester bonds are more susceptible to water and microbial (enzymatic) activity; therefore, they easily undergo the hydrolysis process when compared to persistent C-C bonds in polyolefins. For this reason, biodegradable polymers have a great potential for revolutionizing agriculture because soil is a very active and dynamic environment, able to (bio)degrade bioplastics or biodegradable polymers to biomass, carbon dioxide, and water.

In agriculture, most polymers are used for mulching (approximately 13 million hectares of cultivated areas), covering foil tunnels—both high (more than 700,000 hectares) and low (900,000 hectares)—and as direct covers (40,000 hectares). Given the problem of water scarcity during crop cultivation, irrigation pipes and drip tapes, in addition to mulching films, help to direct water precisely to the plant roots, improving water use efficiency. In crop production, seedling plugs and nursery pot trays are frequently utilized. Seedling plug trays maximize plant growth and enable efficient germination. Furthermore, certain crops—such as vines and climbing species—require support when being cultivated. Lastly, plastics are employed to create agricultural packing materials, such as storage containers, fertilizer bags, and nursery plant trays for transportation [37].

Over recent decades, the environment has been increasingly impacted by the widespread use and subsequent disposal of plastic materials. Plastic and polymers have been utilized in countless applications without much thought given to their eventual disposal [38]. Residues of these substances and all kinds of chemical additives persistently accumulate in soils as a result of incomplete collection. Despite this, non-biodegradable polymers are still used in some aspects of agriculture (Figure 1).



**Figure 1.** Non-biodegradable/biodegradable polymers for agriculture.

Polyethylene (PE) film is widely used as mulch in agricultural fields to limit weed growth, retain soil moisture, and increase the soil temperature, which accelerates plant growth. Another important area where this polymer is widely used is tunnels and greenhouses. PE film is used to cover tunnels and greenhouses, providing protection for plants against adverse weather conditions, pests, and diseases. Polyethylene is also used in the production of irrigation pipes and hoses due to its water resistance and flexibility. PE remains an indispensable material for creating packaging. It is used to produce packaging for fertilizers and other chemical products used in agrochemistry due to its durability and chemical resistance [39–42]. Such wide applications are the result of numerous advantages of the polymer. These include durability, as polyethylene film is resistant to tears, mechanical damage, and weather phenomena. Another advantage is flexibility, which allows its easy shaping and adaptation to various applications. Due to its chemical resistance, PE does not react with most chemicals used in agrochemistry, making it ideal for packaging. The relatively low production cost of polyethylene makes its products economically attractive. However, the material is not without its drawbacks. These include degradation issues. PE film is long-lasting and difficult to biodegrade, leading to environmental problems associated with plastic waste in the soil. Another important issue is its impact on the soil. The long-term use of polyethylene film can lead to the depletion of soil microflora and reduced permeability. Prolonged soil coverage with film can adversely affect soil biodiversity and ecosystem health [40,43,44].

The second dominant thermoplastic polymer that is also widely used in agriculture is polypropylene (PP). For instance, polypropylene is used to create composites reinforced with glass fibers, elastomers to increase impact resistance, and antioxidants. Such reinforced composites exhibit high strength and a modulus of elasticity, making them suitable for agricultural applications due to their cost-effectiveness and versatile range of uses [45,46]. Polypropylene agrofabrics are used to protect crops from low temperatures, pests, and excessive sunlight. Thanks to their durability and permeability to water and air, they enable healthy plant growth, providing better living conditions and increasing reliability during early plantings or unfavorable weather conditions [47–49]. Bags and packaging made of polypropylene are used in agriculture as durable solutions for storing and transporting seeds, fertilizers, and other substances. Thanks to their resistance to mechanical damage, they provide solid protection for the product both from external factors and during storage under various conditions [50–52]. Polypropylene nets for wrapping bales of hay and straw are used to protect these materials from moisture and quality loss. Thanks to their tear re-

sistance and high flexibility, polypropylene is an ideal material for nets that must withstand weight and tension during wrapping and protect bales from atmospheric factors [53–55]. Such wide applications of polypropylene are possible due to the numerous advantages of this material. These include durability and hardness. Polypropylene is durable, flexible, and resistant to most chemicals, which is important for producing agrochemical packaging and agricultural tools. Another significant advantage is its impact on soil and plants. Thanks to its properties, it can be used as part of irrigation systems, offering longevity and efficiency. Moreover, the use of polypropylene is an economically attractive solution, especially in the mass production of agricultural tools or packaging. However, PP is not without its drawbacks. Similar to polyethylene, polypropylene is not biodegradable, which can lead to environmental problems related to plastic waste in the soil. Polymer fragments can pose a risk to soil microflora and plant health [48,50,56,57].

In agriculture, PVC (polyvinyl chloride) finds applications mainly through its inclusion in photovoltaic systems, known as agrivoltaics. Agrivoltaics is an innovative approach combining photovoltaic energy production with traditional farming methods. An example of PVC use in agriculture is agrivoltaic systems that allow the simultaneous production of food, water, and energy through crops grown alongside or under photovoltaic panels [58]. This technique enables the efficient use of agricultural areas and introduces modern solutions that increase agricultural profits through the production of clean energy [59]. Additionally, PVC can also be used in irrigation pipes, greenhouse coverings, and packaging films for agricultural products [60–62]. This is possibly due to the numerous advantages of this material, such as its durability and weather resistance. PVC is known for its high durability and resistance to various weather conditions, making it an ideal material for irrigation pipes, greenhouse coverings, and packaging films for agricultural products [63]. Furthermore, due to its properties, PVC products are generally lightweight and easy to install and maintain, reducing labor and maintenance costs on farms [64]. PVC is also waterproof, providing effective moisture protection for stored agricultural products, as well as being crucial in irrigation systems [64,65].

Polyethylene terephthalate (PET), as one of the most commonly used packaging materials in the industry, finds wide applications in both food packaging and bottles for agrochemicals. PET is recognized as safe for contact with food and beverages by many regulatory agencies worldwide. It ensures the safe storage of food products without affecting their taste and quality. Additionally, the high transparency of PET is an advantage when packaging food products, allowing the easy recognition of the contents by consumers. PET is also resistant to most acids, bases, and solvents, making it an ideal material for packaging agrochemicals such as pesticides and liquid fertilizers. It provides the durable and safe storage of these substances, minimizing the risk of leaks and contamination. PET is fully recyclable, making it an environmentally friendly choice. Recycling PET bottles and other packaging helps reduce the environmental burden and demand for raw resources. Despite these advantages, it is also important to consider potential drawbacks associated with the widespread use of PET, especially issues related to waste management and the need for effective recycling infrastructure. Additionally, in the context of agrochemicals, the total seal and resistance of the packaging are crucial to prevent potential leaks [66–68].

Polystyrene (PS), as a versatile material, finds applications in many sectors, including, potentially, agriculture. Its primary use is in the production of food containers. Due to its insulating properties and moisture resistance, polystyrene is often used for food packaging, which can also be useful for agricultural products [69,70]. Additionally, polystyrene can be used in precision agriculture, e.g., as a floating material in hydroponic systems, allowing the easy control of plant growth without the use of traditional soil. Due to its insulating properties, polystyrene boards can also be used to protect crops from frost [71–74].

Polytetrafluoroethylene (PTFE), due to its exceptional properties, has found wide applications in various industries, including agrochemistry and agriculture. Its resistance to chemicals, high and low temperatures, and non-stick properties make it an ideal material for applications requiring the highest reliability and safety [75–77]. PTFE is often used as a

material for seals and coatings in the agrochemical industry, where resistance to corrosion and chemicals is crucial. Equipment used for the production, storage, and transport of chemicals, such as fertilizers and pesticides, requires seals that do not degrade under the influence of highly aggressive substances. PTFE seals offer exceptional chemical resistance, preventing leaks and the contamination of products while extending the equipment's lifespan. Additionally, due to its low adhesion properties, PTFE coatings facilitate cleaning and maintenance, minimizing the risk of contamination by agrochemical residues [75,78,79]. In agriculture, PTFE is also used in the form of films for specialized applications. Thanks to its resistance to weather conditions, ultraviolet light (UV), and biostability, PTFE films can be used as advanced greenhouse covers, providing protection for crops against harmful external factors and extending their growing season. These films, due to their non-stick properties, are also easy to clean from deposits and contaminants, which is crucial for maintaining the proportion of light necessary for plant growth. Additionally, PTFE can be used in irrigation systems, where its coatings can protect pipes from salt and other deposits that can clog systems and reduce their efficiency [80–84].

Polyamides, also known by the trade name nylon, find various applications in agriculture, benefiting from their strength, flexibility, and resistance to weather conditions and chemicals [85]. Nylon can be used to produce nets used in fish farming (aquaculture) [86]. Polyamides are also used to produce components used in agricultural irrigation systems, such as pipes and fittings, where their chemical resistance and high-temperature resistance are valuable [87]. Nylon fabrics can also be used to produce protective covers for machines or tarps protecting stored crops [88,89]. In modern agrochemistry, nylon materials can also find applications in soil moisture sensors or control system components in greenhouses [90].

Polyurethanes (PU) are polymers with a wide range of applications, which have also found a place in agriculture, mainly due to their versatility, durability, and resistance to various environmental conditions. Polyurethanes can be hard or flexible, allowing their use in many different applications [91]. Therefore, polyurethanes are used as protective coatings for various materials used in agriculture. Thanks to their resistance to abrasion, chemicals, and weather conditions, they protect metal and wooden structural elements from corrosion and rot, which is crucial for their long-term use outdoors, e.g., in greenhouse constructions, foil tunnels, or irrigation systems [92,93]. In agriculture, polyurethane is used to produce hydrogels, which, when applied to soil, increase its water storage capacity. This is particularly important in areas with limited water availability or drought conditions, helping to maintain adequate soil moisture levels, which affects plant growth and development [94,95].

Polycarbonates (PC) are a group of thermoplastic polymers containing carbonate groups in their structures. Due to their transparency, impact resistance, and high temperature resistance, polycarbonates find applications in many fields, including agriculture. One of the main uses of polycarbonates in agriculture is greenhouses. Polycarbonate films and panels are commonly used as materials for greenhouse walls and roofs due to their durability, UV resistance, and thermal insulation. These properties help maintain optimal conditions for plant growth, providing an appropriate temperature and protection from harmful sunlight and weather conditions [96–98].

Polyvinylidene fluoride (PVDF) is a fluoropolymer known for its high chemical and thermal resistance and is used in various industrial applications. Due to its ability to form durable and efficient membranes, PVDF can be used in water treatment systems used in agriculture, including wastewater treatment and water recycling [99,100]. PVDF can also be used as a carrier for immobilizing bacteria used in methanogenic fermentation processes of organic substances, such as propionic acid, which can be applied in bioenergetic processes related to agriculture [101,102].

Polychlorotrifluoroethylene (PCTFE) is a fluoropolymer characterized by high chemical resistance, excellent electrical insulation, and low gas permeability. One application of PCTFE in agriculture could be the production of packaging for agrochemicals, such as

pesticides or fertilizers. The chemical resistance of PCTFE makes it ideal for the safe storage and transport of these substances, minimizing the risk of leaks and contamination [103,104].

In summary, despite many advantages, non-biodegradable polymers intended for long-term use seem unsuitable for applications where plastics are used for a short period of time and then require disposal, but in some cases, their use is necessary. Additionally, plastics are often contaminated with food and other biological substances, which poses a problem in subsequent cleaning. An attractive solution to this problem may be the use of biodegradable and biorecyclable polymers, which can reduce the release of unacceptable pollutants into the environment.

### 3.2. Biodegradable Polymers in Agriculture

In recent years, biodegradable polymers have become a notable alternative to conventional plastic materials in agriculture. Certain biodegradable polymers, including, poly(vinyl alcohol) (PVA), poly(butylene adipate-co-terephthalate) (PBAT), poly(butylene succinate-co-adipate) (PBSA), and poly(lactic acid) (PLA), are employed in the formulation of biodegradable agricultural films (Figure 1). These polymers are engineered to decompose rapidly and safely in the environment, minimizing the environmental impact of plastic waste on land and waterways. Beyond waste reduction, the utilization of biodegradable polymers in agriculture provides various benefits, including enhanced soil health and increased crop yields [105].

Biodegradation refers to the breakdown of macromolecules by microorganisms, occurring in two distinct steps. Initially, fragmentation takes place, breaking down the high-molecular-weight polymer chain into smaller units, such as oligomers or monomers, through processes like hydrolysis, oxidation, or other chemical reactions. The occurrence of hydrolysis may involve enzymatic or non-enzymatic mechanisms, influenced by environmental factors and polymer chemical structures. Subsequently, in the second step, microorganisms mineralize the oligomers and monomers generated in the first step, producing carbon dioxide, methane, water, and biomass. The specific products formed can vary depending on the microorganisms involved and the aerobic or anaerobic conditions of the process [106].

A biodegradable polymer commonly used in agriculture is poly  $\epsilon$ -caprolactone (PCL), a biodegradable semicrystalline linear aliphatic polyester, which is synthesized chemically from crude oil through the ring opening polymerization of the caprolactone monomer [107].

Polybutylene succinate (PBS) is a thermoplastic polyester with physico-chemical properties resembling conventional non-biodegradable plastics. While its melting point surpasses that of other synthetic polymers, it falls short compared to natural polymers, enabling quicker melting and blending with other materials for film development. However, its high polymer crystallinity diminishes its susceptibility to degradation by enzymes or microorganisms [108]. To address this, amorphous domains are introduced into the polymer through blends with other materials. There are also reports of attempts to use PBS on mitigating the environmental impact of mass-produced grapevines, an agricultural waste, by utilizing biochar derived from grapevines along with PBS to create an eco-friendly bio-composite [109].

Poly(butylene adipate-co-terephthalate) is derived from common petrochemicals, making it fossil fuel-based. It is formed from a combination of 1,4-butanediol, adipic acid, and terephthalic acid, resulting in an aromatic-aliphatic polymer. This unique structure grants PBAT properties like high elongation at the break, flexibility, stretchability, impact resistance, and heat resistance, which are ideal for mulch film applications. The presence of the butylene adipate group enhances its biodegradability in soil, offering an eco-friendly alternative to traditional plastic mulches. However, PBAT does have drawbacks. It is costly and susceptible to UV radiation, which can degrade its properties. In field applications, PBAT can become brittle due to severe cross-linking, limiting its effectiveness, especially for longer-term use or with certain crops [110].

Poly(lactic acid) is a biopolymer synthesized by lactic-acid-forming microorganisms using renewable resources like corn or sugar beet starch. It is commonly a blend of poly L-lactic acid and poly D-lactic acid, with their ratio affecting properties like the melting temperature and crystallinity. Although cost-effective on a large scale, PLA remains pricier than traditional plastics. Despite its brittleness, PLA boasts thermoplasticity, biocompatibility, and processability, making it versatile for various agriculture applications [111]. To address cost and brittleness concerns, PLA is often blended with starch, enhancing its mechanical properties and reducing the manufacturing expenses [110]. However, blending PLA with other polymers poses challenges, such as poor compatibility leading to film defects like wrinkles and tears. Plasticizers are added to mitigate these issues, but some non-biodegradable options are restricted due to agricultural regulations. Additionally, commercial PLA production using genetically modified organisms (GMOs) faces regulatory hurdles in regions like Europe and the USA, limiting its large-scale adoption [112]. Research is also being conducted into the production of new mats, aphid-repellent fiber mats, based on Poly(lactic acid)-containing ionic liquids. The development of this type of repellent based on biopolymers is crucial for safeguarding crops, as well as the health of humans and animals, especially considering the increasing global population [113].

Poly(hydroxy alkananoates) (PHA) are aliphatic polyesters synthesized intracellularly by various bacteria, serving as carbon storage granules. They vary in composition and structure based on the producing microorganism, carbon source, and fermentation conditions. Over 150 PHA variations exist, with poly 3-hydroxybutyrate (PHB) and poly 3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV) being the most common and commercially available [114]. Although PHAs alone lack mechanical strength for mulch films, blending them with other polymers enhances their performance. Agricultural nets are also produced in this way. They are crucial in agriculture for various reasons. They enhance the crop yield and quality, shield crops from weather-related risks such as hailstones and wind, and offer protection against birds and insects. Additionally, shading nets help regulate sunlight exposure, reducing the need for chemical inputs and preventing crops overheating [115]. They also extend the planting period for crops, particularly for low-light plants, and serve as substitutes for natural shade, thereby supporting diverse agricultural practices [116]. PHAs, particularly PHB blends, are effective as controlled-release systems for agricultural chemicals, slowly dispensing pesticides and fungicides. These blends, including PHB with PLA, exhibit mechanical properties comparable to polyethylene mulch films. Furthermore, PHB rapidly degrades in aerobic and anaerobic environments, posing a minimal environmental impact. Despite their potential, large-scale PHA production remains costly due to extraction methods from bacterial cells. Efforts to lower production costs involve utilizing waste materials as carbon sources and developing efficient biological extraction methods to preserve the polymer's properties [42]. Table 1 summarizes the application possibilities, advantages, and disadvantages of conventional and biodegradable polymers used in agriculture.

**Table 1.** Comparison of Conventional and Biodegradable Polymers.

| Polymers              | Application                                               | Advantages                                            | Disadvantages                                          |
|-----------------------|-----------------------------------------------------------|-------------------------------------------------------|--------------------------------------------------------|
| Conventional Polymers |                                                           |                                                       |                                                        |
| PE                    | Mulching films;<br>Greenhouse covers;<br>Irrigation pipes | Durability;<br>Chemical resistance;<br>Cost-effective | Environmental pollution<br>due to non-biodegradability |
| PVC                   | Agrivoltaic systems;<br>Irrigation pipes                  | High durability;<br>weather resistance                | Recycling difficulties;<br>Cost issues                 |
| PP                    | Agrofabrics;<br>Packaging                                 | Flexibility;<br>UV resistance                         | Environmental hazards due<br>to non-biodegradability   |

Table 1. Cont.

| Polymers               | Application                                                      | Advantages                                | Disadvantages                             |
|------------------------|------------------------------------------------------------------|-------------------------------------------|-------------------------------------------|
| Biodegradable Polymers |                                                                  |                                           |                                           |
| PHA                    | Controlled release systems                                       | Biodegradability;<br>environmental safety | High production cost                      |
| PBS                    | Controlled release systems;<br>Mulching films;<br>Composites     | Biodegradability;<br>suitable for blends  | High crystallinity reduces<br>degradation |
| PLA                    | Controlled release systems;<br>Agricultural films;<br>Containers | Biodegradability;<br>Flexibility          | High cost;<br>Brittleness                 |

### Natural-Origin Polymers in Agriculture

The structural complexity of plant materials and bacterial biomass provides a large amount of natural polymers as raw materials. Among natural polymers, the most commonly used biopolymers are polysaccharides such as chitin, alginate, starch, and cellulose, which are characterized by unique properties and are environmentally friendly [117]. Chemically, these polymers consist of monosaccharide units linked by glycosidic bonds, yet their diverse functional groups and charges confer versatility. Their utilization for agriculture offers notable advantages, including heightened biodegradability, non-toxicity, widespread availability, and affordability. Bacteria can utilize carbohydrates to produce polymers, with polylactic acid (PLA) and polyhydroxyalkanoates (PHA) being notable examples. These polyester compounds are derived from carbohydrates [38].

Chitosan (CS) is one of the most common natural polysaccharides, produced by the deacetylation of chitin, which is extracted mainly from the external skeleton of crustaceans, the cell walls of some bacteria, and fungi [118–121]. It consists of  $\beta$ -(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units.

The use of chitosan formulations in agriculture is diverse, encompassing plant protection against microorganisms, the stimulation of plant growth, the controlled release of agrochemicals, pest control, and postharvest applications. Chitosan products can be applied in various forms such as seed coatings, soil amendments, foliar sprays, or supplements in hydroponic systems [122]. Due to its multifunctional role in plants, chitosan is increasingly recognized as a valuable component of polymer matrices for sustainable agriculture. It is particularly favored as a carrier for agrochemicals, either alone or in combination with other materials like gum, starch, or alginate, to improve properties for the slow release of active ingredients [123–126]. Recent attention has focused on chitosan nanoformulations for agrochemical delivery, offering a sustainable alternative to conventional methods in crop disease management. Active ingredients are loaded or encapsulated into chitosan nanoparticles, forming potent biocides. These non-toxic and biocompatible nanoparticles act as protective barriers, safeguarding plants from the harmful effects of the contained agrochemicals [127–129].

Alginate, a water-soluble polymer derived from brown algae, consists of  $\beta$ -d-mannuronic acid and  $\alpha$ -l-guluronic acid monomers, arranged in various proportions. Its ability to form three-dimensional networks with cations, particularly calcium ions, allows for the production of gels or films for controlled release applications. Research on alginate-based composites for agricultural applications has seen a steady increase, with studies focusing on enhancing the soil water-holding capacity, improving the controlled release of pesticides, and maximizing soil nutrient utilization [130].

Starch is a common polysaccharide that comes from renewable sources and can be successfully used as a substitute raw material for plastics based on fossil fuels. Starches can be extracted from plant sources such as potatoes, corn, rice, wheat, barley, cassava, etc. It consists of two main components: amylose and amylopectin. Both amylose and amylopectin are polysaccharides composed of glucose units but linked by different glyco-

sidic bonds. Amylose is connected by a direct  $\alpha$ -(1,4) glycosidic bond, while amylopectin, in addition to the same main chain as amylose, also contains a branched chain structure formed by  $\alpha$ -(1,6) glycosidic bonds [120,131,132]. A wide geographical distribution, ease of growth, and low cost have sparked research interest in starch as a biopolymer. It is characterized by appropriate chemical and physical properties, such as easy dissolution in solvents and temperature-induced pasting, the ability to gelatinize and retain water, and the easy optimization of its functional properties. Additionally, this polysaccharide can be processed by traditional polymer processing techniques such as extrusion and injection molding in the presence of plasticizers. Despite these advantages, starch features such as retrogradation, hydrophilicity and brittleness, and low thermal stability limit its widespread use in industrial applications. Therefore, the modification of the hydroxyl functional groups on its surface is required to alleviate the above limitations and achieve the required properties for its use in industrial materials [133].

Cellulose, the primary structural component of plant cell walls, is the most abundant polysaccharide in nature. It consists of linear chains of D-glucose units linked by  $\beta$ -1,4 glycosidic bonds. While cellulose is naturally found in plants, it can also be produced by various microorganisms, including soil-borne bacteria [134–136]. Two crystalline forms of cellulose exist, I $\alpha$  and I $\beta$ , distinguished by their hydrogen bonding patterns. Bacterial cellulose, primarily in the I $\beta$  form, offers advantages over plant cellulose due to its abundance, ease of production, and superior properties such as biodegradability, purity, water-holding capacity, transparency, flexibility, and mechanical strength [137]. These qualities make bacterial cellulose an excellent candidate for replacing plastic, for example, in mulch films, as demonstrated in field trials where it improved soil moisture retention and created a favorable microclimate for plant growth [138]. Composite films of bacterial cellulose can also be tailored to release nutrients by incorporating fertilizers [139]. Cellulose derivatives can also be utilized in the development of biodegradable superabsorbent hydrogels, aimed at optimizing water resources in agriculture, horticulture, and overall, promoting a more sustainable approach to water usage [140]. In addition, the utilization of cellulose biopolymers as composite matrices for controlled-release (CRF/SRF) fertilizers presents a sustainable prospect due to their abundance, renewability, and biodegradability [141]. Some research also reports the possibility of synthesis cellulose-based acrylic acid hydrogel starting from rice straw as a source for the lignocellulosic material, where cellulose was first isolated after alkaline–acid pulping treatment followed by a bleaching step with sodium hypochlorite, resulting in 90.8% holocellulose [142]. However, the main hurdle for large-scale cellulose production remains its high cost. To address this challenge, researchers are exploring the use of inexpensive waste materials as substrates for bacterial cellulose production, aiming to reduce production costs. Additionally, efforts are underway to develop cost-effective fermentation methods and optimize production processes.

In summary, the use of polymers in agriculture and agrochemistry not only increases yields and improves crop efficiency, but also contributes to environmental protection. Based on the topics presented in this section, we conclude that there are many opportunities to improve the use of polymers in agriculture. It is essential that polymers are used in an environmentally, technically, economically, and socially sustainable manner. There are key opportunities to produce polymers with biodegradable and renewable properties for various agricultural applications.

#### 4. Polymeric Agrochemicals and Related Biocides

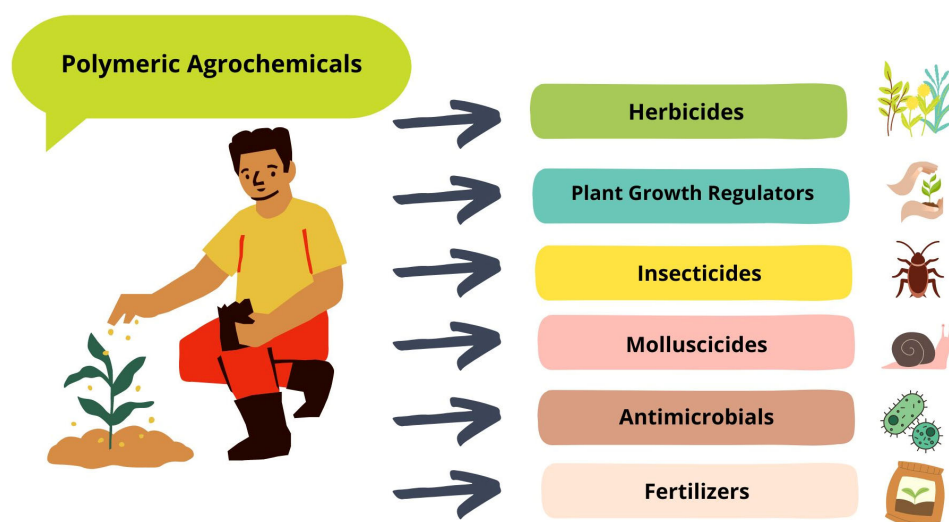
Agrochemicals are substances used for controlling plant or animal life to improve crop production in both quality and quantity. They help reduce competition for crops that would interfere with harvests. Therefore, to increase agricultural production, it is often necessary to significantly increase the amount of expensive and toxic chemicals used. The threats posed by plant protection products to both nature and humans necessitate the strict regulation of their use. Depending on the method of application and climatic conditions, as much as 90% of the applied agrochemicals never achieve their target. Inefficiency often

requires repeated treatments, leading to undesirable side effects for both the plant and the environment. Controlled release technology is a way to reduce and minimize the problems associated with the use of excess agrochemicals [143–145].

In addition to improving the effectiveness of some existing agrochemicals, the method of combining the active ingredient with a polymer has several advantages:

- (1) Prolonging the action by providing continuous, smaller amounts of biocides at levels that ensure their function is fulfilled for a longer period of time.
- (2) Reducing the number of applications by achieving a long duration of action in a single treatment.
- (3) Cost reduction due to saving time and costs associated with multiple treatments.
- (4) Reducing environmental pollution by eliminating the need to distribute large amounts of biocides.
- (5) Reducing eco- and phytotoxicity by reducing the high mobility of biocides in the soil, thereby reducing their residues in the food chain.
- (6) Increasing the duration of action of non-persistent or less persistent biocides that are unstable in the environment, thereby protecting them from environmental degradation.
- (7) Enhancing the convenience of using and transporting agrochemicals [146].

This chapter is devoted to presenting the basic types of polymer agrochemicals used in agriculture (Figure 2).



**Figure 2.** Types of polymeric agrochemicals.

#### 4.1. Herbicides

Growing plants for economic purposes requires a constant fight against losses caused by weeds, which, due to competition for water, sunlight, and soil nutrients, reduce crop yields. To combat this issue, herbicides are used to selectively kill weeds without harming the crops.

The main problem with conventional herbicides is that achieving the desired biological response in plants often requires using larger amounts of herbicides for extended periods of time. This is due to the need to compensate for losses caused by environmental factors such as rain, evaporation, leaching, and photodegradation. However, the extensive use of herbicides is undesirable due to their frequent inclusion in the food chain, posing a danger to both humans and animals [147–149]. Therefore, in agriculture, it is necessary to improve production by using smaller amounts of herbicides. This approach helps limit the harmful impact on the surrounding environment while maintaining high biological activity.

Recently, there has been increasing interest in the use of polymers for the controlled release of herbicides. This method allows the active ingredients to be released into the plant in controlled doses, providing optimal amounts required at specific times. Although

the delivery of herbicides using polymers offers many economic advantages, their use involves managing excessive amounts of polymer carriers. Since the remaining non-degradable polymer carrier, after the herbicide content is exhausted, poses a threat to the environment, efforts have been made to reduce this issue by using biodegradable carriers for herbicides [143–145].

#### 4.2. Plant Growth Regulators

Plant growth regulators are chemical substances that, by positively affecting the physiological processes of plant growth, protect crops against environmental stress. They mainly influence (1) increasing the initiation of flowering, flower and fruit retention, root growth, the germination rate, tolerance to low and high temperatures, and an overall increase in yield; and (2) a reduction in the internode length, wilting, and senescence. They contain various classes: auxins (indole-3-yl acetic acid, 1-naphthylacetic acid, 4-(indol-3-yl)butyric acid), gibberellins, cytokinins (kinetin, zeatin), and inhibitors (abscisic acid). They are applied directly to the plant to beneficially change its life processes or structure, thereby increasing yields or improving quality. Plant growth regulators are used to modify the yield by changing the rate of the plant's reaction to internal and external factors at every stage of crop development, from germination to aging, including post-harvest preservation. Polymer-based plant growth regulators are characterized by the ability to release active groups from the polymer system under certain conditions [143–145].

#### 4.3. Insecticides

Insects present one of the largest animal populations in terms of the number of species and individuals, and they can be found in all possible environments around the world. Some species are particularly valuable to humans due to their ability to produce products such as honey, dyes, and silk. On the other hand, many insects are carriers of diseases and contribute to the destruction of crop plantations, causing serious health and economic problems. Insects are common pests of flowers, fruits, and vegetables. Their feeding on germinating seeds, seedlings, and flowers can cause significant agricultural damage. Fruits and vegetables can be protected from insect damage by spraying insecticides several times during the growing season. A number of chemicals used to kill or inhibit the reproduction of insects are generally called insecticides. These agents interfere with the metabolism of insects, preventing them from feeding on crops and harvests, and depriving them of the ability to reproduce. Depending on the purpose, the area of application, and the physicochemical properties of the chemical substance, insecticides can be used in different ways. A typical use of insecticides in agricultural crops involves spraying a solution, emulsion, or colloidal suspension containing an active chemical compound, which may pose a threat to animals and humans [146–149].

#### 4.4. Molluscicides

The use of conventional molluscicides leads to significant environmental contamination, rendering water toxic for aquatic plants, birds, fish, and mammals, which limits their practical value. Additionally, achieving effective distribution in moving water is challenging, often requiring multiple applications. There is a need for more efficient snail elimination using smaller amounts of molluscicides with a minimal environmental impact but high biological activity. In recent years, a novel approach has surfaced, involving the combination of molluscicides with polymeric materials to enhance and improve their efficiency. This method enables the continuous release of a lethal quantity of toxicant for controlling snail vectors of schistosomiasis. Not only does this technique extend the persistence of conventional molluscicide activity, but it also addresses the environmental and toxicological issues associated with their traditional use. Additionally, it provides the opportunity to integrate both an attractant and toxicant into the same polymeric matrix, attracting snails with a species-specific attractant and inducing them to ingest the polymers containing the toxicant [146].

Polymeric molluscicides are substances designed to control or eliminate mollusks, such as snails and slugs, that can be pests in agriculture or horticulture. These compounds are often formulated using polymeric materials, which can enhance the effectiveness and persistence of the molluscicide. The polymeric formulations can provide a controlled release of the active ingredient, prolonging its efficacy and reducing the frequency of application. The polymeric molluscicides may come in various forms, such as granules, pellets, or gel formulations. The choice of polymer and formulation depends on factors such as the specific target mollusk, the environment, and the desired mode of application.

Snail eradication is crucial in schistosomal control procedures aimed at reducing bilharzial transmissions. Parasites of the genus *Schistosoma* cause the infectious disease Schistosomiasis, also known as bilharziasis. The disease is common in tropical and sub-tropical countries and can lead to serious complications such as pneumonia, hepatitis, and kidney disease. Next to malaria, bilharziasis is the most serious parasitic health problem worldwide. Traditional approaches necessitate higher molluscicide concentrations for rapid snail population reduction, but the World Health Organization (WHO) recommends combining effective schistosomal drugs with snail control.

Niclosamide is a chemical compound commonly used as a molluscicide. However, the widespread use of this chemical has led to significant environmental toxicity and economic consequences. Polymeric molluscicides, created with the integration of molluscicides with functionalized polymers, have been used against molluscs as a replacement for the traditional use of niclosamide alone. This is significant in the context of disease control, as snails often serve as intermediate hosts for parasites that can cause diseases in humans, such as schistosomiasis [150].

Undoubtedly, molluscicides play a crucial role in controlling schistosomiasis transmission in endemic countries. Ideal molluscicides should meet specific criteria, including: (1) high toxicity to snails at low concentrations; (2) minimal acute and chronic toxicity to non-target organisms; (3) the absence of adverse effects in the food chain; (4) stability for at least 18 months; and (5) cost-effectiveness and safety for users [151].

#### 4.5. Antimicrobials

Antimicrobials are materials capable of killing pathogenic microorganisms, providing quality and safety benefits for many materials. They are used to sterilize water, sterilize soil, and as food preservatives. Antimicrobial polymers, as a class of polymeric biocides, inhibit the growth of microorganisms such as bacteria, fungi, or protozoa. Additionally, polymeric biocides can increase the effectiveness of some existing antimicrobials and minimize environmental problems associated with conventional antimicrobials by reducing the residual toxicity of the agents, increasing their efficiency and selectivity, and extending their duration of action. Antimicrobial polymers kill bacteria in several ways: by direct binding through the adsorption of the cationic antimicrobial polymer onto the negatively charged bacterial cell wall, resulting in cell wall disruption and cell death, or by depleting the bacterial food source, preventing the bacteria from reproducing [146,152].

The activity of antimicrobial polymers depends primarily on: (1) the molecular weight of the polymer, which influences the diffusion of the polymer through the bacterial cell wall and cytoplasm; (2) ionic strength—most bacterial cell walls are negatively charged, so most polymeric antimicrobials must be positively charged to facilitate the adsorption process; and (3) spacer groups—increasing the length of spacer groups between the main chain and the antimicrobial groups increases the activity of the antimicrobial polymer by increasing the availability of active sites for adsorption in the bacterial cell wall and cytoplasmic membrane.

In addition, the industrial production of antimicrobial polymers must meet several requirements: (a) the antimicrobial polymer should be easily obtainable by techniques at a relatively low cost; (b) it should be stable for long periods at storage temperature; (c) it should not decompose during use or emit toxic decomposition products; (d) it should be insoluble in water to prevent toxicity when used for water disinfection; (e) it must not

be toxic; and (f) it should have a biocidal effect against a broad spectrum of pathogenic microorganisms within a short contact time.

#### 4.6. Fertilizers

Fertilizers are compounds used to increase soil fertility by providing nutrients essential for plant growth. These nutrients can be divided into macronutrients and micronutrients. The macroelements, i.e., essential elements, include: nitrogen (N), phosphorus (P), potassium (K), as well as calcium (Ca), magnesium (Mg), and sulfur (S). Typically, the first three elements, called NPK, are the most important. Deficiencies of macroelements in the soil are generally supplemented by the use of NPK fertilizers such as urea, diammonium phosphate (DAP), and single superphosphate (SSP). It is estimated that approximately 40–70% of nitrogen, 80–90% of phosphorus, and 50–70% of potassium from applied fertilizers is lost to the environment (losses due to runoff or the escape of gases such as  $\text{NH}_3$  into the atmosphere) and cannot be absorbed by the plant, causing serious environmental and financial damage [153–155].

Over the past few years, efforts have focused on the use of controlled-release fertilizers (CRF), primarily because of their environmental and economic benefits. There are many reports on the controlled release of nutrients and fertilizers, especially urea, as a nitrogen source. The aim of CRF technology is to increase the efficiency of fertilizers by regulating the correct dose of nutrients for the plant in the target place and at the right time and mitigating environmental pollution. Fertilizers coated with a polymer layer consist of active ingredients surrounded by a barrier that prevents the fertilizer from quickly entering the environment. As a result of diffusion through pores or the erosion and degradation of coatings, active ingredients are slowly released. The release rate depends on the composition, thickness, and cross-linking density of the coating [143–145].

### 5. Controlled Released Systems in Agrochemistry

Due to the constantly growing world population and the need to meet the demand for food, it is estimated that global grain production must be increased by at least 70% [156]. Although the use of agrochemicals over the last half century has played a decisive role in increasing agricultural productivity, recent studies on the long-term effects of pesticides and fertilizers confirm the deterioration of soil health [157,158].

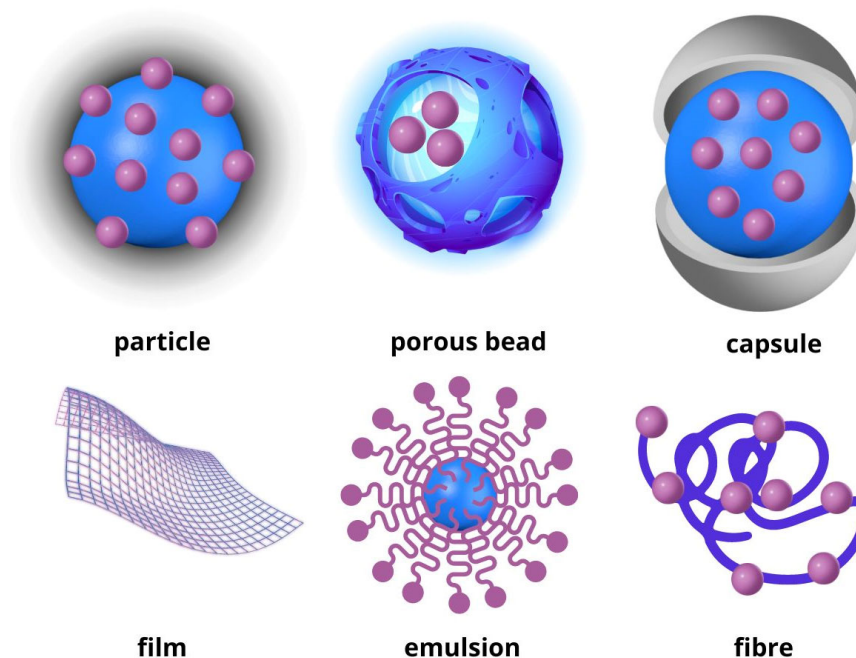
Conventional agrochemicals cause an initial increase in the concentration, which quickly drops below the effective level over time due to the degradation, leaching, or volatilization of the compound. This phenomenon leads to the repeated use of plant protection products or conventional fertilizers, ultimately resulting in the deterioration of the soil quality and eutrophication of water bodies [159,160]. In order to supplement the soil with nutrients, very large amounts of fertilizers in the form of urea, ammonium salts, nitrates, or phosphate compounds are used in the fields, and extremely high local concentrations negatively affect crops. Therefore, there is a need to develop new methods that will make it possible to reduce the amount of chemicals used while maintaining the desired effect of the active agent for an optimal period of time [161].

In recent years, sustained-release agrochemical technology has emerged as a promising solution to these problems. A controlled-release system (CRS) is a method by which active substances are enclosed in carriers and then released onto the target surface in order to maintain a specific concentration level of this substance for a specified period of time [143,162]. The undoubted advantages of this system include: reduced doses of the active substance, which is released at a constant level for a longer period of time, thus reducing evaporation losses, environmental pollution, and phytotoxicity [143].

CR preparations have been used for years in different industries, including biomedical [163–165], pharmaceutical [166–169], cosmetology [170,171], food [172–174], and agricultural [175], to deliver biomolecules, drugs, pesticides, and fertilizers. The extensive experience with biomedical CRSs can help agricultural applications benefit from improvements in controlled delivery.

### 5.1. Formulation Technology of Agrochemicals

CRSs of agrochemicals are classified based on their structure and include films, particles, capsules, porous beads, emulsions, layered systems, fibers, and hydrogels (Figure 3). Capsules have been and continue to be widely used in the delivery of crop protection products and play a key role in the development of CRSs [135,176,177].



**Figure 3.** Selected types of controlled-release systems most common in agriculture.

Encapsulation is the process of coating or surrounding an active compound to achieve a more controlled release, protecting the active ingredient from degradation before reaching its site of action, and reducing the associated side effects that accompany some non-encapsulated compounds [159,170,173]. The encapsulation process can be carried out using various techniques, including: solvent evaporation, polymerization, crystallization, spray-drying, freeze-drying, spray-cooling, emulsification, extrusion, and photo techniques. Research on encapsulation using polymers and their derivatives is an actively chosen direction in the development of research in agriculture, based on differences in the size of the obtained particles. Encapsulation at the microscale (1–1000  $\mu\text{m}$ ) is called microencapsulation, while encapsulation at the nanoscale (1–1000 nm) is called nanoencapsulation.

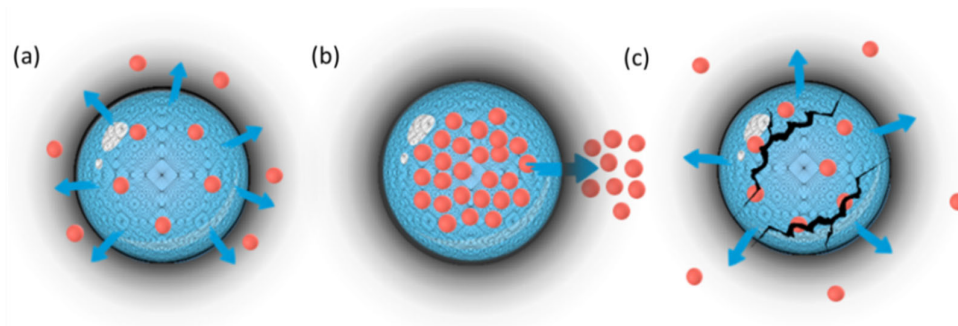
There are different types of microsphere-based systems, such as microcapsules and microsphere-coated granules. Microcapsules can vary in their core content, which can include gases, liquids, and solids. Also, the carriers surrounding them can be customized using various materials such as metal oxides, organic compounds, plastics, and polymers [118]. The release rate of the active ingredient can be controlled by selecting parameters such as the size of the spheres, the thickness of the polymer membrane, porosity, and the degree of polymer cross-linking [178,179].

Since the use of microcarriers is limited to the soil and plant surfaces, such as leaves or stems, it was necessary to develop nanocarriers that control the release of agrochemicals into the plants. The undoubted advantage of nanoparticles is their surface-to-volume ratio, which is usually the driving force behind their colloidal behavior. They can be synthesized using organic and inorganic compounds or as a hybrid. Another interesting solution is to obtain nanoporous structures that have ordered pores throughout the entire volume of the sphere [180–183]. Nanocarriers promote the release of active substances, which can be released as a result of a difference in chemical potentials, by diffusion, or the release can be triggered by the degradation of the shell [184].

As long-acting preparations based on a carrier and polymer coating ensure high effectiveness and selectivity compared to conventional plant protection products, these systems constitute an important perspective for the development of modern agriculture.

### 5.2. Mechanism of Release of Active Ingredients

An important factor in the design of a CR polymer matrix is its ability to release the active ingredient at the target site. Depending on the design of the CR device, several release mechanisms are possible (Figure 4), such as (1) diffusion from the pores; (2) release due to osmotic pressure; and (3) release by matrix erosion [130,135].



**Figure 4.** Schematic illustration of mechanism of release of active ingredients: (a) diffusion through pores, (b) active substance movement due to osmotic pressure, and (c) release due to polymer degradation.

Diffusion is a common mechanism in which dissolving fluid penetrates the shell, dissolves the core, and allows the active substance to leak out through the pores or channels. The total release depends on the speed of the fluid penetrating the walls of the microcapsules, the rate of dissolution of the active ingredient in this fluid, and the rate of leakage of the substance to the outside. The dissolution rate of the polymer coating directly affects the release rate of the active ingredient [130,185].

An osmosis-controlled release and swelling-controlled release are based on the flow of water across a selective membrane. The polymer coating of the microcapsule acts as a semi-permeable membrane and allows the creation of an osmotic pressure difference between the inside and outside of the microcapsule. The pressure difference causes the active ingredient to be lost through the pores in the shell. Swelling-controlled systems are closely related to cases in which water not only activates drug release, but also influences the drug release rate. In a broader sense, the term is used to describe systems in which polymer swelling is one of many mechanisms controlling the release process [135,185,186].

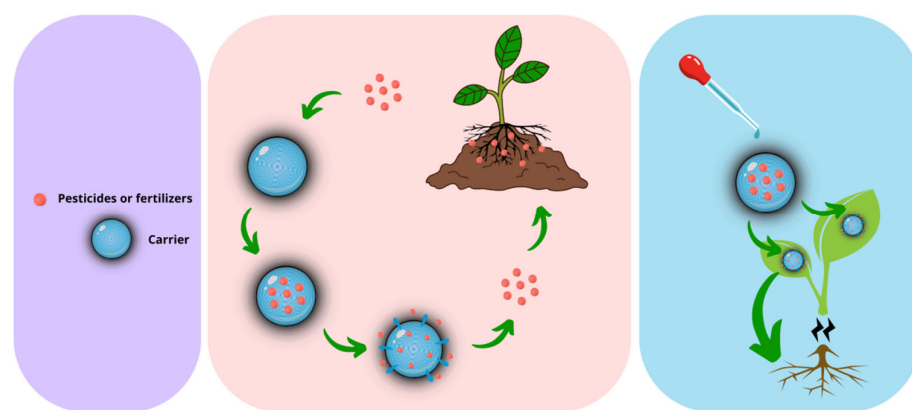
The erosion of the polymer support can occur at the surface or the bulk of the polymer, or a combination of both, while the degradation process of the erodible device can be controlled by various factors such as the pH, temperature, pressure, and enzymatic activity. Furthermore, mechanical triggers, such as sonication, shaking or vortexing, can also release active substances that are physically bound to the polymer carrier. Surface erosion is the preferred phenomenon because the release kinetics are repeatable, so the process can be controlled. However, in this case, only surface active ingredients that are sensitive to water are protected. Bulk erosion is less predictable and does not protect active ingredients from the environment, making this process suboptimal for controlled delivery. The combination of both mechanisms may prove to be an interesting way of delivering substances through shell erosion.

In practice, erodible materials can be controlled by more than one mechanism (such as water and active ingredient diffusion, polymer dissolution, swelling, or chemical degradation) and the interaction of these processes can lead to a satisfactory active ingredient release profile [130,135].

### 5.3. Polymer-Controlled Release System

Optimizing the use of agrochemicals along with the development of green herbicide, insecticide, fungicide, and fertilizer products is essential to reduce harmful impacts on the environment and human health. In this context, controlled-release plant protection products may be a promising solution to optimize administration through the sustained release of active substances, which will prevent pathogen resistance, soil contamination, and risks to human health [187–189].

So far, agriculture has typically used conventional pesticides as sprays or by their application to the soil, but the concentration levels used were too high or too low to be effective in a given location. Too high concentrations cause undesirable side effects in the target area, while too low concentrations result in poor activity, which makes it necessary to use repeated doses throughout the growing season. The controlled release of pesticides is of great importance, improving the efficient use of active ingredients, thereby reducing environmental pollution. The CR preparations are based on the fact that only part of the active ingredient is immediately available; however, a significant part of the active substance is enclosed in the matrix and released slowly over a long period of time (Figure 5) [143].



**Figure 5.** Scheme of controlled release of agrochemicals.

Controlled-release fertilizers (CRF) are promising nanofertilizers that provide nutrients to plants over an extended period of time, typically weeks to months, improving crop yields [190]. CRF encapsulate nutrients in nanocarrier materials composed of polymers, lipids, or inorganic substances. The release process from this type of carrier depends on environmental factors such as temperature, humidity, pH, the presence of enzymes, etc., [134,191]. This system, through controlled release, also allows for a balanced and targeted delivery of nutrients, which leads to a reduction in the doses of fertilizers used and, consequently, a reduction in the impact of agricultural practices on the environment. In addition, the use of controlled-release nanofertilizers minimizes the leaching of nutrients, reducing the pollution of water reservoirs, and limiting eutrophication [134,192].

The use of polymer matrices as carriers for plant protection products may be of particular importance for controlled release systems. Preparations in polymeric carriers are characterized by better properties regarding extending the period of activity compared to non-encapsulated preparations [193,194]. Polysaccharides are macromolecules commonly found in nature and composed of monosaccharides, connected by glycosidic bonds. The sources of polysaccharides are mainly natural organisms, e.g., animals (chitosan), plants (cellulose, starch, pectin, and gums), microorganisms (dextran), fungi (pullulan and glucans), and algae (alginate and carrageenans) [195]. Moreover, to compensate for the shortcomings of the controlled release from natural materials, the use of chemically synthesized polysaccharide derivatives is also of great importance [196].

### 5.3.1. Chitosan

To develop an effective chitosan-based agrochemical formulation, the technique of encapsulating the active ingredient using ionic or covalent inter/intramolecular bonds or entrapment in a chitosan polymer matrix can be used [124]. Chitosan-based agrochemicals can be obtained by various methods, such as emulsion cross-linking, ionic gelation, precipitation, spray-drying, reverse micellar methods, and sieving [197]. Of these, the simplest and most direct method is the sieving method, but its use produces particles of an irregular size and shape. The ionic gelation method is also a relatively simple and cheap method of forming chitosan nanoparticles, and it does not require the use of many chemicals. The cross-linking method uses negatively charged polyanions to bind to the positive charge of the protonated amino group of chitosan under acidic conditions. Through this procedure, stable nanoparticle systems can be obtained. However, to obtain stable particles, cross-linking agents such as glutaraldehyde, alginate, and formaldehyde must be used. The particle size of such systems can be selected by changing parameters such as the type of surface agent, the molecular weight of chitosan, the degree of cross-linking, and the mixing speed. The reverse micellar method allows for obtaining chitosan nanoparticles of relatively small sizes and uniform size distribution, but it is necessary to use a solution of a surfactant such as cetyltrimethylammonium bromide, an organic solvent and a cross-linking agent, which limits its use mainly for cost and time-consuming reasons. Precipitation methods are based on blowing the chitosan solution using a compressed air nozzle. The nanoparticles created using this method have low mechanical strength and irregular shapes. Spray-drying methods are used to produce chitosan powders, dry granules, and pellets, which are based on adding active ingredients and a cross-linking agent to a solution of chitosan dissolved in acetic acid. The solution is evaporated in a stream of hot air, which leads to the formation of the desired nanoparticles [198].

Due to the amphiphilic properties of chitosan, encapsulation with chitosan could overcome the poor solubility of many agrochemicals in water, contributing to increasing the possibility of using environmentally friendly formulations. Additionally, the bioadhesive properties of CS protect the encapsulated active agents, increasing their stability and ability to be used by plants [199,200]. Therefore, chitosan is the most frequently researched polymer for the production of nanocarriers of active compounds in agriculture. Chitosan nanocarriers have been reported to facilitate the delivery of many pesticides [201] and fertilizers [202,203].

Wang et al. (2021) reported the preparation of a spinosad–chitosan controlled-release suspension (SCCS). By comparing the commercially available spinosad-in-water emulsion and the resulting spinosad suspension concentrate, it was shown that the insecticidal activity of SCCS against *Plutella xylostella* larvae had the best rapid-acting efficacy as well as long-term effectiveness, which exceeded 20 days [204].

Also, Wang et al. (2023) produced an eco-friendly formulation of chitosan-encapsulated chlorantraniliprole (CAP) insecticide based on co-precipitation. The resulting CAP/Chitosan (CTS) formulation showed high encapsulation efficiency of approximately 75%, and in vitro release tests showed marked pH and temperature sensitivity. In a toxicity test against *Plutella xylostella* larvae, the effectiveness was comparable to that of a commercially available suspension concentrate [205].

Xu et al. (2024) developed, using the film casting method, carboxymethyl chitosan films with the controlled release of two pesticides, Avermectin and Spinetoram. The developed films had different thicknesses and pesticide contents, but were characterized by the same tendency to release pesticides, which indicates complex release mechanisms based on the swelling and erosion of the carboxymethyl chitosan-based carrier [206].

Feng et al. (2020) prepared amphiphilic biopolymers by introducing hydrophobic (7-diethylaminocoumarin-4-yl)methyl succinate (DEACMS) into the main chain of hydrophilic carboxymethyl chitosan (CMCS). By the formation of amide bonds, the formed structures were able to self-assemble into spherical micelles in an aqueous medium. 2,4-dichlorophenoxyacetic acid (2,4-D) was used as the active ingredient. The release of

2,4-D from the micelles was promoted by sunlight, during which the coumarin moieties were cleaved from the CMCS framework, which resulted in a shift of the hydrophilic–hydrophobic balance and destabilization of the micelles [207]. Maan et al. (2024) synthesized nanopreparations based on chitosan and guar gum containing the pesticide chlorpyrifos. The researchers obtained spherical nanoparticles (NPs) that showed good stability when stored at 25 °C for 60 days. Chlorpyrifos nanoformulations cross-linked with glyoxal showed an almost 25% slower release compared to conventional preparations, dependent on the diffusion and degradation of the polymer matrix in different pH ranges [208]. Singh et al. (2022) developed a pesticide formulation using chitosan (CS)–alginate (Alg) and cenosphere (Cn) composite hydrogel beads to release imidacloprid (IMI). Importantly, the preparation protected the pesticide against UV radiation. The obtained IMI-CS-Alg-Cn beads, thanks to their hollow structure and porous cross-linked mesh, had high encapsulation efficiency (80%) and showed a slower release profile under different pH conditions compared to the commercial preparation [209].

Chitosan nanoparticles can be successfully used as carriers for the controlled release of fertilizers, and importantly, chitosan is a compound that easily forms complexes with fertilizer molecules, making them available to plants [134,210].

dos Santos Pereira et al. (2020) prepared microspheres of chitosan and sugarcane bagasse using the inversion phase method followed by the sorption of fertilizer with potassium nitrate ( $\text{KNO}_3$ ). The release of fertilizer ions was assessed in water and soil and the plateau state was reached after an hour for all analyzed samples. Since the matrices acted as the ion carrier, the microspheres released nutrients in smaller amounts than conventional fertilizers. The released process caused the formation of cavities on the surface of the microspheres and, particularly visible during the release in the soil, the process took place by diffusion and depended on humidity. Hence, watering has been shown to act as a release trigger and control its release profile [211]. Suratman et al. (2020) developed a glutaraldehyde cross-linked chitosan capsule for coating NPK fertilizer. The resulting hydrogel granules can absorb significant doses of NPK and release them in a controlled manner with high efficiency. The researchers also showed that the release profile of NPK from chitosan capsules was dependent on the soil pH. Comparing two methods, freeze-drying and air-drying, showed that the particles obtained during freeze-drying have larger pore sizes, which results in a higher percentage of fertilizer release [212]. Siri et al. (2021) developed an environmentally friendly nanofertilizer based on chitosan and activated coir fiber. The analysis of the release profile of plant macronutrients—nitrogen, phosphorus, and potassium (NPK) and the effectiveness of the fertilizer were assessed in comparison to conventional bulk fertilizers. The developed system was characterized by a controlled release of macronutrients even after 3 months, while the commercial fertilizer initially released very rapidly with a negligible release after 30 days. Additionally, pot tests carried out on rice showed that, compared to fertilizers available on the market, the developed nanofertilizer significantly increased the crop yield [213]. Jayanudi et al. (2021) obtained, using the emulsion cross-linking method, a chitosan microsphere filled with urea, using glutaraldehyde-saturated toluene (GST) as a cross-linking agent. The conducted research showed that changing the volume ratio between the continuous phase and the dispersed phase (CP/DP) has a significant impact on the efficiency and cumulative nitrogen release, and the nitrogen release mechanism from chitosan microspheres was controlled by diffusion and swelling [214]. Eddarai et al. (2023) reported a chitosan–clay composite (CSGC) coating material for coating NPK fertilizer. The proposed coating (NPK/CSGC) improved the mechanical strength of the fertilizer and influenced the soil's ability to retain water. The use of slow-release fertilizer and a 50% reduction in the amount of NPK fertilizers can significantly improve the metabolism of tomatoes, increasing the biomass and chlorophyll content. The resulting carrier based on chitosan and kaolinite clay can be an effective way to maintain nutrients in the soil and improve the quality of crops [215].

Ma et al. (2023) used emulsification and cross-linking techniques to obtain chitosan microspheres as a carrier for urea. The urea encapsulation efficiency was 89%. The

obtained controlled-release nitrogen fertilizers based on chitosan microspheres showed promising results in terms of all analyzed physicochemical parameters for the tested Chinese cabbage, i.e., higher plant height, larger number of leaves, and more favorable seed germination [216].

### 5.3.2. Cellulose

To meet the requirements for materials used in the controlled release of agrochemicals, cellulose always requires various modifications. There are three hydroxyl groups in each cellulose unit, one primary at C-6 and two secondary ones at C-2 and C-3, and it is through the hydroxyl groups that chemical modifications can be carried out, e.g., esterification, etherification, grafting, and cross-linking.

Esterification is the basic method of improving some properties of cellulose, such as mechanical strength, oxidation properties, hydrophilicity, hydrophobicity, and others. As esterification reagents, carboxylic acid, carboxylic acid anhydride, and acyl halide are usually used. Among the most useful cellulose derivatives is cellulose acetate (CA), which is a commonly used membrane material and is used in controlled release systems [217,218].

Etherification can also improve the properties of cellulose or modify the functions of cellulosic materials. As ether bonds are much more stable in the basic state than ester bonds, derivatives of this type can be used in a wider range. Etherified cellulose derivatives such as carboxymethyl cellulose (CMC), hydroxyethyl cellulose (HEC), and ethyl cellulose (EC), etc., are commonly used in controlled systems. They have pH-responsive properties and exhibit surface active properties, while the hydrophilicity and hydrophobicity of cellulose ether derivatives can be adapted to the needs of agrochemistry [219–221].

Grafting is a convenient method of giving cellulose the properties of other polymers. Cellulose grafting can occur by combining the cellulose skeleton with active polymer end groups (graft-to) or by polymerization from the initiation site of monomers on cellulose (graft-with). The most commonly used method in controlled release systems for agrochemicals is to graft hydrophilic monomers, e.g., acrylic acid and acrylamide, onto a cellulose backbone to produce hydrogels. Also, creating polymer blends of cellulose with other polymers can have the same effect, but the factor determining the success of mixing is achieving the good compatibility of the blends [222,223].

The cross-linking process is a way not only to improve the mechanical properties and release profile, but above all, it causes the materials to swell in water instead of dissolving. Moreover, cellulose has the ability to create three-dimensional networks as a result of cross-linking, which may slow down the release process. Cross-linking involves combining two or more cellulose molecules with the use of a cross-linking agent. The cross-linking agent contains active groups that can be attached to cellulose through a chemical reaction, including esterification, etherification, radical polymerization, etc. [218]. Commonly used cross-linking agents are diisocyanate, epichlorohydrin, dicarboxylic acid, or diacrylate [223–226]. An interesting solution is also cross-linking cellulose with other polymers such as chitosan, sodium alginate, poly(vinyl alcohol), and others [227–229].

Polymer matrices based on cellulose diacetate as carriers for plant insect repellents and attractants for the release of citronellol, terpineol, and methyl salicylate were developed by Mphateng et al. (2022). Matrices of cellulose diacetate and organic clay containing 35% by the weight of active ingredients were prepared by mixing by twin-screw extrusion; additionally, the active compounds also acted as plasticizers. The matrix acted as a reservoir of active substances, simultaneously controlling their release into the environment [230].

A microcapsule of nanofibrillated cellulose (NFC) as the shell wall material and isophorone diisocyanate (IPDI) as the cross-linker filled with chlorpyrifos (CPF-CM) was obtained by Xiao et al. (2021). The prepared CPF-CM showed approximately 30% charging efficiency and favorable adhesion to the surface of cucumber and peanut leaves compared to the conventional preparation. The release and control effectiveness of the CPF-CM microcapsule against *P. xylostella* were dependent on the temperature change [231].

Carboxymethyl cellulose (CMC), as one of the most promising cellulose derivatives, due to its mechanical strength, viscosity, water absorption, and availability, is one of the most promising materials in the agricultural sector, allowing not only the fight against water shortages, but also the targeted supply of agrochemicals [232].

Ma et al. (2020) developed citral-loaded modified chitosan/carboxymethylcellulose copolymer (CS/CMC) hydrogel microspheres. Citral is an effective agent inhibiting the growth of various pathogenic fungi, but because it is characterized by high volatility and chemical instability, its use in agriculture remains limited. Citral was incorporated into the microspheres by combining the carbonyl group of citral with the amino group of CS, forming a Schiff base structure. The obtained structures had improved in vitro antibacterial activity against *E. coli*, *B. subtilis*, and *S. aureus* and showed good in vivo antifungal activity, reducing the incidence of diseases caused by *Botrytis cinerea* [233].

Hao et al. (2020), to encapsulate the model pesticide avermectin (AVM), used a graft copolymer of carboxymethylcellulose (CMC) and diallyldimethylammonium chloride (DM-DAAC), i.e., CMC-g-PDMAAC, in which phosphorylated zein (P-Zein) was incorporated. The obtained AVM-P-Zein/CMC-g-PDMAAC nanospheres were characterized by high encapsulation efficiency, and the pesticide release profile can be controlled by changing monomer ratios and pH values [234].

Zhao et al. (2021) prepared a carboxymethylcellulose (CMC)- and rosin (RS)-based CMC-g-PRSG carrier for the model pesticide avermectin (AVM). Research has proven that the developed nanopesticide showed the increased dispersibility and stability of AVM in water, and importantly, it effectively adhered to the leaves, limiting its losses. Similar to previous studies, the release profile of this pesticide can be controlled by adjusting the pH. Additionally, a 3-fold increase in the half-life of AVM was observed, which translates into a longer period of activity and pest control [235].

Sharif et al. (2021) determined the suitability of carboxymethylcellulose (CMC) as a matrix in the controlled release of the herbicide bispiribac (BP). The release rates of BP into aqueous solutions of  $\text{Na}_3\text{PO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{NaCl}$  were measured using a UV spectrophotometer. CMC exhibited hygroscopic properties and formed gels, which resulted in a delayed release, and thus reduced pollution resulting from the overuse of pesticides [236].

Ahmad et al. (2023) developed an environmentally friendly carrier based on cellulose fibers derived from waste paper, epichlorohydrin (ECH) as a cross-linking agent, and carboxymethyl cellulose (CMC) as a gelling agent. Urea was used as a model fertilizer. During the analysis of the urea release from the developed matrix, more than a 30-day extension of release compared to free urea was observed [237].

Sharma et al. (2023) developed cellulose nanofibers obtained from rice straw, which were filled with ammonium chloride. The release profile of the obtained cellulose fibers showed a cumulative release of 58% ammonium ions over 8 days, while the control showed a release rate greater than 80% over this time. The study serves as the basis for the use of rice straw cellulose as an alternative to current environmentally harmful practices [238].

Jha et al. (2024) synthesized a hydrogel composed of cellulose nanofibers (CNF) and carboxymethyl cellulose (CMC) as a carrier for urea. The urea release rate was relatively slow, and the complete release took approximately 30 days, with effective improvements of seed germination and plant growth relative to the control and plant samples containing pure urea [239].

Sultan et al. (2024) reported the carboxymethylcellulose-g-polyacrylamide copolymer (CMC-g-PAM) as a urea-based fertilizer carrier. The urea-loaded CMC-g-PAM copolymer exhibited a slow and sustained release regulated by diffusion and dependent on the environmental pH. The maximum cumulative release percentage was close to 70% at pH 9 and 40% in saline conditions [240].

### 5.3.3. Alginate

The ionotropic gelation technique is used to prepare the agrochemical preparation of alginate beads. Alginate beads are produced by adding a solution of sodium alginate

containing the desired active substance dropwise to a solution of metal ions, which acts as a cross-linking agent. Although the presented method is a simple and quick method for obtaining agrochemical preparations, it is associated with a certain limitation, which is the loss of the active ingredient during the bead preparation process. One way to solve this problem is to prepare biopolymer beads using alginate, another natural polysaccharide. An important aspect of using alginate as a carrier for active substances in agriculture is the fact that it undergoes enzymatic or radiolytic degradation in the soil, creating oligoalginates that are plant growth stimulators. They have a positive effect on the processes of germination, shoot elongation, and root growth, which translates into increased yields [130].

Various alginate-based formulations have been used to control pesticides' release profiles. Artusio et al. (2021) synthesized alginate nanoparticles using an inverse miniemulsion matrix in sunflower oil as a carrier for the hydrophilic herbicide, Dicamba. The developed stable nanohydrogel particles promoted the sustained release of Dicamba over 10 days. The nanoformulation of the pesticide slowed down the release rate and exerted a protective effect on the hydrophilic active substances [241].

Du et al. (2023) developed, using spray-drying technology, dinotefuran (DIN) microspheres with the addition of sodium alginate (SA), gelatin (GEL), and polyvinylpyrrolidone (PVP). Sodium alginate (SA) is a material that has the ability to immobilize, adsorb, and displace metal cations, and combining it with other materials can improve its physical properties. The obtained SA-GEL-PVP system, due to the presence of PVP, shows good surface activity and a strong ability to form hydrogen bonds and complexes. However, the improvement of the strong mechanical properties of SA and PVP was achieved by the addition of relatively elastic gelatin, which additionally affects the water absorption capacity. The obtained microspheres showed a variable controlled release ability depending on different temperatures and soil types. In addition, they showed the improved control of *Protaetia brevitarsis* larvae during early pesticide applications, with the potential to control pest outbreaks at high temperatures. Empty microspheres influenced the growth of cucumber seedlings, prevented soil acidification, increased the nutrient content as well as the number of beneficial bacteria in the soil [242,243]. Zheng et al. (2021) developed an intelligent pesticide delivery system in which imidacloprid (IMI) was adsorbed by polydopamine (PK)-modified kaolin along with calcium alginate, which is a pH-sensitive protective coating that hinders the release of pesticides from PK. Increasing the adhesion of the composite to the leaves was achieved by using an amino-silicone oil (ASO) coating. However, the ability to regulate the release with light was achieved by the addition of a detonation nanodiamond (DND) and poly(N-isopropylacrylamide) (PNIPAm). The developed structure (IPKCPD-ASO) allows the regulation of the IMI release rate depending on the pH and access to light, allowing it to adapt to the feeding habits of pests with changes in daylight. The use of the ASO coating affects the viscosity and increases the adhesion of the beads to the leaf surface, which reduces IMI losses and increases the efficiency of the system [244]. Xie et al. (2020) developed an environmentally friendly controlled release system for spirotetramat, a systemic pesticide, in an alginate carrier. Four preparations were tested: gel beads composed of starch, chitosan, and calcium alginate (SCCA); starch alginate and calcium (SCA); and chitosan, calcium alginate (CCA), and calcium alginate (CaA). The SCCA preparation had the highest pesticide entrapment efficiency and the slowest release rate, allowing the duration of action of spirotetramat to be extended and environmental contamination reduced [245].

El Bouchtaoui et al. (2022) developed sodium alginate–lignin (SA-L) blends at a low-cost, a biodegradable coating material for diammonium phosphate (DAP)-based fertilizers. The use of polymer coatings allowed for the creation of a uniform and compact film on the fertilizer surface, which improved the mechanical properties and extended the maximum availability of nutrients. Furthermore, increasing the lignin content had a beneficial effect on the slow release, exceeding one month, instead of only four days obtained with uncoated DAP [246].

Llive et al. (2020), in line with current bioeconomic trends, proposed recycling industrial yerba mate by-products to obtain capsules for designing controlled-release fertilizers. The capsule matrix consisted of calcium alginate with 83% *w/w* added yerba mate powder (YMP). The aim of the research was to investigate the kinetics of the release of mineral fertilizers containing urea, potassium, and phosphorus, both into soil and water. Retention and degradation in the soil depended on the structure of the capsules as well as on their thermal properties, which was related to the content of alginate and YMP. Taking into account that fertilizers are always exposed to a wide range of climatic conditions, thermal analysis confirmed the high stability of the obtained systems, regardless of the type of fertilizer, which has a beneficial effect on the suitability of this type of capsules. The fertilizer release profile was assessed for 120 min. The results showed high potassium release efficiency, which was stable and close to 100% during this time. A plateau effect was also achieved for urea and phosphorus, with release percentages of 72% and 45%, respectively, which confirms the effectiveness of the obtained systems and the possibility of their use as agents for the controlled release of fertilizers [247].

Nooeaid et al. (2024) proposed hydroxyapatite/alginate (NPK-HA/Alg) biocomposite balls for the release of nitrogen, phosphorus, and potassium using the dropwise and external gelation method. The addition of HA improved the structural and thermal stability of the alginate beads. The resulting structures made the prolonged and controlled release of nutrients in deionized water for 35 days possible. The effectiveness of the biocomposite was tested for the growth of flowering Chinese cabbage in a controlled greenhouse environment. The obtained results showed that non-toxic NPK-HA/Alg balls increase the height, number of leaves, and fresh and dry weight of the plant [248].

A slow-release fertilizer formulation based on alginate was also developed by Stanley and Mahanty (2020). Urea was introduced as an active ingredient into the hydrogel core of polyvinyl alcohol and alginate, covered with a calcium carbonate coating. High urea encapsulation efficiency was achieved for both  $\text{CaCO}_3$ -reinforced ~24 and plain ~39% *w/w* hydrogel matrices, while the release profile into the aqueous phase did not differ significantly between the two hydrogel variants. The release in soil was characterized by a two-stage urea release pattern. The first phase is slow, followed by a rapid growth that may last for hours. Hence, the modified controlled-release hydrogel can be widely used as a slow-release fertilizer in agriculture [249].

#### 5.3.4. Starch and Its Derivatives

In recent years, there has been great interest in modifying the physical and chemical properties of starch and its derivatives through graft copolymerization. Starch-grafted copolymers, e.g., starch-g-polystyrene or starch-g-polyvinyl alcohol, have been synthesized by generating free radicals on the surface of starch grains and copolymerizing these free radicals with vinyl monomers. However, these copolymers with vinyl polymer branches have limited biodegradability due to the presence of a non-degradable portion of the polymer, although their properties are acceptable in applications. The solution to this problem is grafting starch with biodegradable polymers such as polylactide (PLA) or poly( $\epsilon$ -caprolactone (PCL). Graft copolymers, such as starch-g-PLA and starch-g-PCL, are characterized by improved mechanical properties and are capable of completing biodegradation by bacteria or in natural conditions [250].

One of the recent studies concerned the use of SNCs (starch nanocrystals) as promising nanocarriers due to their stability, ease of preparation, and biodegradability. SNCs with a stable structure and uniform porosity were obtained by removing the amorphous region of corn starch using sulfuric acid and ultrasonic treatment. TMX (thiamethoxam) nanoparticles were obtained as a result of electrostatic interactions with these nanocrystals. Compared to the TMX suspension (without a carrier), the TMX-loaded SNC carrier showed significantly higher insecticidal activity against *Diaphorina citri*, a notorious pest in citrus cultivation. SNC obtained by the hydrolysis of sulfuric acid and ultrasound can be successfully used as TMX carriers, thus increasing the degree of its utilization while reducing toxicity to bees.

This approach is a valuable contribution to the development of environmentally friendly nanopesticide carriers and the control of pests such as *D. citri* [251].

The release of one of the most widespread herbicides, glyphosate, on corn starch microspheres was analyzed by Dong et al. (2021). The results showed that the adsorption capacities of glyphosate on native corn starch, microporous corn starch, and microporous corn starch with xanthan gum increased sequentially. During the desorption process, glyphosate was released in a controlled manner onto microporous corn starch with 0.02% xanthan gum, with a cumulative release of approximately 60% over 48 h. The obtained results indicate that microporous corn starch with 0.02% xanthan gum is a good carrier of glyphosate with a controlled and prolonged release. This study provides useful insight into the development of high-concentration sustained-release glyphosate formulations [252].

In the study by Fabiyi et al. (2020), a porous starch citrate biopolymer was designed to release carbofuran. Highly stabilized porous starch citrate biopolymers with porous structures and gradients suitable for controlled release studies were obtained. The release rate of carbofuran from the starch citrate biopolymer matrix was much lower than with a direct application and, despite the slow release, a higher mortality of knot nematode *Meloidogyne incognita* and reduced egg hatching were achieved [253].

Our research group grafted PCL onto the surface of dextrin and maltodextrin via ring-opening polymerization and sequentially prepared polymer blends with previously developed terpolymers with a chain composed of two blocks, namely an L-lactide/glycolide copolymer block and a polyethylene glycol (PEG) block. Thanks to this modification, homogeneous blends were obtained with better susceptibility to uniform enzymatic degradation, which resulted in a controlled release process of two soil herbicides, Metazachlor and Pendimethalin, dependent on the degradation of the polymer carrier. The developed polymer blends containing dextrin and maltodextrin grafting with 10% metazachlor showed an almost 100% release into the soil within 12 weeks, while mixtures containing 10% pendimethalin showed an almost 40% release over the same period of time. The release rate of immobilized herbicides depended on their solubility in water and the composition of the polymer blends, consistent with the assumption that in the case of agricultural applications, the release rate of active substances should be optimal during the plant's growing season in order to combat weeds in crops [250].

The issue of developing biodegradable composite films with the controlled release of fertilizers for agricultural applications was raised by Versino et al. (2019). They developed composite materials from cassava and pomace containing urea as an active substance and plasticizer. The research analyzed the biodegradation rate of these composites and the release of urea into the soil. The films consisted of cassava starch with cassava pomace particles as a strengthening agent, while the urea content ranged from 0 to 50% by weight based on the starch content. It was shown that the rate of the biodegradation of material in the soil increased with the increase in the urea content. Weight loss for a film with a urea content of 50 wt% was 57%, with an almost complete release of the active substance of 95% after 15 days. The obtained results confirm that composites based on cassava starch are suitable for designing ecological materials for dosing urea in the soil [254].

An innovative and functional biomass-based fertilizer with a slow, controlled release was proposed by Sofyane et al. (2021). Various starch acetate/polyvinyl alcohol (PVA)/glycerol (GLY)-based biocomposites were prepared to control the phosphorus (P) and nitrogen (N) release from diammonium phosphate (DAP) fertilizers. Compared to uncoated DAP granules, in which N is completely dissolved after 95 min, the maximum N dissolution rate was achieved after 230 min for DAPs coated with a single layer of CF-2 (composition in weight percent of the SA/PVA/GLY 55:28:17), and for DAPs coated with a double layer of CF-2 after 300 min, which indicates an improvement in slower N release properties. It is expected that with more detailed research on slow-release nutrient fertilizers that reduce phosphorus and nitrogen losses, environmentally friendly SA/PVA/GLY composites can be obtained by adjusting their composition [255].

Lü et al. (2024), in order to improve the efficiency of biomass use and reduce environmental pollution, developed a coating fertilizer system based on starch acetate (SA) and weakly cross-linked carboxymethyl starch/xanthan gum (CMS/XG). Encapsulated urea with a diameter ranging from 2.5 to 3.0 mm is characterized by good mechanical properties and a low moisture content. The nitrogen release profile depended on the coating thickness and the plasticizer content in the SA film, while the nitrogen release equilibrium state was achieved within 20 days. Moreover, it was shown that soil mixtures with coated fertilizers retained more water than the control soil, and the water content increased with the increase in the amount of coated fertilizer in the soil. The obtained products based on starch derivatives as coating materials are characterized by a preferred slow release, and the introduction of natural polymers can improve the efficiency of biomass use, improve water use efficiency, and, above all, reduce the loss of nutrients [256].

One of the recent studies conducted by the group of Agrawal et al. (2024) presents biodegradable dextrin-based microgels (PDXE MG) having phosphate-based cross-linking units for the slow release of urea. PDXE MG was obtained by cross-linking lauroyl-functionalized dextrin chains with sodium tripolyphosphate. The developed composites are characterized by the high loading (~10%) and encapsulation efficiency (~88%) of urea. The functionalization of PDXE MG with lauroyl chains slowed the release of urea in water (90% in ~24 days) compared to unfunctionalized microgels (PDX MG) (99% in ~17 days). Tests on seed germination and overall plant growth showed a significant acceleration of corn germination and visible plant growth after the use of Urea-PDXE MG preparations compared to pure urea fertilizer. These experimental results present the developed formulation as a potential candidate for moving towards sustainable agricultural practices [257].

#### 5.3.5. Aliphatic Polyesters

In the context of concern for the environment, replacing plastic products is becoming a natural choice, and the development of bioplastics has become one of the most frequently discussed topics in recent years. Aliphatic polyesters are among the most frequently studied biodegradable plastics due to their potentially hydrolyzable ester bonds, which make them biodegradable. Polyesters widely introduced for agricultural applications include polylactic acid (PLA), polycaprolactone (PCL), polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), polyhydroxyvalerates (PHV), and polybutylene succinate (PBS) and its copolymer poly(butylene succinate-co-adipate) (PBSA).

Poly lactide is a thermoplastic, completely biodegradable and biocompatible aliphatic linear polyester, enabling the surface adsorption or encapsulation of a wide spectrum of bioactive, hydrophilic, or lipophilic ingredients [258–260]. However, despite favorable properties such as biodegradability and processability, PLA is characterized by high brittleness and often requires another agent to improve flexibility. One of the most practical methods to overcome this disadvantage is to mix PLA with other polymers and/or plasticizers. Our research group analyzed the impact of one of the most commonly used plasticizers, poly(ethylene glycol) (PEG), on improving the mechanical, thermal, and morphological properties of PLA and the possibility of using the obtained PLA/PEG blends in agriculture [261].

In another study, we investigated the potential use of the terpolymer poly(l-lactide-co-glycolide)–poly(ethylene glycol)–poly(l-lactide-co-glycolide) (PLGA–PEG–PLGA) as an environmentally friendly polymer carrier for agrochemicals. PEG, as before, acted as a plasticizer. By slightly increasing the hydrophilicity of the polymer chain, its susceptibility to hydrolysis also increased, which had an unexpectedly strong impact on enzymatic degradation in the soil environment [262].

Poly caprolactone is an aliphatic, biodegradable polyester with a linear structure,  $[O(CH_2)_5CO]_n$ , produced from petrochemical products. It is commonly used as a biodegradable packaging material because it can be broken down by microorganisms. Moreover, it has been shown that it can be degraded by a hydrolytic mechanism under physiological

conditions. Due to its appropriate physical and biological properties, PCL is also widely used in the production of biomedical and agrochemical materials. Due to its low melting point (57–60 °C), its mixtures with agrochemicals can be processed into plant protection product preparations at temperatures lower than their degradation temperature, using the extrusion method [263,264].

Polyhydroxybutyrate (PHB) belongs to the PHA family and is a polyester naturally produced by bacteria of the genus *Alcaligenes*, *Azobacter*, *Bacillus*, and *Pseudomonas* as a reserve material. The most widely used organism for the production of PHB is *Alcaligenes eutrophicus*, which is able to achieve a high reproductive rate with significant accumulation of up to 80% dry matter. Before extraction, PHB is completely amorphous, and after extraction, it crystallizes. As a result of the copolymerization of 3-hydroxyvaleric acid with PHB, poly(3-hydroxybutyrate/3-hydroxyvalerate) (PHBV) copolymers with a 3-hydroxyvalerate (HV) content ranging from 0 to 90% are obtained, which allows obtaining a material with modified properties. Since the rate of the hydrolytic degradation of PHB and PHBV under physiological conditions is slow, the influence of some bacteria and fungi, both aerobic and anaerobic, such as *Pseudomonas*, *Streptomyces*, and *Penicillium lilacinus*, significantly accelerates the decomposition of these polyesters [260,265].

PBSA is a thermoplastic aliphatic polyester synthetically produced from 1,4-butanediol, succinic acid, and adipic acid. In line with the latest emerging trends in agriculture, bio-based PBSA is currently used in the production of foils, bags, and pots, but also in controlled release systems of agrochemicals. PBSA exhibits good mechanical and thermal properties and is easily processed by conventional techniques such as extrusion, injection molding, and thermoforming. Depending on the comonomer ratio, molecular weight, branching, and specific environment such as the pH, salinity, temperature, and crystallinity, both PBS and PBSA are easily degraded in freshwater, seawater, soil, activated sludge, and compost [266].

The encapsulation of pesticides in biodegradable carriers is currently one of the main approaches to develop an environmentally friendly and efficient controlled-release delivery system.

Liu et al. (2016) used the membrane emulsification process to develop polylactide carriers for the controlled delivery of  $\lambda$ -cyhalothrin. Compared to the commercial LC microcapsule formulation, the PLA carrier-based microcapsule systems showed a significantly sustained LC release over a longer period. The studies demonstrated the possibility of regulating the release of LC as a result of LC diffusion and matrix degradation depending on the LC content and the size of the microcapsule particles. Preliminary biological tests against *Plutella xylostella* revealed that LC-loaded microcapsules showed activity similar to the commercially available preparation. The developed system is of great importance for achieving the precisely controlled release of pesticides [267].

Roshani et al. (2016) developed thiram-loaded nanofibers which were successfully fabricated by the electrospinning technique. Thiram is a pesticide designed to control fungi and protect crop products. The results confirmed that thiram-containing electrospun polylactide nanofibers could be used for the controlled release of thiram pesticides over long periods in agricultural applications [268].

In the study by Takei et al. (2008), a combination of polylactide (PLA) and polycaprolactone (PCL) was used to immobilize and encapsulate acetamiprid using an O/O emulsion by the solvent evaporation method. The release of this pesticide from PLA-based microspheres allowed the release of only a small amount, approximately 18%, while creating a combination with PCL significantly increased the release percentage to 89%. Such a low percentage of release from pure PLA may be due to the fact that this material has strong hydrophobic properties. The addition of PCL with a lower molecular weight than PLA allowed the structure to loosen and hydrophobicity to decrease [269].

The herbicide metribuzin was successfully released from a PCL-based carrier. Within 7 days, an 81–96% release of initially loaded metribuzin in water and 37–55% release in soil was achieved. The lower percentage of release in soil is due to the partial degradation of

the herbicide in this medium. The developed system is a promising approach for obtaining long-term release preparations for soil applications [263].

Suave et al. (2010) assessed the effectiveness of the controlled release of the malathion pesticide placed in microspheres of pure poly(3-hydroxybutyrate) and poly( $\epsilon$ -caprolactone) polymers and blends of these polymers. Release tests were performed in an aqueous environment and malathion was quantified using ultraviolet spectroscopy. The results confirmed that the addition of PCL in the mixtures improved the release of malathion, making it possible to modulate the release of the pesticide in these biodegradable blends [270].

Environmentally friendly slow-release herbicide formulations of metribuzin, Triennuron-methyl, and fenoxaprop-P-ethyl from a poly-3-hydroxybutyrate (P(3HB)) matrix were developed in the study of Kiselev et al. (2019). The rate of the herbicide release depended on the degree of their solubility: the rapidly dissolving metribuzin and Triennuron-methyl were released at a higher rate than the less soluble fenoxaprop-P-ethyl. The development of a polymer matrix consisting of slowly degraded P(3HB) and natural materials enabled both the long-lasting action of the preparations in the soil (lasting from 1.5 to  $\geq 3$  months) and the stable activity of quickly inactivated herbicides, such as Triennuron-methyl and fenoxaprop-P-ethyl [271].

A series of experimental slow-release pesticide formulations using composites of degradable poly(3-hydroxybutyrate) polyester and natural materials as a matrix for tebuconazole (a fungicide) and metribuzin (a herbicide) were presented in the study of Prudnikova and Volova (2019). The experimental formulations gradually released active ingredients into the soil over a two-month period without sudden emissions, maintaining the long-term protection of plants against pathogens and weeds. The antifungal activity of tebuconazole was confirmed on model plants of *Triticum aestivum* infected with a complex of root rot pathogens (*Alternaria*, *Fusarium*, and *Bipolaris*), while the effectiveness of the herbicide metribuzin was analyzed on the model weed *Melilotus albus*. The effects of the obtained preparations were comparable to the effectiveness of the free forms of these agrochemicals [272].

Wang et al. (2018) developed a controlled release system azoxystrobin and difenoconazole from microspheres constructed from blends of poly(butylene succinate) (PBS) and poly(lactic acid) (PLA). The obtained microspheres were characterized by a longer sustained release period than a difenoconazole–azoxystrobin suspension concentrate. The developed system makes a significant contribution to optimizing the effectiveness of agrochemicals and minimizing environmental pollution [273].

Biodegradable poly(butylene succinate) microspheres containing the pesticide  $\lambda$ -cyhalothrin were prepared by a phase separation method induced by solvent evaporation. Studies have shown that different microsphere morphologies affect the encapsulation efficiency and pesticide release profile. Systems developed on the basis of PBS were characterized by a long release time, with interesting adhesive properties that allowed them to adhere to the surface of leaves, making them suitable for spraying plant protection products [274].

Cen et al. (2021) developed a biochar-based controlled-release nitrogen fertilizer (BCRNF) to improve N availability in maize crops. Biochar-impregnated ammonium sulfate granules were coated with 3%, 6%, and 10% polylactic acid (PLA). The studies showed that the PLA coating increased the N content of BCRNF particles to 16%. The PLA concentration in the coating layer influenced the time, N release rate, and the morphology and thermal properties of BCRNF. The use of higher concentrations of PLA extended the N release time. Further research on the BCRNF system will allow for the optimal synchronization of the time and amount of available N with the N demand in crops [275].

In the study by El Assimi et al. (2021), they proposed a biodegradable coating based on polylactic acid (PLA) and cellulose acetate (CA) for the encapsulation of diammonium phosphate (DAP) granules. The introduction of CA reduces the crystallinity of PLA while accelerating the degradation of the coating in the soil. The retarding effect of the PLA/CA

system meets the requirements set by European standards, i.e., 20% P released in the first 24 h [276].

Also, El Assimi et al. (2020) presented PCL-based coatings grafted onto guar gum (GG) and halloysite nanotubes (HNT) for delaying the nutrient release from diammonium phosphate (DAP). It was shown that the hydrophilic nature of the fillers (GG and HNT) positively influenced the adhesion between the coating agent and the granule surface (DAP) and, therefore, DAP granulates were successfully coated by dip coating. The release rate from the composites (PCL-g-GG and PCL-g-HNT) can be controlled by adjusting the filler content. The encapsulation treatment used extended the release of N and P to over 50 h instead of only 2 h in the case of uncoated DAP granules [277].

Also, the same group of Boutrouia et al. (2024) developed coated fertilizer copolymers grafted with poly( $\epsilon$ -caprolactone) and chitosan. CS-g-PCL was applied using a laboratory rotary drum to evenly cover the granulated diammonium phosphate (DAP) fertilizer. Studies on the degradation of CS-g-PCL in aerobic conditions showed an increase in degradability compared to pure PCL, while the release of nitrogen and phosphorus was significantly delayed compared to that observed in the case of conventional DAP fertilizers [278].

In order to improve the uptake of nutrients by plants, polymer compounds based on biodegradable poly(3-hydroxybutyrate) and montmorillonite clay (MMt) were fused with  $\text{KNO}_3$  and NPK fertilizers. An analysis of the release profile of potassium ( $\text{K}^+$ ), nitrogen ( $\text{NH}_4^{4+}$  and  $\text{NO}_3^{3-}$ ), and phosphorus ( $\text{PO}_4^{3-}$ ) from the PHB/MMt/fertilizer complex showed a lower but longer release of nutrients than in the case of pure fertilizer. Moreover, it was shown that cations are released faster than anions through their diffusion through the MMt phase. Additionally, the simple preparation method also ensures the durability of the entire process [279].

A slow-release fertilizer prepared by melt-mixing poly(butylene succinate) PBS filled with 30% urea and 5% montmorillonite clay was developed by Baldanza et al. (2018). The release study was tested gravimetrically and spectrophotometrically. Vegetable growth analysis was also carried out to assess the development of lettuce (*Lactuca sativa* L.). The results showed a 67% increase in the lettuce diameter for the best composite material compared to the conventional urea formulation, which increased this diameter by 48% [280]. All information about polymers used as carriers for the agrochemicals controlled are collected in Table 2.

**Table 2.** Controlled-release pesticide and fertilizer formulations.

| Polymer Carrier                          | Active Ingredient                         | Reference |
|------------------------------------------|-------------------------------------------|-----------|
| chitosan (CS)                            | Spinosad                                  | [204]     |
| chitosan (CS)                            | Chlorantraniliprole                       | [205]     |
| carboxymethyl chitosan (CMCS)            | Avermectin/<br>Spinetoram                 | [206]     |
| carboxymethyl chitosan (CMCS)            | 2,4-D                                     | [207]     |
| chitosan–guargum                         | Chlorpyrifos                              | [208]     |
| chitosan–alginate                        | Imidacloprid (IMI)                        | [209]     |
| chitosan/carboxymethylcellulose (CS/CMC) | Citral                                    | [233]     |
| chitosan/Bagasse                         | $\text{KNO}_3$                            | [72]      |
| chitosan (CS)                            | NPK                                       | [212]     |
| chitosan/activated coir fiber            | NPK                                       | [213]     |
| chitosan (CS)                            | urea                                      | [214]     |
| chitosan–clay composite (CsGC)           | NPK                                       | [215]     |
| chitosan (CS)                            | urea                                      | [216]     |
| cellulose diacetate                      | Citronellol, Terpeneol, Methyl salicylate | [230]     |

Table 2. Cont.

| Polymer Carrier                                                                                                                     | Active Ingredient                                     | Reference |
|-------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|-----------|
| nanofibrillated cellulose (NFC)                                                                                                     | Chlorpyrifos                                          | [231]     |
| carboxymethylcellulose (CMC)/diallyldimethylammonium chloride (DMDAAC)/phosphorylated zein (P-Zein)<br>(P-Zein/CMC-g-PDMDAAC)       | Avermectin (AVM)                                      | [234]     |
| carboxymethylcellulose (CMC)/rosin (RS)<br>(CMC-g-PRSG)                                                                             | Avermectin (AVM)                                      | [235]     |
| carboxymethylcellulose (CMC)                                                                                                        | Bispiribac (BP)                                       | [236]     |
| Cellulose                                                                                                                           | urea                                                  | [237]     |
| Cellulose                                                                                                                           | ammonium chloride                                     | [238]     |
| Cellulose                                                                                                                           | urea                                                  | [239]     |
| carboxymethylcellulose-g-polyacrylamide copolymer (CMC-g-PAM)                                                                       | urea                                                  | [240]     |
| Alginate                                                                                                                            | Dicamba                                               | [241]     |
| sodium alginate–gelatin–polyvinylpyrrolidone (SA-GEL-PVP)                                                                           | Dinotefuran (DIN)                                     | [242]     |
| polydopamine–kaolin–calcium alginate–poly(N-isopropylacrylamide)(PNIPAm)–nanodiamond (DND)–amino-silicone oil (ASO)<br>(IPKCPD-ASO) | Imidacloprid (IMI)                                    | [244]     |
| starch–chitosan–calcium alginate (SCCA); starch–alginate–calcium (SCA); chitosan–calcium alginate (CCA); calcium–alginate (CA)      | Spirotetramat                                         | [245]     |
| sodium alginate–lignin (SA-L)                                                                                                       | diammonium phosphate (DAP)                            | [246]     |
| Ca(II)-alginate–yerba mate powder (YMP)                                                                                             | urea, potassium, phosphorus                           | [247]     |
| hydroxyapatite/alginate (HA/Alg)                                                                                                    | NPK                                                   | [248]     |
| polyvinyl alcohol alginate (PVA-SA)                                                                                                 | urea                                                  | [249]     |
| SNCs (starch nanocrystals)                                                                                                          | Thiamethoxam (TMX)                                    | [251]     |
| corn starch                                                                                                                         | Glyphosate                                            | [252]     |
| starch citrate                                                                                                                      | Carbofuran                                            | [253]     |
| PLGA/PEG- dextrin-g-PCL or maltodextrin-g-PCL                                                                                       | Metazachlor Pendimethalin                             | [250]     |
| cassava starch                                                                                                                      | urea                                                  | [254]     |
| starch acetate (SA)/polyvinyl alcohol (PVA)/glycerol (GLY)                                                                          | diammonium phosphate (DAP)                            | [255]     |
| starch acetate (SA)/carboxymethyl starch/xanthan gum (CMS/XG)                                                                       | urea                                                  | [256]     |
| dextrin-based microgels (PDXE MG)                                                                                                   | urea                                                  | [257]     |
| PLA                                                                                                                                 | $\lambda$ -cyhalothrin (LC)                           | [267]     |
| PLA                                                                                                                                 | Thiram                                                | [268]     |
| PLA/PCL                                                                                                                             | Acetamiprid                                           | [269]     |
| PCL                                                                                                                                 | Metribuzin                                            | [263]     |
| P(3HB)                                                                                                                              | Metribuzin, Triennuron-methyl, and fenoxaprop-P-ethyl | [271]     |
| P(3HB)                                                                                                                              | Tebuconazole, Metribuzin                              | [272]     |
| PBS/PLA                                                                                                                             | azoxystrobin and difenoconazole                       | [273]     |
| PBS                                                                                                                                 | $\lambda$ -cyhalothrin                                | [274]     |

Table 2. Cont.

| Polymer Carrier                                                                           | Active Ingredient          | Reference |
|-------------------------------------------------------------------------------------------|----------------------------|-----------|
| biochar-based controlled-release nitrogen fertilizer (BCRNF) coated polylactic acid (PLA) | ammonium sulfate           | [275]     |
| polylactic acid (PLA) and cellulose acetate (CA)                                          | diammonium phosphate (DAP) | [276]     |
| PCL-guar gum (GG)-halloysite nanotubes (HNT) (PCL-g-GG and PCL-g-HNT)                     | diammonium phosphate (DAP) | [277]     |
| poly( $\epsilon$ -caprolactone)–chitosan CS-g-PCL                                         | diammonium phosphate (DAP) | [278]     |
| poly(3-hydroxybutyrate) (PHB)–montmorillonite clay (MMt)                                  | KNO <sub>3</sub> and NPK   | [279]     |

In summary, polymer-controlled release systems offer significant advantages for extending the activity period of plant protection products compared to non-encapsulated preparations. Utilizing natural polysaccharides such as chitosan, cellulose, alginate, and starch, along with their chemically synthesized derivatives, enhances the controlled release, biocompatibility, and biodegradability of agrochemicals. Additionally, aliphatic polyesters such as polylactide, polycaprolactone, poly(hydroxy butyrate), and poly(butylene succinate-co-adipate) provide versatile and environmentally friendly options through their capacity for mechanical, thermal, and hydrophilicity improvements. These polymers facilitate effective and sustainable delivery systems, advancing agrochemical applications and contributing to environmentally responsible agricultural practices.

## 6. Polymer-Based Materials for Agricultural Runoff Treatment

### 6.1. Natural Polymers as Adsorbents for Removal of Pesticides from Agricultural Runoff

Agricultural runoff refers to the water that runs off farmland after rainfall or irrigation. This runoff is known to contain a variety of pollutants, which can have negative impacts on the environment, human health, and animal health. The common pollutants present in agricultural runoff include nutrients such as nitrogen, phosphorus, and potassium, as well as agrochemicals like pesticides, insecticides, and fertilizers. Other pollutants may include sediments, heavy metals, bacteria, and antibiotics [281,282].

The elimination of pesticides and their residuals as persistent chemicals from agricultural runoff is a critical concern that warrants attention due to the resultant pollution of diverse ecosystems. The presence of these hazardous chemicals in agricultural runoff can have deleterious effects on the environment, leading to the disruption of habitats and the degradation of the water quality. Therefore, it is imperative to develop effective strategies to mitigate the release of these harmful substances into the environment. This can be achieved through the implementation of polymers for removing pesticides from the agricultural effluent [283]. Polymers, whether derived from natural sources or created synthetically, have exhibited promise as remediation agents for the treatment of pesticide solutions.

Chitin and chitosan have been tested as adsorbents for the removal of 2,4-dichlorophen oxyacetate (2,4-D) from aqueous media. The adsorption experiments at various pH values were effectively carried out by Harmoudi et al. (2014) using chitin and chitosan extracted from shrimp shells. An electrostatic interaction between protonated chitin/chitosan and anionic pesticide at pH 3.7 achieved the maximum herbicide removal. Chitin and chitosan were able to remove 67% and 90% of the pesticide, respectively. Moreover, the pesticide adsorption on the surface of chitin and chitosan took place at heterogeneous sites [284].

Rissouli et al. (2017) also studied the efficiency of chitin and chitosan from shrimp shells in relation to the adsorption of the herbicide glyphosate under various conditions. They noted that glyphosate adsorption was pH-dependent, with an acidic pH being more effective. Moreover, the Langmuir isotherm was considered to be more suitable for describing the adsorption behavior. Desorption experiments have shown that chitin can be regenerated and reused multiple times, making the adsorption process more cost-effective [285]. In addition, Rissouli et al. (2016) tested the above-mentioned biopolymers for the removal of

Linuron from aqueous samples. The results obtained by the researchers demonstrated that chitin and chitosan are effective adsorbents for removing Linuron from aqueous solutions. The adsorption kinetics of these materials for the studied pesticide, however, were relatively slow. The maximum adsorption of the pesticide on chitin and chitosan occurred at pH 5.75. The adsorption was characterized using both the Freundlich and Langmuir models, and the corresponding isotherms were well suited to both models [286].

Abdeen and Mohammad (2014) also investigated the use of chitosan as an inexpensive and readily available adsorbent for the removal of ethoprophos pesticides from aqueous solutions. The removal percentage of ethoprophos increased from 85.7 to 89.2% as the adsorbent dose was increased from 0.02 to 0.1 g/100 mL. The obtained kinetic data were well fitted with the pseudo-second order kinetic model, whereas the Freundlich model provided the best fit to the isotherm data [287].

The potential of nanocellulose as a nanosorbent for the removal of chlorpyrifos as a model of an organophosphate insecticide from water was studied by Moradeeya et al. (2017). They noted that the adsorption process was very fast, reaching an equilibrium within 60 min. Furthermore, they discovered that 1.5 g/L nanocellulose adsorbed 5 mg/L of the pesticide in 20 min, yielding a 99.3% efficiency [288].

Insoluble polymers of  $\beta$ -cyclodextrin, a cheap, environmentally friendly glucose macrocycle, are also useful for removing pesticides from water via adsorption. Alsaiee et al. (2016) tested a porous  $\beta$ -cyclodextrin polymer for the removal of metolachlor. The results indicated that the target molecule was rapidly sorbed. By flowing the adsorbate solution through a thin layer of the prepared material, a percentage removal efficiency of the pollutant of about 75% was achieved [289]. In turn, Hu et al. (2020) applied a quaternary ammonium functionalized  $\beta$ -cyclodextrin polymer for the removal of 2,4,6-trichlorophenol (2,4,6-TCP) from water. They demonstrated that this sorbent could rapidly adsorb the pollutant, much faster than commercial AC and resins. Furthermore, a  $\beta$ -cyclodextrin polymer can be easily regenerated under mild conditions after use, with no significant decrease in the adsorption performance. In addition, at environmentally relevant concentrations, the  $\beta$ -cyclodextrin polymer demonstrated an outstanding performance (93.9%) in eliminating 2,4,6-TCP from a mixture of contaminants [290].

In order to remove pesticides from contaminated water, various composites based on biopolymers are frequently applied. Mostafa et al. (2021) described the preparation and application of a Chitosan/Zelite-A nanocomposite (CS/ZA) for the successful removal of three organophosphorus pesticides (Acephate (AC), Omthosate (OM), and Methyl parathion (MP)). This composite was able to successfully adsorb 650.7 milligrams per gram (mg/g) of AC, 506.5 mg/g of OM, and 560.8 mg/g of MP. These uptake capacities demonstrate the high efficiency of this sorbent in removing pesticides from an aqueous environment, even in the presence of other anionic or cationic pollutants. During continuous column studies, the effectiveness of the CS/ZA particles as fixed beds was tested. The results showed that after treating approximately 7.5 L of polluted solutions, the bed achieved a total removal rate of 78% for AC, 57.6% for OM, and 74.3% for MP. This sorbent was highly efficient and recyclable, and its properties could make it well-suited for use in effective remediation procedures. In turn the Imidacloprid pesticide was found to be effectively adsorbed on a magnetic chitosan/activated carbon bio-nanocomposite with an UiO-66 metal organic framework when other pollutants were present. This composite's adsorption capacity for the pesticide was 25.2 mg/g [291].

A chitosan/gelatin (CS/Gel) natural polymer composite was utilized for decontaminating pesticide wastewater samples, as studied by Attalah et al. (2022). The samples were created by adding atrazine and fenitrothion to distilled water to simulate large-scale wastewater treatment. After 120 min, the percentage of model pesticides removed ranged from 85.65 to 96.45%. The reusability experiments showed that the chitosan/gelatin composite had a pesticide removal efficiency of around 70%, even after its third use [292].

Zhang et al. (2015) employed the cellulose/graphene composite for the effective removal of triazine pesticides from water. This composite was created by combining graphene oxide and dissolved cellulose, then reducing the mixture with hydrazine hydrate. With the help of an easy-to-use organic solvent, the cellulose/graphene composite could be recycled with great stability. The composite maintained an adsorption efficiency of over 85% after being recycled six times [293].

Biopolymer-modified montmorillonite (MMT)-CuO composites were tested by Sahithya et al. (2015) for the removal of dichlorvos [294] and monocrotophos [295] from the aqueous environment via adsorption. In the case of the chitosan-MMT-CuO composite, under optimal adsorption parameters (pH 10.0, time = 5 h, temperature = 30 °C, initial concentration = 80 mg/L, and adsorbent dosage = 1.5 g/L), a 93.4% removal of dichlorvos was achieved [295]. For the polylactic acid-MMT-CuO composite, under the following conditions (pH 6.0, time = 6 h, temperature = 30 °C, initial concentration = 120 mg/L, and adsorbent dosage = 15.0 g/L), the removal of monocrotophos was 83.9% [296].

Alginate beads with silver nanoparticles were made and investigated by Pal et al. (2015) for the purpose of atrazine removal. The adsorbent was able to achieve a 96% removal efficiency for an initial atrazine concentration of 5 mg/L; using 2 g of the adsorbent resulted in the maximum removal of atrazine from the aqueous solution. Moreover, it was discovered that the combined adsorbent could be reused for at least 26 treatment cycles, with easy regeneration using HNO<sub>3</sub> [296]. The montmorillonite–alginate beads, prepared by Etcheverry et al. (2017) for the removal of paraquat, are a type of alginate composite bead that has been studied for pesticide uptake. The beads, with a montmorillonite content of 70%, exhibited the best adsorption results, with a maximum adsorption capacity of 0.278 mmol/g [297].

In order to remove different pesticides as a mixture from water, Narayanan et al. (2016) prepared the carboxymethyl cellulose–nanoorganoclay. The composite removed all of the pesticides tested, with thiophanate methyl having the highest adsorption rate (99.7%) and atrazine having the lowest (45.5%) [298]. In a different study, atrazine, imidacloprid, and thiamethoxam were adsorbed using a composite material made of carboxymethyl cellulose and an organomodified clay (nanomontmorillonite modified with dimethyl dialkyl amine) [299]. The best removal was achieved in the case of imidacloprid, with thiamethoxam and atrazine following closely behind.

A summary of the natural polymers and biopolymer composites used as adsorbents for pesticide removal is presented in Table 3.

**Table 3.** Natural polymers and biopolymer composites as adsorbents for pesticide removal.

| Polymer            | Pesticide  | Adsorption Process Parameters                                                      | Adsorption Capacity (mg/g) | Reference |
|--------------------|------------|------------------------------------------------------------------------------------|----------------------------|-----------|
| Chitin<br>Chitosan | 2,4-D      | pH 3.7, contact time = 60 min, 20 mL treated volume, 2.5 g/L dosage                | 2.5<br>6.2                 | [284]     |
| Chitin<br>Chitosan | Glyphosate | pH 3.76–5.04, contact time = 60 min, 10 mL treated volume, 1.6 g/L dosage          | 14.04<br>35.08             | [285]     |
| Chitin<br>Chitosan | Linuron    | pH 5.75, contact time = 120 min, 25 mg of chitin and chitosan in 20 mL of solution | 5.91<br>21.73              | [286]     |
| Chitin<br>Chitosan | 2,4-D      | pH 3.7, contact time = 60 min, 20 mL treated volume, 2.5 g/L dosage                | 2.5<br>6.2                 | [284]     |
| Chitin<br>Chitosan | Glyphosate | pH 3.76–5.04, contact time = 60 min, 10 mL treated volume, 1.6 g/L dosage          | 14.04<br>35.08             | [285]     |

Table 3. Cont.

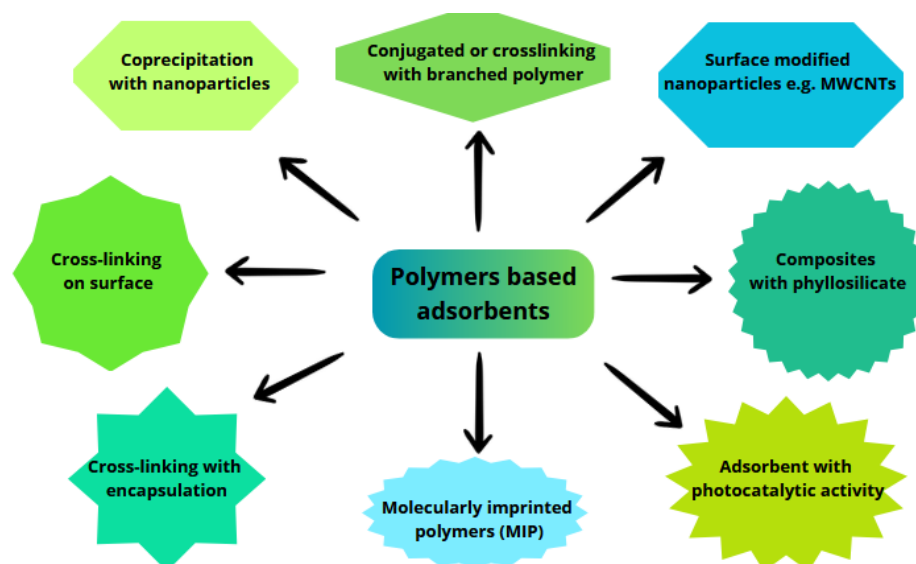
| Polymer                                     | Pesticide                                                                                                                                | Adsorption Process Parameters                                                            | Adsorption Capacity (mg/g)                                                    | Reference |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------|
| Chitin<br>Chitosan                          | Linuron                                                                                                                                  | pH 5.75, contact time = 120 min,<br>25 mg of chitin and chitosan in 20 mL<br>of solution | 5.91<br>21.73                                                                 | [286]     |
| Chitosan                                    | Ethoprophos                                                                                                                              | contact time = 24 h, pH 5.48, 100 mL<br>treated volume, 1.0 g/L dosage, 25 °C            | 121.75                                                                        | [287]     |
| Nanocellulose                               | Chlorpyrifos                                                                                                                             | contact time = 300 min, 25 mL<br>treated volume, 2.0 g/L dosage, 25 °C                   | 7.24                                                                          | [288]     |
| $\beta$ -cyclodextrin polymer               | 2,4,6-TCP                                                                                                                                | solid/liquid, ratio = 1 mg/mL,<br>contact time = 20 min, 25 °C                           | 108                                                                           | [290]     |
| Chitosan/Zelite-A<br>nanocomposite          | Acephate<br>Omothosate<br>Methyl parathion                                                                                               | contact time = 480 min, pH 8,<br>250 mL treated volume, 0.2 g/L<br>dosage, 20 °C         | 650.7<br>506.5<br>560.8                                                       | [291]     |
| Chitosan/gelatin<br>composite               | Atrazine<br>Fenitrothion                                                                                                                 | contact time = 120 min,<br>0.1 g/L dosage, 50 mL<br>treated volume                       | 75.19<br>36.23                                                                | [293]     |
| Cellulose/Graphene<br>Composite             | Ametryn                                                                                                                                  | pH 9, 10 mL treated volume, 3.0 g/L<br>dosage, 25 °C                                     | 8.53                                                                          | [294]     |
| chitosan-MMT-CuO<br>composite               | Dichlorvos                                                                                                                               | pH 10, 1.5 g/L dosage, 30 °C                                                             | 500.0                                                                         | [295]     |
| polylactic acid -MMT-CuO<br>composite       | Monocrotophos                                                                                                                            | pH 6, 15.0 g/L dosage, 30 °C                                                             | 200.0                                                                         | [296]     |
| Alginate beads with<br>silver nanoparticles | Atrazine                                                                                                                                 | contact time= 14 h, pH 6, 100 mL<br>treated volume, 20.0 g/L dosage,<br>room temperature | 1.57                                                                          | [297]     |
| Montmorillonite-alginate<br>beads           | Paraquat                                                                                                                                 | four beads, contact time = 6 h,<br>pH 5.5, 10 mL treated volume, 25 °C                   | 51.78                                                                         | [299]     |
| carboxymethyl<br>cellulose-nanoorganoclay   | Atrazine<br>Butachlor<br>Carbendazim<br>Carbofuran<br>Imidacloprid<br>Isoproturon<br>Pendimethalin<br>Thiophanate methyl<br>Thiamethoxam | contact time = 4 h,<br>10 mL treated volume,<br>10 g/L dosage                            | 0.333<br>0.204<br>0.667<br>0.625<br>0.385<br>0.227<br>0.313<br>0.263<br>0.345 | [299]     |
| carboxymethyl<br>cellulose-nanoorganoclay   | Imidacloprid<br>Thiamethoxam<br>Atrazine                                                                                                 | contact time = 4 h,<br>10 mL treated volume,<br>10 g/L dosage                            | 2.00<br>1.67<br>1.43                                                          | [300]     |

Overall, the investigation and use of natural polymers as adsorbents offer a hopeful approach for effectively eliminating pesticides from agricultural runoff. Chitin, chitosan, nanocellulose,  $\beta$ -cyclodextrin, and various biopolymer composites have demonstrated prominent potential in adsorbing different types of pesticides under diverse environmental conditions. These natural polymers offer several advantages, including cost-effectiveness, a high adsorption capacity, and reusability, making them suitable for large-scale remediation efforts. The efficacy of these materials relies on their capacity to be regenerated and sustain their performance during numerous usage cycles, hence promoting sustainable and eco-friendly techniques in the management of agricultural pollution runoff.

#### 6.2. (Semi)synthetic Polymers as Adsorbents for Removal of Pesticides from Agricultural Runoff

Synthetic and semisynthetic polymers are a group of compounds obtained through various chemical reactions, resulting in a wide range of properties. In the case of removing pollutants like pesticides, these polymers can be applied in the form of adsorbents, such as cross-linked networks, pendant/grafted binding groups, or components of composites. These polymers tend to be more expensive and laborious in preparation; thus, biopolymers

should be more favored due to their easy access from natural resources and cheap extraction protocols. On the other hand, (semi)synthetic polymers are characterized by well-defined structures, which allow the preparation of precise materials for the removal of pesticides from agricultural runoff/wastewater. These properties enable targeting specific pollutants and also increase the adsorption capacity and rate of adsorption. Therefore, (semi)synthetic polymers seem to be an excellent alternative to adsorbents based on biopolymers with limited capabilities. Figure 6 presents information about the strategies in the designing of polymer-based adsorbents.



**Figure 6.** Scheme of strategies towards the designing of polymer-based adsorbents for the removal of pesticides.

Natural fabrics seem to be a suitable choice as polymeric adsorbents, but they lack a high sorption capacity. The modification of these materials can result in improved removal efficiency and selectivity. For instance, the conjugation of polyethyleneimine (PEI) to cotton or wool increases the binding sites for pesticides. PEI-modified fabrics have been applied for the adsorption of pirimiphos-methyl and monocrotophos. Pirimiphos-methyl is characterized by its bioactivity towards a wide range of pests and can protect crops such as vegetables, maize, sorghum, and fruits. Monocrotophos, on the other hand, is bioactive towards insects and acts as an acaricide [301]. Both compounds contain phosphorus and varying amounts of nitrogen, which are linked with the sorption capacity and nitrogen content in PEI-fabrics (%). More nitrogen in the adsorbent results in a higher sorption capacity, with the most effective removal observed for pirimiphos-methyl, which contains more nitrogen than monocrotophos. The studies indicated a remarkably high sorption capacity of 500–625 mg/g for wool fabrics (with an addition of 10% PEI). These materials are highly efficient, with reusable cycles, supporting the Langmuir isotherm model and pseudo-second order kinetics. The addition of PEI increased the sorption capacity by around three times and accelerated the adsorption process. The molecular mechanism is based on hydrogen bonding between amino and hydroxyl groups of PEI-fabrics and polar groups of adsorbates like phosphate or amino groups [302].

The meso-sorbent silica/polyaniline (MSNPs/PANI) composite can also be considered an effective adsorbent for the removal of pesticides from aqueous environments. El-Said et al. (2018) applied this composite for the removal of chloridazon from synthetic solutions [303]. Chloridazon is considered a selective herbicide that easily degrades and migrates into groundwater, resulting in water contamination and severe illnesses such as apathy, dyspnea, or paralysis [304]. MSNPs were used as filler/core particles, and PANI molecules were used as the coating surface. The anilinium ions, characterized with positive

charges, were deposited onto the negatively charged silica particles through electrostatic interactions to form the composite. The sorption capacity of the composite was 30.15 mg/g, which is lower than 75.60 mg/g for activated carbon. Despite its lower sorption capacity compared to activated carbon, the sorbent performed efficiently for up to seven cycles of sorption–desorption. The mechanism of adsorption was based on electrostatic interactions between the adsorbent and adsorbate, as well as the aggregation of adsorbate molecules on composite surfaces.

Another type of composite can be based on iron nanoparticles  $\text{Fe}_3\text{O}_4$  which are coated with a  $\beta$ -cyclodextrin ( $\beta$ -CD) polymer cross-linked via diphenylcarbonate. In this case, there are improved sorption properties of nanoparticles due to their strong affinity to organic molecules through inclusion complexation inside CD's cavity. This sorbent was applied towards the removal of aromatic chlorinated pesticides such as 4-chlorophenoxyacetic acid and 2,3,4,6-tetrachlorophenol. Exposure to these compounds can result in lung irritation, shortness of breath, or pulmonary edema [305]. The studies indicated the favoritism of inclusion complex formation with smaller size adsorbate molecules based on a higher sorption capacity for 4-chlorophenoxyacetic acid than 2,3,4,6-tetrachlorophenol [306].

In order to increase the affinity of nanoparticles or polymers towards organic compounds, the molecular imprinting allows the synthesis of material with a well-designed structure. So et al. (2018) have prepared surface molecularly imprinted polymers (MIP) on silica gel particles. The surface-synthesized copolymer was based on cross-linked ethylene glycol and methacrylic acid [307]. The silica gel particles were the matrix for surface polymerization and the template molecules were carbaryl (CBL). CBL easily bioaccumulates into fruits which results in toxic and harmful foods for humanity [308]. Such a designed molecular adsorbent is characterized by a good recognition ability and selectivity towards carbaryl molecules. The selective removal was observed through the comparison of the adsorption capacity towards other pesticides such as carbofuran (CBF) and metolcarb (MTMC). The adsorption capacity for CBL was 41.15 mg/g. This value was 5 and 10 times higher than for CBL and MTMC, respectively. This type of material is characterized by good sorption properties based on molecularly designed pores targeted towards exact molecules. This strategy mimics key-hole behaviors which is observed in protein–drug interactions studies.

The other type of polymeric adsorbent can be obtained through the covalent linking of polymers with non-soluble compounds like multi-walled carbon nanotubes (MWCNTs). The esterification of MWCNTs with poly(vinyl alcohol) (PVA) resulted in novel functionalized MWCNTs and the further cross-linking of PVA on its surfaces via citric acid. The novel MWCNT/PVA was applied towards the removal of organophosphorus pesticides (OPPs) like diazinon, chlorpyrifos, pirimiphos-methyl, and malathion, which are described as quickly degrading insecticides into the environment. All OPPs were efficiently removed while maintaining stable work during four cycles of sorption–desorption. Presumably, the molecular mechanism of OPPs' adsorption was based on hydrogen bonding between hydroxyl groups of PVA and (thio)phosphates of OPPs [309].

The MWCNTs can be combined with other polymers to form nanocomposites, especially with adsorptive and photocatalytic properties, to remove pesticides. Shahnazi et al. (2020) designed molecularly imprinted poly-N-isopropylacrylamide (poly-NIPAM-coated MWCNTs/ $\text{TiO}_2$ ) for the removal of pendimethalin [310]. Pendimethalin (PM) is a herbicide responsible for a wide range of mutagenic or endocrine-disrupting effects, disturbing the physiological homeostasis of the liver and kidney [311]. Firstly, the MWCNTs were combined with  $\text{TiO}_2$  to form nanocomposites, which were then modified with surfaced free radical polymerization of NIPAM and acrylamide as monomers and N,N'-methylenebisacrylamide (MBA) as a cross-linker. During polymerization, PM was added as a template for the molecular imprinting process to increase the material's affinity for this pesticide. The main factors responsible for the adsorption–photocatalysis were molecular imprinting/well-designed adsorptive sites for PM and  $\text{O}_2$ - radicals as the main scavengers, which degrade PM.

Sharma et al. (2020) synthesized a nanohydrogel based on chitin-cl-poly(acrylamide-co-itaconic acid) as an efficient adsorbent of atrazine [312]. Atrazine is a herbicide known in agriculture for its extremely dangerous mechanism of seizing the electron transport chain, which causes plant death based on oxidative stress [313]. Chitin was chosen based on its hydrophilicity connected to the presence of carboxyl and amine groups which increased its swelling capacity, especially for the monomers' sorption. The adsorption capacity of atrazine was estimated to be 204.08 mg/g based on the Langmuir model. The material was synthesized through microwave irradiation to supply energy for the cross-linking of acrylamide and itaconic acid. The mechanism of sorption is considered complex due to many binding sites in the nanohydrogel, electrostatic interactions, and hydrogen bonding from nitrogen, oxygen, and hydrogen atoms in atrazine. The most effective removal was observed for up to five cycles of adsorption, with the 6th cycle reduced to 50.8% [312].

Another type of composite can be formed with activated carbon (AC) and cross-linked  $\beta$ -CD using hexamethylene diisocyanate through carbamate species. The CD was applied as an encapsulating medium for AC, while AC was utilized as an efficient adsorbing particle. The AC/ $\beta$ -CD composite was used for the removal of cymoxanil (CYM) and imidacloprid (IMD). Both pesticides are characterized by fungicidal activity as cyanoacetamide oxime for CYM, and insecticidal activity as a neonicotinoid for IMD, respectively [314,315]. The sorption capacity was estimated to be around 50 mg/g for both compounds. NaCl or urea did not interfere with the sorption processes. The sorbent-sorbate interactions are based on the inclusion complexation inside the CD cavity, hydrogen bonding, and hydrophobic interactions with AC [316].

All comparative information about the equilibrium uptake capacity, initial concentrations, and other parameters for the adsorbent based on (semi)synthetic polymers can be found in Table 4.

**Table 4.** Comparison of equilibrium uptake capacity and other parameters of different adsorbents for pesticides.

| Adsorbent                                                                             | Pesticide                                                       | Initial Concentration [mg/L] | Other Parameters                         | Adsorption Capacity [mg/g] | Reference |
|---------------------------------------------------------------------------------------|-----------------------------------------------------------------|------------------------------|------------------------------------------|----------------------------|-----------|
| PEI-cotton                                                                            | Pirimiphos-methyl Monocrotophos                                 | 100                          | 10% of PEI in fabrics, 5 h, 5 cycles     | 454.6<br>333.3             | [302]     |
| PEI-wool                                                                              | Pirimiphos-methyl Monocrotophos                                 | 100                          | 10% of PEI in fabrics, 5 h, 5 cycles     | 625.0<br>500.0             |           |
| MSNPs/PANI composite                                                                  | Chloridazon                                                     | 2–100                        | Natural pH, 1 h, 7 cycles                | 30.1                       | [303]     |
| Iron nanoparticles coated with $\beta$ -CD polymer cross-linked via diphenylcarbonate | 4chlorophenoxyacetic acid<br>2,3,4,6-tetrachlorophenol          | 150                          | pH = 9, 1 h, 8 cycles                    | 125.2<br>17.8              | [306]     |
| MIP on silica gel particles with templated CBL                                        | Carbaryl                                                        | 30                           | pH = 7, 40 min, 8 cycles                 | 41.5                       |           |
| Cross-linked PVA with citric acid on MWCNTs' surface                                  | OPPs (diazinon, chlorpyrifos, pirimiphos-methyl, and malathion) | 0.1                          | 4 cycles, Flow rate at 5 mL/min          | -                          | [309]     |
| Poly-NIPAM coated MWCNTs/TiO <sub>2</sub>                                             | Pendimethalin                                                   | 10–40                        | Adsorptive photocatalysis, 1 h, 5 cycles | 35.1                       | [310]     |
| Chitin-cl-poly(acrylamide-co-itaconic acid)                                           | Atrazine                                                        | 5–30                         | 3 h, 5 cycles                            | 204.08                     | [312]     |
| AC/ $\beta$ -CD composite                                                             | Imidacloprid                                                    | 200–500                      | 3 cycles                                 | 50                         | [316]     |

### 6.3. Polymer Membranes in Agriculture

There are several methods for purifying agricultural pollutants, ranging from chemical methods such as electrocoagulation, electro-oxidation, and photocatalysis to physical methods such as adsorption, coagulation–flocculation, and membrane technologies [300]. Polymer membranes, due to their structure and pores of various sizes, prevent the entry of a wide range of contaminants, including compounds with a medium and high molecular weight, suspended particles, bacteria, and viruses [317]. The use of polymer membranes for the removal of agricultural contaminants has shown certain advantages over other traditional processes due to reduced operating costs, low space requirements, minimal energy consumption, and no chemical additive requirements, making them a promising technology for the treatment of organic contaminants [318].

Given the wide variety of methods for synthesizing membranes, polymers, and nano-materials available on the market, the possibilities of obtaining membranes that adapt to the various variables and properties associated with a specific pollution, e.g., pesticides, are relatively wide. The hydrophilic properties of polymer membranes and their pore size depending on the polymers used and their overall effectiveness in removing organic compounds can be improved by the appropriate selection of the polymer and/or its functionalization [319]. A review of the literature showed that there is a greater number of studies on the use of polymer membranes for biodegradable and non-biodegradable harmful wastes/pollutants' removal compared to other types of membranes, and this research shows an increasing trend.

Currently, over 50 polymers are used to produce membranes, among which the most commonly used polymers for removing agricultural pollutants are polyacrylonitrile (PAN), polyethersulfone (PES) [320–322], polysulfone (PSf), polyvinyl alcohol (PVA), polyvinyl acetate (PVAc), polyvinylidene fluoride (PVDF) [323], and polystyrene (PS) [324,325] (Table 5).

Although polymer membranes have been the subject of research and development for several decades, they still have some drawbacks that limit their widespread use [317,326]. Most synthetic polymers used to produce membranes are non-biodegradable and have hydrophobic properties. Unfortunately, the hydrophobicity of these membranes makes them susceptible to membrane fouling [323,327]. When micropollutants settle on the membrane surface, water permeability deteriorates. Consequently, this increases the need for the frequent cleaning of the membrane, thus increasing the maintenance costs of the membrane system. What is important is that the non-renewable and non-biodegradable polymers can be harmful to the environment over time. This is because after their half-life, they are usually disposed of in landfills and sometimes end up in the aquatic environment. In some cases, these materials burn, leading to secondary pollution [318,328,329].

One synthetic polymer is, among others, polyacrylonitrile, which is considered one of the preferred synthetic polymers for the production of polymer membranes due to their cost-effectiveness, exceptional solvent stability, and high mechanical resistance. Other polymers synthesized include polyurethane with cellulose acetate in blended membranes, which are typically used for chromium (VI) elimination. Cellulose acetate is a common filtration membrane due to its hydrophilic nature, good resistance to contamination, and cost-effectiveness [330]. Polyethersulfone is a widely used commercial material for the production of polymer membranes due to its several unique properties, such as excellent chemical and thermal stability, excellent mechanical strength, and the ability to be used over a wide pH range of 2–12. Despite all the wide applications of polyethersulfone, it has some drawbacks, such as fouling caused by the adsorption of nonpolar solutes and hydrophobic molecules or bacteria, which leads to a shorter membrane life. Other problems are biocompatibility related to aggregation and its neutral state in water [331].

Therefore, the solution to these problems may be technologies based on the use of biopolymers. Biopolymers, or natural polymers, are among the main materials used in the adsorption of agricultural pollutants, dyes, heavy metal ions, and other pollutants, even in low concentrations. Renewable and biodegradable materials are used to produce them, which is due to the presence of nitrogen and oxygen in their chemical structure [332].

The use of chitosan-based membranes is a common practice as it is the most preferred adsorption method due to its excellent kinetics, improved reusability, and practicability of scale-up [330]. It has an excellent performance in removing heavy metals and pesticides from wastewater due to the amine functional group that forms surface complexes with several metal ions. One of the disadvantages of flat chitosan membranes is poor mechanical resistance. This can be carried out using chitosan in the form of thin-film composites to take advantage of a good substrate, or it can be embedded in compatible nanomaterials [333]. As a result, other polymers can be blended with chitosan to overcome these problems, and increase chemical stability and mechanical resistance [334].

In recent decades, significant efforts in the development of polymer nanocomposites have resulted in nanoscale filling materials. However, the composite is not necessarily at the nanoscale, as it can be micro- or macroscopic. Such advances have resulted in a unique combination of nanomaterial properties that include the size, mechanical characteristics, low concentrations required to induce a change in the polymer matrix, and ease of production because they can be manufactured as a conventional polymer composite. Moreover, nanocomposite technology shows significant improvement in biodegradability and significant improvement in mechanical, thermal, and electrical properties. However, the implementation of nanotechnology in the production of mixed-matrix membranes is associated with certain challenges, including the high possibility of the agglomeration of fine particles and difficulties in determining the composition, strength, and functionality of the interfacial region. Polymer-based nanocomposite membranes appear to be heterogeneous substances. Their characteristics are influenced by factors that determine the attributes of traditional composites, namely structure, component properties, interfacial interactions, and composition [328,335]. It has been reported that many polymers as well as composite membranes exhibit excellent separation properties in Palm Oil Mill Effluent [336]. Anwar et al. (2019) synthesized silver nanoparticles, which were used for the coating of hydroxyapatite ( $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$ ) nanotubes [336]. This coated nanofiller was incorporated into the polyphenylsulfone and nanocomposite membranes were prepared by the phase inversion technique. Nanofillers were key factors in changing the membrane properties, increasing the separation efficiency of the membrane. The composite membranes were effective in removing all organic matter present in the Palm Oil Mill Effluent, and the separation efficiency of the membrane was so high that it showed potential for industrial applications. This technology represents a promising development in the field of adsorption membranes, but still requires further research to be beneficial in water purification applications due to the above limitations.

The use of nanoadsorbents is a promising technology for the removal of low-molecular-weight solutes, which is due to their large surface area, large number of adsorption sites, and fast kinetics. However, nanoadsorbents are produced as fine powders, which causes separation and regeneration problems, in addition to their high cost and some potential toxicity problems resulting from leaching into water bodies [299]. Combining the advantages of nanoadsorbents and ultrafiltration membranes and overcoming their disadvantages in water purification remains a challenge.

New trends on adsorptive membranes' preparation techniques were developed to overcome the disadvantages of the mixed matrix adsorptive membrane. Porous membranes are typically used in micro- and ultrafiltration applications, where the main feature is the pressure acting on the membrane and only the smallest particles pass through it. In the case of ultrafiltration, the membrane is capable of retaining particles larger than  $0.001\ \mu\text{m}$  [337]. As with dense nanomembranes, the pore size and arrangement are important features needed to ensure the mechanical strength.

Sundarrajan et al. (2013) indicated that conventional ultrafiltration membranes can be integrated into the thin film composites (TFC)-type configurations that consist of three layers: a microfibrinous nonwoven support providing mechanical strength and an ultrafiltration membrane providing resistance to permeate flow, covered with a thin layer as a barrier layer to exclude solutes and monitor the flow rate [338]. Another application of microporous

membranes is membrane distillation microfiltration processes. The microfiltration process requires hydrophobic membranes that have narrow pore size distribution, good mechanical strength, and high liquid entry pressure values [339]. The phase inversion technique is one of the easiest techniques used as a manufacturing method and has the advantage of achieving a large variety of pore sizes depending on the type and concentration of the polymer, as well as the precipitation method and temperature. Electrospun membranes are suitable candidates for microfiltration processes due to their effectiveness in controlling material and structural properties [339,340].

Nonporous membranes consist of a polyurethane layer between microporous polyethylene layers because porous layers usually provide structural support to thin nonporous membranes [341]. The most important applications of these membranes include the removal of organic compounds from the environment. Typically, dense-phase materials (e.g., silicone rubber) are used to design semi-permeable hydrophobic membranes. A very important aspect of the use of polymer membranes, especially in the case of nanofiltration, is the precise control of their morphology, as well as chemical, thermal, and mechanical integrity, in order to completely remove target contaminants without affecting the permeate stream [342,343]. The thin film composite membranes widely used in nanofiltration applications are designed on an asymmetric porous substrate obtained by the phase inversion method [344]. Recently, conventional support systems in TFC membranes have been replaced by electrospun scaffolds, which exhibit excellent interactions between the barrier and support layers, improving the separation efficiency [340,345,346]. Electrospun structures offer thin films with good mechanical properties and can also be a reliable option for forward osmosis, and when combined with electrospun scaffolds, can lead to high flux due to the interconnected pore structure [347,348].

Overall, the use of polymer membranes for purifying agricultural contaminants provides several benefits, including financial efficiency, low energy usage, and positive environmental impacts. The integration of nanomaterials and biopolymers into mixed matrix membranes might improve the membrane performance and stability. Biopolymers offer sustainable and environmentally friendly options as substitutes for traditional synthetic polymers, while nanocomposites enhance the mechanical and thermal characteristics of membranes. Although there are some constraints, such as membrane fouling and toxicity problems, progress in membrane technology and the development of new materials offer great possibilities for efficiently tackling the increasing concerns around agricultural pollution.

**Table 5.** Several applications of polymer membranes.

| Polymer Materials       | Membrane Types                                   | Application                                                                                                                                                                                                                                 | References    |
|-------------------------|--------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|
| carrageenan             | membrane                                         | adsorption and desorption of heavy metals                                                                                                                                                                                                   | [323]         |
| cellulose/polydopamine  | TFC membrane, membrane                           | MgSO <sub>2</sub> , adsorption and desorption of heavy metals (Zn(II), Co(II), Cd(II), and Ni(II)), dyes (methyl blue, methyl orange, Congo red) and oils (hexane, cyclohexane, petroleum), 4-nitrophenyl phosphate, pesticide (avermectin) | [343,345,348] |
| chitosan                | nanofibrous membrane, nanofiltration membrane    | removal of heavy metals, dyes, pesticides, less cytotoxicity, mutagenicity, and soil sorption                                                                                                                                               | [333]         |
| chitin                  | nanofibrous membrane, adsorption membranes       | removal of organic hydrophobic organic contaminant                                                                                                                                                                                          | [333]         |
| polyacrylonitrile       | polymer membranes                                | agricultural pollutants, Cr(VI)                                                                                                                                                                                                             | [348]         |
| polyethersulfone        | polymer membranes                                | adsorption of nonpolar solutes and hydrophobic molecules or bacteria                                                                                                                                                                        | [331]         |
| polysulfone             | nanocomposite membranes, nanofiltration membrane | fermentation waste, dyes                                                                                                                                                                                                                    | [349,350]     |
| polyvinyl alcohol       | nanofiltration membrane                          | removal of dyes                                                                                                                                                                                                                             | [324,325]     |
| polyvinyl acetate       | polymer membranes                                | removal of heavy metals, dyes, pesticides                                                                                                                                                                                                   | [324,325]     |
| polyvinylidene fluoride | polymer membranes                                | water treatment                                                                                                                                                                                                                             | [347]         |
| polystyrene             | polymer membranes                                | pesticides, validamycin                                                                                                                                                                                                                     | [324,325]     |

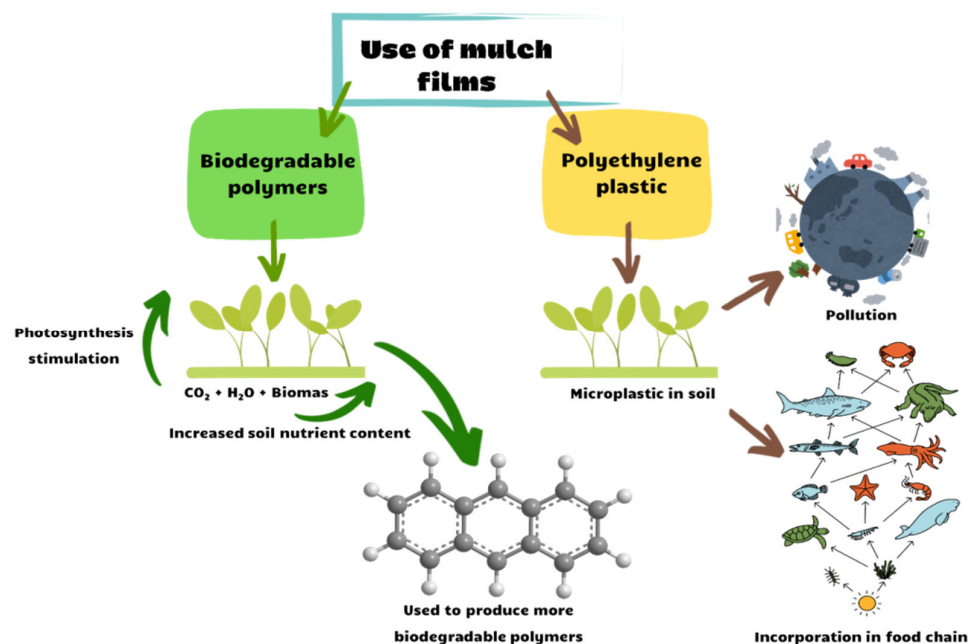
## 7. Mulching Films

The utilization of mulching film to enhance the growth and yield of both annual and perennial crops has been acknowledged for an extended period [42]. Mulching film serves to retain heat and moisture, alleviate weed and pathogen pressure, and conserve water and fertilizer. Consequently, the use of mulching film plays a role in promoting sustainable agricultural production [108]. In addition, the presence of heavy metals in soil can adversely affect plant growth. Mulches provide a remediation strategy helping to remove heavy metals from the soil. Organic and plant-based mulch materials form complexes with heavy metals, converting them into a non-toxic form for plants. Additionally, mulches can serve as controlled-release composite films embedded with fertilizers, herbicides, or pesticides [106]. This approach enables the gradual and slow release of these substances from the mulch films, ensuring their constant availability for plant uptake rather than being washed away after the initial application [105].

There are two types of mulch: organic, composed of organic materials and which are biodegradable, and inorganic, primarily consisting of plastic-based materials. Both types have gained popularity in recent years [351]. However, it is worth noting that remnants of mulch persist in soil and watersheds, forming microplastics capable of absorbing harmful pesticides, insecticides, and herbicides, thus transporting them into the food chain (Figure 7). Plastic residues that are persistent accumulate in soils as a result of incomplete collection after usage. Moreover, mulch sheets may let chemical compounds seep out. In this regard, the buildup of plastic residues and released additives from many mulch treatments may have a negative impact on the health and productivity of the soil. Therefore, thin (<20–25 µm) conventional mulch films are being replaced by certified soil-biodegradable mulch films. In addition, the extensive use of this type of plastic in agriculture has been found to alter the physical, chemical, and biological properties of the soil. With conventional plastics persisting in the environment, plastic remnants gradually accumulate in soil, breaking down into micro- and nanoplastics (MNPs) and releasing additives, which can detrimentally affect soil health. Consequently, this can adversely affect plant growth and crop yields. The impact of plastics on soil properties and fertility largely depends on the characteristics of the material, including the size, shape, and chemical composition. Residues from conventional mulch films in soil can impede water infiltration, reduce the water retention capacity, disturb microbial communities and macrofauna, and diminish soil fertility [37]. In general, the selection of a suitable mulching material is influenced by various factors such as the type of materials available, ecological conditions, the color, thickness, perforations, material availability, cost-effectiveness, and compatibility with the specific crop being cultivated. Determining the superior option for agriculture remains a topic of debate, and ongoing research seeks to provide clarity on this matter [352].

Non-biodegradable polymers play a significant role in agriculture, particularly in the context of plant mulching. Despite the increasing popularity of biodegradable polymers, conventional polymers are currently widely used.

One of the primary benefits is weed control. Non-biodegradable polymer films effectively block sunlight, reducing weed growth. This decreases the competition for water and nutrients, positively affecting the growth and development of cultivated plants. Another significant advantage is moisture retention. Using plastic mulch helps maintain soil moisture, reducing the need for frequent irrigation and decreasing water loss through evaporation. Additionally, the temperature regulation of the soil is highly beneficial. Mulching can influence the soil temperature, raising it during cooler periods and preventing excessive heating during hot days, which is advantageous for plant growth. It is also worth noting that plastic films prevent a direct rainfall impact on the soil, reducing the risk of erosion. Mulching films are also highly effective as a barrier against pests. Under certain conditions, non-biodegradable polymer mulch can serve as a physical barrier to soil pests, protecting crops from damage [353–357].



**Figure 7.** Materials available for use as mulch films.

However, the use of non-biodegradable polymers comes with several environmental risks. One of the most widely publicized issues is environmental pollution. Non-biodegradable polymers do not naturally decompose, meaning they must be removed from the field and disposed of after the growing season, often leading to environmental contamination. Similarly, disposal costs are a common problem. Removing and recycling used plastic mulch generates additional costs for farmers and can be logistically challenging. Mulching films can also pose a threat to wildlife. Animals can nest in the mulch or become entangled in plastic remnants, posing a direct threat to wild species. A widely discussed risk associated with polymer use is the accumulation of microplastics in the soil. The long-term use of non-biodegradable polymer materials can lead to the accumulation of microplastics in the soil, which can adversely affect the soil structure and the health of soil microorganisms. Furthermore, plastic mulching films do not always provide ideal conditions for plants. Under certain conditions, such as very high temperatures, films can excessively heat the soil or lead to its drying, negatively impacting plant growth [357,358].

Currently, three main types of non-biodegradable polymers are commonly used for mulching films. Polyethylene (PE) is the most commonly used material for agricultural mulching films. Polyethylene is characterized by good mechanical strength, resistance to weather conditions, and the ability to retain soil moisture. It also effectively blocks sunlight, limiting weed growth under the mulch [354,358,359]. Polyvinyl chloride (PVC), although less commonly used due to higher costs and recycling difficulties, is sometimes used for specific mulching applications requiring greater mechanical strength or specific properties like transparency [359–361]. Polypropylene (PP), due to its UV resistance and chemical durability, can be used in agriculture, particularly where long-term mulching is needed, offering prolonged soil and plant protection [359,362,363].

Given the risks associated with the use of non-biodegradable polymers and their advantages, primarily low costs, ongoing research aims to develop new solutions. One such solution involves the use of plastics containing pro-oxidant additives (PAC). These act like low-density polyethylene but contain chemical pro-oxidants that facilitate breakdown through oxidation in the presence of light. During photo-oxidation, the polymer's molecular weight decreases and oxidized groups are introduced, making the material more susceptible to microbial degradation dependent on oxygen [363,364]. Such plastics are termed "oxo-degradable", exemplified by Oxo-PP (oxo-degradable polypropylene) [365]. Although PAC-based mulching films can be as effective in weed control as traditional plastic

films without negatively impacting soil health, they lack durability and structural integrity, leading to premature disintegration when used in fields. Their brittleness and lightness pose challenges, and low ultraviolet radiation can slow their degradation once in the soil. While they can degrade in the soil, they are not fully biodegradable, leaving fragments in the soil and water as microplastic sources that can adsorb pesticides, insecticides, and herbicides, and then enter food chains. Studies show that despite higher costs compared to polyethylene films, PAC films equally contribute to soil microplastic problems [42,366,367].

Vegetables and other specialized crops can produce sustainably using biodegradable mulch (BDM) films that are used as an alternative of traditional polyethylene (PE) mulches [368]. After harvest, these biodegradable films can be ploughed into the soil, where they will fully biodegrade into CO<sub>2</sub> and microbial biomass in a toxic environment [369].

Biodegradable mulch films have proven effective in weed control in agriculture, contributing to increased agricultural yields. By utilizing BDM, there is potential to reduce the reliance on fungicides, insecticides, and herbicides, contributing to more environmentally friendly pest and disease management [370]. These films are known to minimize the weed pressure, ultimately enhancing agricultural productivity. However, the widespread production of weed mulch films often leads to significant environmental contamination due to herbicide dispersion in the surrounding areas. Wang et al. devised an environmentally friendly coating strategy for biodegradable weed mulch films. Their approach involved adding a herbicide to a poly (vinyl alcohol) water-soluble solution containing dopamine. Using a low-temperature coating technique, they successfully created effective weed mulch films on a biodegradable poly (butylene adipate-co-terephthalate)/poly (lactic acid) film [371].

A variation of BDM is the “liquid mulch” technology, which employs an innovative approach of spraying biopolymer-based protective coatings directly onto the soil instead of using pre-made films. This process forms a film layer on the soil surface, providing functions similar to traditional mulch while also stabilizing sandy soil surfaces and protecting topsoil. Liquid mulch technology offers the advantage of requiring simpler equipment and incurring lower labor costs compared to the application of plastic films [9]. Liquid mulch is the esterification product of tamarind xyloglucan (TXG) from forestry wastes which was synthesized with benzoic anhydride (BA). The addition of waterborne polyurethane and urea increases its mechanical strength and improves its nutritional properties. The xyloglucan-based liquid mulch has excellent UV protection, a high haze value (approximately 90%), and retains water at a rate of 80.5%. Tamarind xyloglucan-based liquid mulch exhibits powerful and diverse optical properties as well as sand fixation functions, indicating its great potential in sustainable agriculture as an alternative to plastic mulch [372]. Overall, biodegradable mulch films offer numerous advantages for weed control in agriculture, contributing to increased yields while addressing environmental concerns associated with herbicide use [373].

One of the biodegradable polymers used in the production of mulching films is PCL [374]. However, PCL mulches exhibit a poor impact and weak tear strength behavior, with reported challenges in film extrusion. Although biodegradable, poly caprolactone degrades at a slow rate, prompting its blending with starch or polylactic acid to enhance biodegradability [375]. Field applications of these blends have shown promising results, with better degradation observed compared to polyethylene mulches and positive effects on the root growth and density, crucial indicators of plant growth [376]. Trials have demonstrated that PCL-starch-based and thermoplastic starch (TPS) mulch films degrade effectively in various soil types and contribute to soil moisture conservation across diverse environmental conditions [377]. A polymer that is also significant in this respect is polybutylene succinate (PBS). Notably, PBS-based mulch films serve as controlled-release systems and have demonstrated effectiveness when incorporating various beneficial chemical compounds such as fertilizers or herbicides [42].

In the case of natural polymers, lipids are inherently hydrophobic, rendering them unsuitable to mulch film applications. Moreover, the fabrication and manipulation of films composed solely of lipids pose significant challenges, constraining their practical

utility. The predominant polymers within this category are carbohydrates, predominantly polysaccharides [111]. These may be synthesized by bacteria or occur naturally in plants and animals. Studies demonstrate the effectiveness of PLA-starch blends as biodegradable mulch films with superior mechanical strength and water retention. Furthermore, PLA-based mulch films can function as controlled-release systems, gradually dispensing embedded chemical compounds to boost plant growth without leaching PLA, which can be blended with other polymers like poly(butylene adipate-co-terephthalate)—PBAT—or polypropylene carbonate (PPC). Blends of PLA/PBAT exhibit improved durability, reduced brittleness, and lower manufacturing costs compared to pure PBAT or PLA films. Moreover, PBAT possesses the desirable qualities of stretchability, extensibility, impact resistance, and heat resistance for usage as a mulch film. Consequently, PBAT-based mulch films are now commercially produced in many countries, delivering beneficial effects in agriculture. Moreover, PBAT blends serve as controlled-release systems for fertilizers, fungicides, and herbicides embedded within the films. This slow release enhances the efficiency and promotes crop production [378]. At this point, it should also be noted that the type of polymer determines how the mulching film is spread. If the film is composed of multiple types of polymers, the biodegradation mechanism becomes more intricate. Compared to single-polymer mulches, these co-polymer blends or mulches may decay more slowly or more quickly at times. It has been noted that polylactide blends decompose better than mulches comprised of PLA alone, whereas poly(butylene adipate-co-terephthalate/polylactide) blends deteriorate more slowly than PBAT mulches [379].

Chitosan can also be formed into films, making it suitable for mulch film production. Although pure chitosan films may be brittle, the addition of plasticizers like glycerol enhances their flexibility. In mulching applications, chitosan has demonstrated superior weed control compared to certain herbicides and can serve as an effective controlled-release system for fungicides. Additionally, it contributes to soil nutrient levels and has been shown to enhance plant growth, flowering, and vegetable quality. However, its use can affect soil temperature dynamics, potentially hindering plant growth, and its production from chitin is costly. Consequently, despite its benefits, chitin and chitosan are not commonly preferred as mulch materials due to these drawbacks [380].

Starch is an abundant and inexpensive polymer, its poor water resistance and brittleness hinder its use as a mulching material. Over 33% of starch mulch films degrade within 55 days, and they tear easily during application. Blending or modifying starch with glycol, chitosan, or PLA can enhance the elastic strength, but these films are costly and sensitive to humidity. Despite improvements, their mechanical properties still fall short of those of plastic mulch films, limiting their agricultural applications. Despite this, however, there are reports of attempts to use starch in, among other things, the aforementioned mulching [42]. Biodegradable mulching, particularly starch/chitosan blends, has been explored as a potential substitute for short-cycle crops like vegetables and flowers, aiming for fertilizer-free and microbial-based plant growth. These blends exhibit improved film solubility and stability compared to pure starch films when in contact with soil. The addition of chitosan enhances the film stability, with no visible cracks observed for up to 45 days, indicating their effectiveness as biodegradable mulch. Moreover, incorporating renewable materials into starch blends offers sustainable solutions for agricultural mulch. In another study, composite films made from modified starch, PLA, and natural fibers were developed for mulching applications [132]. Bio-based polyolefins remain widely used in agricultural mulching, contributing to environmental sustainability by reducing the need for pesticides, herbicides, water, and energy. These mulching films typically last for one growing season or longer, depending on crop types and agricultural practices [381].

Also alginate mulches, created by spraying a sodium alginate solution onto soil where it cross-links with calcium ions, have shown benefits in promoting plant growth and enhancing soil microbial populations. Additionally, alginate acts as a biostimulant, improving root development, fruit quality, and plant resilience to salt stress. It is also non-toxic, biodegradable, and has excellent water retention properties. However, the dependency of alginate mulch synthesis

on soil calcium ions poses a challenge, as films cannot be produced without them. Moreover, the stiffness of sodium alginate and resulting cross-linked films can lead to tears, allowing weed growth. Blending with compounds like polyglycerol or hydroxyethylcellulose offers a solution, but increases production costs, limiting efficacy [42].

The use of mulch films in agriculture offers numerous advantages compared to non-mulched crop production, which can be classified into improvements in the soil microenvironment and economic benefits. The soil moisture content plays a crucial role in plant growth, and factors such as the wind, high temperature, adverse weather conditions, and weed infestation can lead to a moisture reduction in the soil. Mulches have been shown to enhance the soil percolation and water retention capacity, thereby reducing the need for irrigation [382]. Additionally, mulching materials contribute to salinity mitigation and aid in soil reclamation by reducing salt toxicity in plants [38]. Mulches also protect the soil from wind and water erosion, as well as soil compaction, which can negatively impact crop growth. By breaking the speed of water flow, mulches increase the soil's infiltration rate and prevent erosion on slopes or hilly areas. Furthermore, mulch materials mitigate the effects of weathering, heavy rain, and machinery, ultimately helping to alleviate soil compaction issues [383].

Despite significant research efforts into developing commercially viable biodegradable mulch films, the widespread adoption of these materials remains limited. The main barriers to their use include costliness, management difficulties, and the need for specialized equipment during application. As a result, despite the availability of alternatives to plastic mulches, they are not being widely embraced by farmers. Governments can play a crucial role in promoting their use by subsidizing biodegradable mulch films and raising awareness about their benefits compared to traditional plastic options. There is also a pressing need to develop polymers suitable for mulching across various climatic zones, encompassing diverse temperature ranges and soil types to cater to different crop productions. Finding a material that meets the criteria of good physical characteristics, durability, and biodegradability poses a significant challenge. While there are established testing methods for determining mechanical strength, biodegradation analysis still presents questions, particularly due to limitations in current testing methodologies [42]. Most biodegradability tests are conducted under controlled laboratory conditions, which may not accurately reflect real-world soil environments. Additionally, even if a polymer degrades in soil, the long-term consequences of any residual matter left behind after degradation remain unclear. Therefore, there is a critical need to develop testing methods that can simulate field conditions more accurately and assess potential residual effects [384].

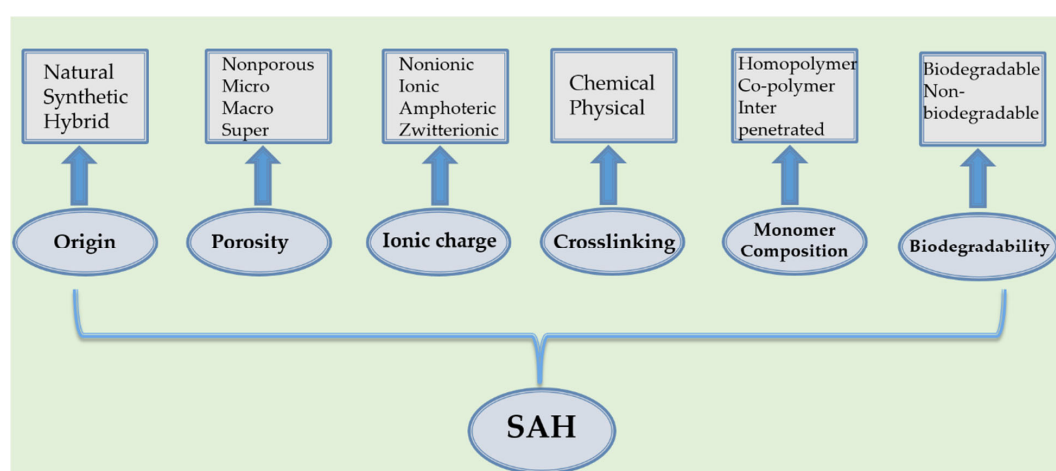
## 8. Superabsorbent Polymers—Hydrogels

Drought is one of the most devastating natural calamities for a country's economic, social, and environmental well-being. Long-term droughts have an impact on the soil ecology, perhaps leading to desertification and soil degradation. This causes significant water distress, which is exacerbated by inadequate water management, irrigation practices, soil degradation, and soil with a limited water retention capacity. Effective land management is the most viable strategy during a drought. When a place with a lot of rainfall experiences drought, the plants/crops become more vulnerable to water stress than those that thrive in dry or semi-arid environments. This is especially concerning in recent decades, when exceptional and harsh weather events have hampered the crop yield in tropical and subtropical climate zones. As a result, the drought scenario may be defined as a circumstance in which plants are unable to draw water from the soil and so are under water stress. Water stress is caused by a combination of the soil's limited water holding capacity, fertilizer migration into the deeper layer, and excess surface runoff. Long-term droughts can lead to desertification, land degradation, and disruptions to the soil ecology. Drought stress has a high impact on the agricultural environment, threatening global food security [385]. It has been demonstrated that using superabsorbent hydrogel (SAH) as a soil supplement can increase the soil structure, water-holding capacity, and plant available

water content due to its hydrophilic three-dimensional network. Superabsorbent hydrogels (SAH), also known as water-absorbing polymers (WAP), are 3D polymer networks that can absorb and retain large amounts of water and solute molecules due to hydrophilic groups attached to the polymeric backbone [386]. Hydrophilic polymers improve soil water retention and alleviate water stress. Commercially available SAH on the horticulture market has a water-absorbing capacity (WAC) of 100–500 g/g [387]. Drought management studies consider soil qualities such as the water retention capacity, water usage efficiency, permeability, infiltration rates, erosion, and surface runoff. Previous research has shown that applying SAH to coarse-textured soil may significantly enhance water retention and minimize infiltration rates, preventing severe percolation loss [388].

### 8.1. Attempts to SAHs Classification

Classifying SAHs is challenging due to their large number and structural variety, which may be overwhelming. SAHs may be categorized based on their manufacturing techniques and physicochemical features, as shown in Figure 8. Based on their origin, SAHs are categorized into three categories: natural, synthetic, and hybrid [389].



**Figure 8.** General categorizing of SAHs utilizing multiple criteria.

Natural SAHs are derived from natural sources such protein, starch, glycogen, cellulose, and chitin, whereas synthetic SAHs are created by chemical polymerization using acrylic acid, acrylamide, and methacrylic acid. The hybrid SAH is made of natural and synthetic polymers bonded together. Hybrid SAH is more biodegradable and absorbs more water than synthetic SAH. Researchers have developed hybrid SAHs called superabsorbent hydrogel composites (SHCs) and superabsorbent hydrogel nanocomposites (SHNCs) over the past few decades. These materials have an excellent swelling capability, salt responsiveness, and mechanical properties due to the incorporation of nano- and micro-sized materials in the polymer framework [390].

For the synthetic SAHs, the literature reports multiple strategies for their production, depending on their use. Generally, there are four polymerization methods: bulk, solution, suspension, and graft polymerization, intensively used for synthetic SAH generation. Bulk polymerization is a simple approach that involves adding a soluble initiator to an undiluted liquid monomer to produce bulk SAHs. One significant drawback of this approach is the rapid increase in the viscosity of the reaction mass as polymerization continues. In the solution polymerization approach, both the monomer and the initiator are dissolved in a solvent (such as water, ethanol, or benzyl alcohol) to limit the solution's viscosity rise. Following the polymerization procedure, the resulting product must be rinsed with distilled water in order to eliminate the solvent and unaltered monomers. The technique's benefit is that the existence of the solvent limits viscosity growth and allows for continuous heat transmission during polymerization. Suspension polymerization involves dispersing

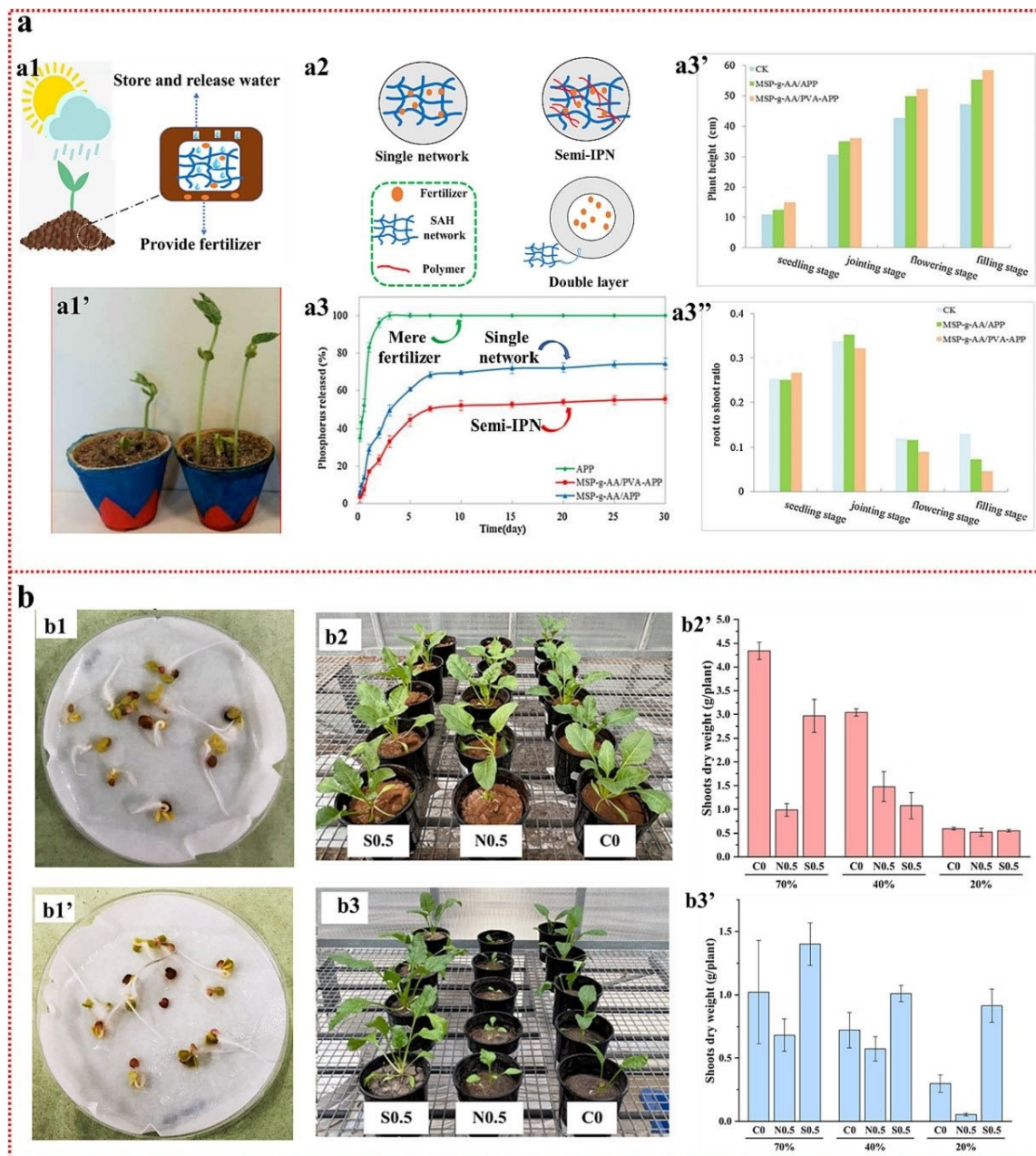
the monomer and initiator in an aqueous solution to form a homogenous mixture. To prevent monomer droplets from coalescing, this approach requires continual stirring. This method maintains the finished product's spherical form and makes product separation simpler than previous procedures. The final product's particle form and size depend on the monomer's viscosity, dispersant type, and agitation speed [391]. Graft polymerization is a promising technology that involves chemically linking one polymer to another's backbone or substrate. SAHs produced by these procedures often have a fragile structure and strong salt sensitivity. SAHs have several levels of porosity, including non-porous, micro-porous, macro-porous, and super-porous. The porosity of SAHs is determined by the reaction temperature and foaming agent used during the polymerization process. SAHs can be non-ionic, ionic, amphoteric, or zwitterionic depending on the existence of a charge in the polymer network's structure. Ionic SAHs are extensively utilized in agriculture, while non-ionic SAHs are employed for contact lens manufacture. Amphoteric SAHs have both acidic and basic groups in their polymer network, whereas zwitterionic SAHs have both cationic and anionic groups and are mainly employed in wound dressings. Xu et al. (2018) describe a simple and fast formation of biodegradable cross-linking as physical or chemical in nature [392]. The physically cross-linked networks are not permanent, but enough to render SAHs insoluble in water. These reversible cross-linked networks are created by hydrogen bonds or interactions between ionic molecules. Chemical cross-linked networks are permanently attached to the polymer network. SAH can be classified into three types based on their monomeric components: homo-polymeric (cross-linked network of one type of hydrophilic monomer unit), co-polymeric (two or more different monomers with at least one hydrophilic component cross-linked together), and interpenetrating (two independent cross-linked synthetic or natural polymer components). The SAHs might be either biodegradable or non-degradable from the standpoint of decomposition. In nature, the majority of synthetic SAHs are not biodegradable. As a result, the current research focuses on creating various biodegradable co-polymeric SAHs by the hydrophilic polymer chain's attachment of a biodegradable waste material (such as yeast, cellulose, starch, chitosan, or sodium humate) [393,394]. The use of biodegradable SAHs in agriculture can mitigate the risk that synthetic SAHs pose to the environment.

## 8.2. Shift to Natural SAHs

### Cellulose-Based SAHs for Agriculture

Across sectors, the development of superabsorbent hydrogels is undergoing a revolutionary age. Notwithstanding their benefits, synthetic superabsorbent hydrogels have caused environmental issues primarily because they are not biodegradable. These materials cause the long-term contamination of the land and water, which stimulates a move towards sustainable alternatives. Increasing focus is being paid to environmentally friendly alternatives, including hydrogels made of natural polymers or biodegradable materials, which have the same absorbency as their synthetic equivalents, but less of an adverse effect on the environment. Superabsorbents made of cellulose and sourced sustainably are becoming more and more popular. Biodegradable polymer hydrogels, naturally occurring cellulose [395–397], chitosan derivatives [398,399], and substitutes based on starch [400] are among the innovations. By improving the soil fertility and water retention, acting as strong hemostatic agents in medicine, assisting in pollution management, and producing environmentally acceptable building materials, these materials are revolutionizing agriculture. Moreover, hydrogels based on cellulose have potential use in depollution [401–403] or high-tech industries [404,405]. Sophisticated characterization methods help to maximize these qualities, and the adoption of circular economy principles emphasizes sustainability even more. The growing interest in environmentally friendly materials such as superabsorbent hydrogels derived from cellulose is changing a number of sectors, including agriculture. Their promise for a wide range of applications is highlighted by their biodegradability, high water-absorption capacity, and adaptability. Hydrogels based on cellulose have become essential components in agriculture for improving soil fertility and water retention. To

increase the characteristics of gels, superabsorbent materials based on cellulose and its functionalized derivatives were created. These materials were augmented with various additions, including reduced graphene oxide, activated carbon, bentonite, and graphite oxide, among many others. The term “soil conditioners” is a highly appealing product label for certain close-to-use uses of cellulose and nanocellulose SAHs. Certain drought-prone areas have little water availability in their soils, which makes them unsuitable for crop cultivation. In theory, SAH soil conditioners have the capacity to absorb significant amounts of water, store it, and release it in a controlled manner during dry seasons, Figure 9(a1). Furthermore, SAHs have the ability to function as a fertilizer or transporter of nutrients for a comparable regulated release. Thus, plants can flourish [406].



**Figure 9.** (a) Cellulose SAH: a schematic representation of the mechanism of SAH in agricultural use (a1), the growth of the plants without (left) and with SAH (right) (a1'), the state-of-the-art for designing various material structures with customized fertilizers releasing activity (a2), the semi-IPN

SAH fertilizer release profile (a3), and the plant growth parameters (a3', a3''). (b) Nanocellulose SAH: the cultivation of radish on the Petri dish without (b1) and with (b1') SAH, and the growth of spinach in clay loam (b2, b2') and sandy soil (b3, b3'). Reprinted with permission from ref. [406] Copyright from Elsevier.

Controlling fertilizer release rates in the soil, where overly rapid delivery rates result in nutrient dysfunction, is a particular challenge for cellulose SAHs. The architectures of SAHs have been adjusted (Figure 9(a2, a3)), i.e., by creating double-layered SAHs and semi-interpenetrating polymer (IPN) networks, in order to modify the rate of the fertilizer release. Semi-IPN might consist of two parts: a linear polymer and a cross-linked polymer (gel network). While a double-layered SAH embeds fertilizer in the core layer and releases it when the outer layer degrades, it can help create a thicker and stronger gel network to slow down the fertilizer release. The release patterns of pure fertilizer (APP) in a single network (cellulose-g-AA) and semi-IPN (cellulose-g-AA/PVA with PVA as the second polymeric component) were compared by Wang et al. [407]. They found that semi-IPN showed improved wheat growth (Figure 9(a3', a3'')) but a slower rate of APP release (Figure 9(a3)). A unique double-coated multifunctional slow-release fertilizer was created by Zhang and Yang [408] with urea as the core, ethyl cellulose as the inner coating, and cellulose SAH as the outer coating. This improved the soil's ability to hold water and produced a slow-release nitrogen profile. Applications for nanocellulose SAH in agriculture have also been reported. When Barajas-Ledesma et al. [409] looked into the effect of TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl)-oxidized nanocellulose on radishes' germination in Petri plates, they observed that nanocellulose SAH increases the germination index by 30–40% (Figure 9(b1, b1')). In a later study, a commercial SAP (superabsorbent polymer) and TEMPO-oxidized nanocellulose SAH were used as soil conditioners for spinach in sandy and clay loam soils [410]. It is noteworthy that plants exposed to nanocellulose SAH showed reduced development ("N0.5" in Figure 9(b2, b2', b3, b3')). The malfunction of the intended soil amendment capability may have been caused by the high degradability of nanocellulose. This discovery also clarified why, although cellulose is a small component (cellulose breakdown did not affect the total soil amendment quality), the cellulose-graft polymer is now the most used soil conditioner in cellulose SAH. In order to investigate the effects of various additives, their amounts, and the types of radiation they absorb, these superabsorbents were tested using electron beam radiation. They displayed potential in agricultural applications, especially with plants like spinach and crown daisies, and showed promising results in swelling testing in a variety of solutions. Using a dissolving method, employing sodium hydroxide and urea, environmentally friendly hydrogels were successfully created from cellulose recovered from water hyacinths. Sodium tetraborate decahydrate (borax) was then utilized to create cross-linking between the hydroxyl groups of the cellulose chains. Boric acid inclusion may give cellulose hydrogels their superabsorbent quality. The swelling ratio of the cross-linked cellulose hydrogels could reach around 900%, whereas the uncross-linked hydrogels had a swelling ratio of only 325%. The gel percentage of the cross-linked hydrogels significantly increased as the concentration of borax was raised. Additionally, the hydrogels made of cross-linked cellulose exhibited antibacterial action against Gram-positive bacteria (*S. aureus*) [411]. To increase the gel characteristics, superabsorbent materials based on carboxymethylcellulose were created and supplemented with graphite oxide, reduced graphene oxide, activated carbon, and bentonite. In order to investigate the effects of various additives, their amounts, and the types of radiation they absorb, these superabsorbents were tested using electron beam radiation. They indicated potential in agricultural applications, especially with plants like spinach and crown daisies, and showed excellent results in swelling testing in a variety of solutions. As the carbon materials and polymer gel had strong binding, superabsorbents incorporating graphite oxide and reduced graphene oxide showed an improved gel fraction and mechanical strength. These composites promoted better plant development by acting as slow-release liquid fertilizers [412]. The citric acid cross-linking of hydroxyethyl cellulose

with sodium carboxymethylcellulose salt resulted in the development of a superabsorbent hydrogel for agricultural use. This procedure included the synthesis of cellulose nanocrystals by acid hydrolysis. It was determined how the cellulose nanocrystals affected the hydrogel's characteristics, such as its 600% swelling rate when 2% citric acid was used as a cross-linker. Optimizing cross-linkers and nanocrystal dispersion inside the hydrogel matrix were the main goals in order to improve agricultural water resource utilization [413]. Using cellulose derivatives, a biodegradable superabsorbent hydrogel was created with the goal of optimizing water resources for agricultural use. The sorption capacity of this hydrogel was assessed in relation to its pH and ionic strength. Its potential in agricultural applications was showcased in experimental greenhouses with tomato growing, where it proved beneficial in efficiently storing and releasing water to the soil and plant roots [140].

## 9. Agrotextiles and Nonwovens in Agriculture

Agrotextiles, nonwovens, and mats have become an integral part of modern agriculture. These materials are being increasingly used as greenhouse covers, fishing nets, layer separation in fields, in nets for plants, rootless plants, and protecting grassy areas, packages for storing grass, fertilizers, seeds, anti-bird nets, weed barriers, crop covers, erosion control mats for ground and plant water management at the time of scarcity and abundance of water, or as a twines broadly used to support crops such as tomatoes and cucumbers [414]. The wide range of applications of agrotextiles requires suitable tensile strength and good permeability and, depending on the final use, they should be fast-biodegradable or non-degradable (e.g., frost protection covers such as nonwoven spunbond, polypropylene, or knitted polyethylene strips).

The potential application of agrotextiles has become of great interest in the past decade because they improve plant and crop health through the reduction of the use of harmful agrochemicals. They were studied particularly regarding their adsorption ability of oyster peptide volatile compounds, mulch mats, geotextiles, lines, fishing nets, ropes, shade fabrics, woven and nonwoven covers for crops, bird protection nets, and antihail nets [415–420].

Nonwovens as materials with high strength, durability, and elasticity effectively optimize the productivity of crops, gardens, and greenhouses. They can be used as crop covers protecting from weather conditions like snow, wind, and rain, as plant protection materials against herbicides, insects, and frost, weed control fabrics, seed blankets, root control bags, biodegradable plant pots, landscape fabric, or lawn coverings [421,422].

The properties of nonwoven agrotextiles depend on the type and production conditions, including, above all, what fibers they are made of. Nonwoven fabric can be produced from natural or artificial fibers as well as their mixtures. Jute is mainly used as a natural fiber, while the most common choice for nonwoven fabric made from artificial fibers is polypropylene. Biodegradable products created from renewable raw materials have an inherent advantage over products that must be initially synthesized and then disposed of in landfills at the end of their life cycle. Environmentally friendly materials, from the production of raw materials and production to the distribution and disposal of products, have a low impact on the environment and are non-toxic [47].

Nonwoven fabrics are materials made of randomly arranged fibers or cut yarns reinforced by mechanical, thermal, or chemical bonding. The properties of nonwoven fabrics depend on the weave, type of fibers, and production parameters. Nonwoven manufacturing systems are either wet-laid, dry-laid, or polymer-laid. Polymer nonwovens or spun-melt nonwovens are produced using polymer extrusion machines. Once the web is formed, the nonwoven fabrics can be bonded mechanically, chemically, or thermally. Such joining methods include needle punching, stitch (mechanical) bonding, chemical bonding, and thermal bonding.

Chemical bonding techniques involve the application of adhesive binders to webs along with processes such as saturation, spraying, printing, or foaming to bond the fibers together, improving the overall stiffness, softness, and water resistance of the final nonwo-

ven fabric. Additionally, binding agents can also be applied during production to improve the aesthetics of the surface roughness or to give the fibers fire-resistant properties. A thermal bonding technique is often used, which involves firstly heating the web to soften the fusible bonding element and then cooling it to fuse the fibers together. This technique is characterized by a lower water consumption and reduced environmental impact due to the possibility of recycling the fabrics. The main methods of fixing the structure of the fibrous network still include mechanical joining using hydroentangling, stitch bonding, and needling. Needle punching is a nonwoven bonding technique that involves mechanically joining fibers by repeatedly piercing a fibrous mat using a series of barbed needles. It is a technique particularly used in the case of thick nonwoven fabrics.

The choice of fibers for various applications depends primarily on product specifications, the demand for composites, and profitability. Natural fibers are characterized by a heterogeneous surface and their chemical composition shows the presence of multiphase structures providing hydrophilic or hydrophobic properties, which may still give an advantage to synthetic fibers, which constitute 60% of the total production of nonwovens. This fact contributed to the further development of the production of nonwovens from natural products, emphasizing the global trend of increased sustainable and renewable production [423–425].

Shi et al. (2024) examined the regeneration ability of octenylsuccinylated starch-pullulan nanofiber mats after the physical adsorption and thermal desorption of off-odor compounds in oyster peptides. The pore area and fiber diameter of the regenerated nanofiber mats gradually decreased, the hydrophobicity gradually increased, and the surface groups changed as the number of cycles grew [416]. Xian et al. 2021 investigated the feasibility and degradability of recyclable natural cellulose- or protein-based nonwoven mulches. They found that the crop yield from the best new mulch treatment and the degradable plastic film treatment were similar, provided excellent thermal insulation, inhibited weed germination, and enhanced the soil moisture retention capacity [417]. Chizhov et al. (2018) used the electrospinning technique for the preparation of fibrous biodegradable nonwoven materials based on biopolymers (poly-hydroxybutyrate and polylactide) and their mixtures. Obtained fibrous materials had a high water absorption and a high oxidation rate when compared to mulching films. These features facilitate biodegradation processes in environmental conditions (more or less five times faster biodegradation), shortening their service life to less than 1.5 months, which is required from a vegetational plant season point of view. Polylactide was found to be a stable material for thermal oxidation and it was present in blend-stabilized PHB. Unfortunately, the application of the nonwoven technology to develop degradable mulch was found to be a relatively expensive method for the valorization of various fibers and filaments, especially when made from biodegradable polymers like PLA, PHB, or their blends [419]. Marczak et al. (2020) worked on the water-absorbing geocomposite, an innovative technology supporting water management and the vegetation of plants in environmental engineering and agriculture sectors. Obtained geotextiles made from wool and linen or reinforced by jute mesh biodegraded within the first vegetation season, by their increased water retention capacity, and by their gradual release of nutrients to the soil enhanced the development of the plant root system [420]. Woolen geotextiles have been successfully used in agriculture and anti-erosion protection. They are not only a source of available nitrogen and phosphorus for plants, which are slowly released during degradation, but also limit evaporation and provide thermal protection to the soil [426–428]. Moreover, the biodegradation of these textiles stimulates microbial activity in the soil, reflected in the release of beneficial enzymes into the soil.

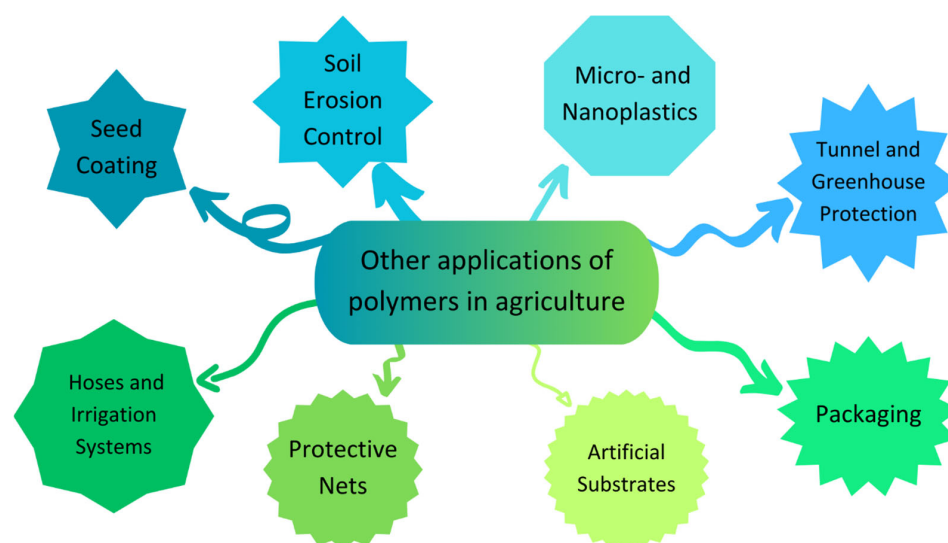
Gabrys et al. (2021) examined modified cellulose nonwoven fabric enriched with potassium nitrate as a fertilizer and coated with polylactide in the tunnel cultivation of tomatoes. The obtained biodegradable material improved the cultivation of plants by slowly releasing fertilizer at optimal thermal and water conditions, as well as protecting the soil against weed growth [429]. Gao et al. (2014) studied the usefulness of nonwoven polyester fabrics with the covalently bounded organophosphate-degrading enzyme in the process of

pesticide degradation. The immobilized enzyme demonstrated good effectiveness and may be successfully used in the bioremediation process. Growing technological innovations in the fibrous industry create new possibilities for the development of nonwoven fabrics with better properties targeted at a particular application that can be used as both a temporary and long-term solution [430].

## 10. Other Application

Polymers, due to their versatility and properties, have found applications in nearly every sphere of contemporary life. These long molecular chains, which can be both natural and synthetic, offer unmatched flexibility in their design, making them indispensable in many industry sectors. In the food industry, polymers such as polyethylene and polypropylene are crucial for the production of packaging, ensuring the safe and hygienic storage of food products. The medical field also benefits from the advantages of polymers, utilizing them in the manufacture of artificial joints, implants, and surgical tools, thereby opening new possibilities in reconstructive surgery and orthopedics. The automotive sector is not left behind, where polymers are employed in creating lighter and more durable components, contributing to the enhanced energy efficiency of vehicles. These examples merely scratch the surface as polymers are also integral to electronics, construction, clothing, and even cutting-edge technologies such as 3D printing and nanotechnology.

Beyond the previously mentioned, polymer materials possess a plethora of other less obvious applications. Examples are shown in Figure 10.



**Figure 10.** Other applications of polymers in agriculture.

### 10.1. Seed Coating

Seed coating with polymers is an innovative method utilized in agriculture aimed at improving seed germination conditions, enhancing their resistance to various external factors and streamlining the sowing process.

Seed coating is a practice in agriculture that involves covering seeds with a layer of material, such as polymers, to enhance their germination, protect against pests and diseases, and provide protection against harmful environmental conditions. This process may also include the application of additional components, such as fertilizers, plant protection products, or growth stimulators, which are released at the appropriate time and place. Seed coating is applied to prevent the leakage of metabolites from the seeds, which is especially important in the context of storing seeds under various conditions. This is achieved by applying a protective layer in conjunction with suitable packaging, as described by Ingmar et al. in the context of soybean research [431]. Zhang et al. point to the beneficial properties of polymers as a seed coating material due to its porosity, water retention ability, and

nutrient richness. The polymer in seed coating contributes to improved germination, plant efficiency, and soil health [432]. Samarah and Aldahadha explain that seed coating using polymers and insecticides helps protect future plants from diseases and pests. Using an optimal content of polymers combined with the insecticide Gaucho<sup>®</sup>, results in high germination and plant emergence rates [433].

The mechanisms of seed coating with polymers utilize various active ingredients, such as sterilizing agents and insecticides, which significantly improve disease prevention and pest control for crops, for example, corn, soy, wheat, potatoes, and rice. This process also results in improved plant germination rates and overall seed quality improvement [434]. Other studies have shown that seed coating using antioxidants and appropriate packaging materials during storage can affect the maintenance of seed viability and vigor. The best results were observed when coating seeds with ascorbic acid combined with aluminum foil packaging, highlighting the importance of these mechanisms in preserving the seed quality over time [431]. Additionally, in a study conducted by Zhang et al., biochar was used as a seed-coating material, proving to be an economical and sustainable approach. Biochar, with its porosity and water retention ability, supports seed germination and contributes to improved plant growth and soil health [432]. Therefore, seed coating methods rely on advanced polymers and other active ingredients to provide protection against mechanical damage and contribute to the application of fungicides, seed coloring, and nutrient packages, supporting better initial germination and crop development, such as wheat [431].

The process of seed coating with polymers is thus a highly effective method used in modern agriculture, enabling the enhancement of the seed quality, increasing the crop yield, and providing efficient protection against pests and diseases. It significantly influences the ease and effectiveness of sowing seeds and improves the efficiency of agricultural crops.

The benefits derived from this procedure include, among others:

- **Improved Seed Protection:** seed coating with polymers provides seeds with better protection against plant diseases, pests, and fungi, making the seeds more resistant from the start of growth [435].
- **The Controlled Release of Nutrients:** seeds can be coated with polymers containing nutrients that are gradually released, supplying the necessary substances to the seeds at a critical moment of their growth [436].
- **Resistance to Adverse Environmental Conditions:** seeds coated are also more resistant to adverse environmental conditions, such as drought or excessive moisture, ensuring better and more uniform germination [437].
- **Increased Seed Viability:** coating with polymers can improve the viability of seeds stored for a long time, thanks to the reduction in moisture loss and protection against harmful external factors [438].
- **Improved Sowing Precision:** by standardizing the sizes of coated seeds, greater precision during sowing can be achieved, leading to a more uniform distribution of plants in the field [439].
- **Improved Germination:** coating can effectively improve germination in fields where environmental conditions are not optimal, giving plants a better start [440].
- **Better Water Consumption Management:** some polymer coatings can help maintain moisture around the seeds, which in turn reduces the demand for water and can contribute to water savings in agriculture [440].

The primary objective of seed priming is to protect seeds from numerous factors. By creating optimal conditions for planting seedlings and utilizing successive growth stages, this process effectively maintains the physiological and sanitary integrity of the seeds. To safeguard the seeds from harmful influences, chemical agents are commonly employed. Consequently, this approach efficiently handles potential attacks during germination and supports the growth and maturation of crops [441]. Various types of polymers can be used for coating, including biopolymers such as chitosan derived from chitin. Chitosan coatings can regulate the water uptake, protect against stress factors such as aging and fungal

invasion, and improve seedling germination under various soil moisture conditions [442]. Some coatings use specific polymers, such as DISCO AG SP RED L-200, combined with other substances, such as tiram and mycorrhiza, to increase the vigor and yield of seeds, as observed in studies with soybean seeds [443]. Additionally, the coating may contain other beneficial additives, such as pesticides, bacterial inoculants, or growth regulators, for additional seed strengthening. In some cases, the coating process aims to temporarily inhibit germination [440].

Seed coating with polymers can be achieved through several mechanisms, each tailored to specific seed treatment goals. Various seed coating processes are designed to provide benefits such as increased germination, protection against pests and diseases, the targeted delivery of nutrients, and controlled water uptake. Here are some of the mechanisms used for seed coating with polymers:

- **Dry Coating Process:** This method involves mixing seeds with a dry, water-dispersible polymer powder. Water is then added to achieve a specific polymer-to-water ratio, creating a film upon drying. The temperature is maintained below the seed degradation point, creating a polymer film around each seed without causing any thermal damage [439].
- **Fluid Bed Coating:** Seeds are suspended and moved in an air stream in a fluid bed apparatus while the polymer coating is sprayed onto them. This method allows for uniform coating and quick drying due to continuous movement and airflow [444].
- **Bowl Coating:** Similar to candy production, seeds are placed in a rotating bowl, while polymers and other additives are added. Through the rotation of the bowl, seeds are uniformly coated, rotating and rolling over each other [445].
- **Immersion Coating:** Seeds are immersed in a polymer solution, allowing them to acquire a thin polymer layer. After removal, the polymer solution dries, forming a continuous film around the seeds [446].
- **Electrostatic Coating:** This uses an electric field to attract charged polymer particles to the seeds. This can lead to a very thin and uniform coating, as the electric field can attract the coating material to all sides of the seeds [447].
- **Encapsulation:** this is a more complex process in which seeds are completely surrounded by a polymer matrix, providing significant protection and can also be designed for the slow release of nutrients or other additives as the seedling grows [448].

Each of these mechanisms provides a unique set of benefits and can be optimized based on the specific needs of the treated seeds, such as the desired release rates of additives, the level of protection needed, and the environmental conditions in which the seeds will be planted. The choice of polymer and application technique is key to achieving the desired outcome in terms of the health, growth, and yield of seedlings.

For seed encapsulation, primarily biodegradable polymers are utilized. Non-biodegradable materials are considered too burdensome for the environment. Non-biodegradable polymers can contaminate soil and aquatic environments, leading to ecological problems, such as disrupting the balance of natural ecosystems or harming aquatic life. Therefore, there is growing interest in developing and applying biodegradable alternatives. Despite certain ecological challenges, seed coating with conventional polymers remains popular due to its effectiveness in protecting and improving seed germination. However, growing ecological awareness is pushing research and development towards greener, biodegradable coating options that could offer similar benefits with a lesser burden on the environment. Seed coating with biodegradable polymers represents an innovative approach that integrates the advantages of traditional coating with the principle of sustainable development and environmental protection. Unlike conventional (non-biodegradable) polymers, biodegradable polymer materials naturally decompose under the influence of microorganisms, such as bacteria, fungi, or algae, into natural, non-toxic products, such as carbon dioxide, water, and biomass. This process reduces potential negative effects on the environment, while still providing key benefits to plants. Biodegradable coatings can be made from a variety of materials, including [449]:

- Polylactic acid (PLA)—popular for its thermoplastic properties and compostability [450].
- Starch—used for its naturalness and ability to absorb water [451].
- Cellulose—exhibits good mechanics and is fully biodegradable [449].
- Proteins, such as gelatin—allow for the creation of fully natural coatings [452].

The use of biodegradable polymers in seed coating is a significant step towards sustainable agriculture and environmental protection. The biodegradability of coatings minimizes the risk of plastic accumulation in soil and water bodies, supporting healthy ecosystems and limiting the negative effects of plastic pollution. Despite numerous advantages, there are challenges related to production costs, scalability, and tailoring material properties to specific applications. Research and development focus on overcoming these barriers, improving the efficiency of biodegradable coatings, and their availability [439,440,449]. Further innovations in this field may offer even better solutions for seed producers, farmers, and the environment.

Advanced polymer seed coating is an innovative agricultural technique that enhances seed germination conditions, protects against pests and diseases, and optimizes the sowing process by enveloping seeds with polymer layers containing supplementary components. This process improves the seed viability, crop yield, and environmental sustainability through mechanisms such as the controlled release of nutrients, resistance to adverse conditions, and enhanced water consumption management. Despite ecological challenges, the use of biodegradable polymers in seed coating represents a promising avenue for sustainable agriculture, offering effective protection while minimizing the environmental impact.

### 10.2. Soil Erosion Control

The use of polymers for soil erosion control encompasses various types of substances that effectively reduce soil loss caused by the action of water, wind, and other external factors. Polymers, such as polyacrylamide (PAM) and polyvinyl alcohol (PVA), have been utilized in laboratory studies, which demonstrated that PAM is more efficient in reducing total runoff during initial rainfall events, whereas both polymers yield positive results in subsequent rainfalls [453]. The employment of biodegradable polymers, such as chitosan and carrageenan, can enhance the soil stability and resistance against water erosion by improving the wettability and resistance to runoff in unstable soils [454].

Biopolymers also offer numerous advantages compared to petroleum-based polymers, including rapid vegetation regeneration and the reduced transport of solids in runoff water, making them an attractive alternative due to biodegradability, costs, availability, and logistics [455]. Compared to traditional stabilizers, polymers stand out for their stable chemical properties and shorter curing time, making them effective in increasing soil resistance to erosion [456]. Furthermore, in arid and semi-arid regions, the application of synthetic polymers as soil structure enhancers helps prevent decreases in the infiltration rates, reduce runoff, and minimize soil losses [457].

An example of a specific application is the use of polyacrylamide (PAM) in controlling wind erosion in sandy soils, which has impacted the physical and chemical properties of the soil, including its temporal variability [458]. Another study involved the application of 80 kg/ha PAM on a silty clay loam embankment, which reduced runoff by 86% and soil loss by 99% during intense storms, remaining effective in controlling runoff and soil loss through multiple artificial rainfall applications [459]. Polymers, such as PVA, have also been used in the control of erosion in granulated soils, providing an effective method of protection [460].

Research suggests that polymers are an effective means for controlling soil erosion, offering structural stability to soils, improving erosion resistance, and promoting vegetation. Their application in practice may require an individual adjustment to specific environmental conditions and soil types.

#### Applications of Polymers:

- Soil Structure Stabilization: Polymers, by interacting with soil particles, can enhance their cohesion and porosity, which improves the water retention and permeability.

This prevents soil erosion by rainwater or runoff, supporting a healthy environment for plant root development [461,462].

- The Creation of a Protective Layer: Some polymers can be applied to the soil surface to create a protective layer that retains soil particles and increases resistance to erosive agents. This is particularly useful in areas with steep slopes or where the soil is exposed to the direct action of wind and water [463].
- Application as Hydrogels: polymer hydrogels can absorb and retain water, not only reducing the risk of erosion, but also supporting vegetation during droughts by providing additional water sources [464].
- Soil Granularity Enhancement: polymers can be used to aggregate fine soil particles into larger, more stable granular structures, further limiting the risk of erosion [465].
- The Construction of Barriers to Prevent Erosive Water Runoff: in areas with varied topographic conditions, polymers can be used to construct small barriers aimed at slowing down and controlling the directions of rainwater runoff [466].

Examples of Applications:

- The protection of embankments and slopes: applying polymers to stabilize road and railway embankments, as well as earth mounds, reducing the risk of landslides and erosion caused by rain and wind [467].
- Hydrologic Engineering: improving soil permeability to ensure effective water drainage, which is key in reclamation projects and wetland management [468,469].
- Land Reclamation: enhancing soil conditions in degraded areas, such as waste dumps, mining sites, or decertified regions [470].

However, it should be noted that the use of synthetic polymers involves potential environmental risks related to their biodegradability and impact on the soil and groundwater. Hence, there is growing interest in biodegradable polymers, which offer similar benefits with less of an environmental burden.

In the face of increasing soil erosion, the use of polymers for its protection presents a promising solution, enabling the integration of production goals with the principles of sustainable development [471].

Non-biodegradable polymers, used to protect soil from degradation, operate through various physical and chemical mechanisms that prevent erosion and the loss of the soil structure and fertility. They are characterized by long-term stability in the environment, meaning they do not easily undergo biological decomposition by microorganisms. Their use in agriculture and environmental engineering can significantly contribute to soil protection, though their durability also leads to increased environmental concern [472–474]. Non-biodegradable polymers pose a challenge for the environment due to their durability and resistance to decomposition. The accumulation of these materials in the soil can lead to potential contamination and affect local ecosystems. Therefore, it is crucial to consider the use of biodegradable alternatives and develop waste management strategies for used synthetic polymers [472,473,475,476].

In the context of growing ecological awareness and the need for sustainable development, research is evolving on new, eco-friendly polymers and their application technologies to minimize negative impacts on the environment while retaining benefits for soil and agricultural production. Biodegradable polymers are an innovative solution in protecting soil from degradation. Their ability to decompose under natural processes, such as the action of microorganisms, makes them attractive from an ecological perspective. The application of biodegradable polymers involves various mechanisms that not only limit soil erosion, but also support its fertility and structure [453,454,456]. While biodegradable polymers present promising solutions, there are still challenges related to the costs, scalability of application, and matching material properties to specific environmental conditions. This requires further research and development to create comprehensive and cost-effective soil protection methods that are widely available and environmentally friendly [454,458,477].

The use of polymers for soil erosion control offers a versatile solution to environmental degradation, with diverse mechanisms like the stabilization of the soil structure, the

creation of protective layers, and the utilization of hydrogels. While non-biodegradable polymers pose environmental concerns, the shift towards biodegradable alternatives requires further research to address challenges in the cost, scalability, and material properties. Ongoing research aims to refine eco-friendly polymers and their application technologies to ensure more effective and sustainable soil protection methods amidst increasing ecological awareness.

### 10.3. Tunnel and Greenhouse Protection

Polymers are widely utilized in covers for tunnels and greenhouses, offering both structural protection and thermal insulation. One example is the use of polymers in tunnel protection through the injection method, which creates a buffer layer, preventing damage to the tunnel lining by falling rocks. This method is characterized by its rapid execution and economic benefits [477–479]. In another application, rolled polyethylene foam with an adhesive method serves as an effective insulation system in dome homes, protecting the living space from external conditions similar to those in a greenhouse [480]. Polymers are also an essential addition to cement used in deep drilling for oil or gas, allowing operations at extreme depths and temperatures up to 260 °C [481]. Polyimide, due to its low solar absorption, resistance to environmental factors, and high thermal stability, is suitable for tunnel and greenhouse covers, as it can withstand harsh conditions and maintain its properties when cast into thin films [482–485].

Recent advancements in the field of biodegradable polymers emphasize their significance as an alternative to non-degradable polymers, with applications based on their sources, properties, degradation patterns, and applications in 3D printing technology, including possible use in tunnel and greenhouse coverings [486]. In addition, biodegradable polymers provide sustainable solutions to environmental challenges posed by non-biodegradable materials, offering durable and eco-friendly alternatives for traditional plastics in agricultural applications, both for tunnel and greenhouse coverings [487,488]. The application of biodegradable films using lamination and creating layered structures can enhance their barrier characteristics for oxygen and moisture, which is particularly important in their use as coverings for tunnels and greenhouses, while also promoting sustainable environmental development [131,489,490]. In conclusion, biodegradable polymers offer extensive application possibilities in coverings for tunnels and greenhouses by promoting the durability, sustainable use, and reduction in the environmental impact, contributing to sustainable agricultural production and crop protection.

#### Polymers in Tunnel Protection:

- **Sealing:** One of the primary applications of polymers in tunnels is waterproofing. Tunnels, especially those constructed underground or underwater, are susceptible to leaks and water damage. Polymer-based waterproof membranes are applied to the interior surfaces of tunnels to prevent water ingress. These membranes are flexible, durable, and adhere well to concrete and other materials used in tunnel construction, ensuring waterproofness [491–493].
- **Structural Reinforcement:** Polymers, combined with other materials such as fiberglass or carbon fiber, are used to create composite materials that can strengthen the structural integrity of tunnels. These composites can be applied to line tunnel walls or repair and reinforce areas that may have weakened over time. The high strength-to-weight ratio of polymer composites makes them an ideal choice for these applications [494–497].
- **Corrosion Protection:** Tunnels, especially those that carry vehicles or are exposed to harsh conditions, can suffer from corrosion. Polymer coatings can be applied to metal components of the tunnel, such as reinforcement bars, to protect them against corrosion. These coatings act as a barrier between the metal and corrosive elements such as water and salts [498–500].

#### In Greenhouse Protection:

- **Covering Material:** Polymers are commonly used as covering materials in greenhouses. Polyethylene (PE), polyvinyl chloride (PVC), and ethylene–vinyl acetate (EVA) are just

a few of the polymers used to produce greenhouse films. These materials are chosen for their transparency, allowing the maximum penetration of sunlight, durability, and resistance to environmental factors such as UV radiation and temperature fluctuations. Furthermore, some polymer films have specific properties, such as light diffusion, for even plant growth or blocking certain wavelengths to combat pests [501–504].

- Insulation: Polymers also play a key role in greenhouse insulation. Double-layer polymer films can trap air between them, providing an insulating effect that helps maintain the internal temperature of the greenhouse. This is particularly beneficial in cooler climates, where maintaining a constant temperature is critical for plant growth [501,505,506].
- Disease and Pest Control: Some polymer films used in greenhouses can be treated with additives that help combat diseases and pests. For example, anti-drip films reduce the formation of condensation droplets, which can spread pathogens. There are also polymer films that can reflect UV light, deterring certain types of pests from entering the greenhouse [232,501,507,508].

The widespread applications of polymers in tunnel and greenhouse coverings encompass structural protection, thermal insulation, and environmental sustainability. From tunnel lining reinforcement to insulation in dome homes, polymers demonstrate versatility and efficiency, offering rapid execution and economic advantages. Moreover, recent advancements in biodegradable polymers signal a promising shift towards eco-friendly solutions, addressing environmental concerns while maintaining durability and barrier characteristics crucial for tunnel and greenhouse protection. In conclusion, the integration of polymers, both traditional and biodegradable, underscores their pivotal role in enhancing agricultural practices, ensuring sustainable production and mitigating the environmental impact in tunnel and greenhouse applications.

#### 10.4. Packaging

Polymers have had a significant impact on the packaging industry, transforming it from its basic beginnings into a highly sophisticated and diverse sector. Polymers, chemical substances of a very high molecular mass consisting of multiple repeating units called monomers, have found widespread use in packaging due to their versatility and adaptability [475,509]. The introduction of polymers to the packaging industry has marked a revolutionary shift from traditional materials such as glass, metal, and paper to more durable, lightweight, and cost-effective solutions. This transformation began in earnest in the early 20th century with the development of synthetic polymers like phenoplasts and, later, polyethylene and polypropylene. These materials enabled the creation of a wide range of packaging products, from simple containers to complex packaging systems, fundamentally changing the way goods are stored, transported, and preserved [510,511].

Non-biodegradable polymers, such as polyethylene (PE), polypropylene (PP), and epoxy resins, are widely used in the packaging industry due to their durability and resistance to environmental factors. For example, polyethylene, known for its flexibility and strength, is commonly used to produce plastic bags, film packaging, and containers. Polypropylene, with its high melting point, is ideally suited for packaging products requiring sterilization at high temperatures. Epoxy resins, known for their excellent adhesive properties and chemical resistance, are used in coatings and laminates for food and beverage cans [512–514].

In response to environmental concerns in the packaging industry, there has been an increase in the use of biodegradable polymers. These polymers are designed to naturally decompose over time, minimizing their impact on the environment. Polylactic acid (PLA) is a popular biodegradable polymer made from renewable resources, such as corn starch. It is used in various packaging applications, including disposable cutlery, cups, and film packaging. Another example is polyhydroxyalkanoates (PHAs) produced by microorganisms, which are used in packaging requiring biodegradability and compostability [509,515,516].

Polymers play a pivotal role in the packaging industry due to their diverse applications and advantageous properties. This article delineates several key applications of polymers in packaging, elucidating their significance in ensuring product integrity and environmental sustainability.

- **Packaging Films:** Polymers, such as polyethylene (PE) and polypropylene (PP), serve as fundamental materials for manufacturing packaging films. These films find widespread usage in packaging food items, industrial products, and various consumer goods, owing to their robustness, flexibility, and ability to shield products from moisture, light, and other external factors.
- **Bottles and Containers:** Polymers like polyethylene terephthalate (PET) and polycarbonate (PC) are integral to the production of bottles and containers for beverages, cosmetics, household chemicals, and more. Their lightweight nature, durability, and resistance to mechanical damage render them highly favored in the packaging industry.
- **Bags and Sacks:** Polyethylene low-density (LDPE) and high-density (HDPE) polymers are utilized for crafting bags and sacks for shopping, waste disposal, industrial packaging, and beyond. They offer cost-effectiveness, ease of production, and safeguard products against moisture and contaminants.
- **Food Containers:** Polymers are also employed in fabricating food containers such as trays, bowls, and single-use packaging. They ensure hygiene, ease of storage, and transportation while being adeptly engineered to preserve the freshness and quality of food products.
- **Pharmaceutical Packaging:** In the pharmaceutical realm, polymers feature prominently in the production of packaging for medications, capsules, patches, and syringes. Engineered to provide protection against moisture, light, and contaminants, they facilitate convenient and safe handling for patients [509,517–520].

The significant advantage of utilizing polymers for packaging lies in their recyclability. The recycling of plastics employed in the packaging industry constitutes a pivotal step towards environmental protection and waste reduction. The process commences with the collection of used packaging from various sources, ranging from households and businesses to collection points. Subsequently, the packaging undergoes meticulous sorting based on its type and properties, facilitating further processing. Once the packaging is adequately sorted, it undergoes a shredding process. During this stage, mechanical, chemical, or thermal methods are employed to shred the packaging into smaller pieces, facilitating subsequent processing. The shredded materials are then subjected to melting or granulation, resulting in the formation of liquid raw material or granules. The obtained raw material is subsequently utilized in the production of new products made from plastics. This may include the manufacturing of new packaging as well as other plastic articles. Through this process, it becomes feasible to reduce the consumption of natural resources and limit the amount of waste ending up in landfills. The recycling of plastics in the packaging industry necessitates collaboration among various stakeholders, including producers, recycling companies, and consumers. The promotion of this process can contribute to mitigating the adverse environmental impact of the packaging industry and support the goals of sustainable development [521–524].

Polymers have revolutionized the packaging industry, offering versatile and adaptable solutions that have replaced traditional materials such as glass, metal, and paper. Their introduction has ushered in a transformative shift towards more durable, lightweight, and cost-effective packaging options, fundamentally altering the storage, transportation, and preservation of goods. From non-biodegradable polymers like polyethylene and polypropylene to environmentally conscious alternatives such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), polymers play a crucial role in ensuring product integrity and environmental sustainability. Through meticulous recycling processes involving collection, sorting, shredding, and reprocessing, polymers contribute to waste reduction and environmental protection, underscoring the importance of collaboration among stakeholders to promote sustainable practices in the packaging industry.

### 10.5. Hoses and Irrigation Systems

Polymers play a crucial role in the design and functionality of garden hoses and irrigation systems due to their unique properties such as flexibility, durability, and resistance to various environmental factors. These synthetic materials have transformed the way water is delivered in horticulture and agriculture, offering efficient and flexible irrigation solutions. Below is a detailed discussion on the use of polymers in garden hoses and irrigation systems, highlighting their significance in these applications [525–527].

In irrigation systems, polymers are used to create precise and controlled watering mechanisms, such as drip irrigation lines and sprinkler hoses. These systems are designed to deliver water directly to the plant's root zone, minimizing evaporation and runoff, thereby maximizing the water use efficiency. The use of polymers in these systems aids in water conservation, an increasingly important factor in areas struggling with water scarcity or those aiming for sustainable gardening practices [528,529].

One of the most valued characteristics of polymers in garden hoses is their flexibility combined with exceptional durability. This allows for the easy maneuvering of hoses around corners, plants, and other obstacles without kinking and breaking. Polymers, such as polyurethane (PU) and polyvinyl chloride (PVC), are commonly used in the production of garden hoses due to their wear resistance, enabling hoses to withstand the rigors of daily use and harsh weather conditions without damage [526,530].

Polymers are inherently resistant to a range of environmental factors, including UV radiation, extreme temperatures, and chemicals. This resistance is crucial for garden hoses and irrigation systems exposed to outdoor conditions, where UV rays can cause the degradation of materials not capable of withstanding such exposure. Polymer-based hoses maintain their integrity and functionality over time, even when left outdoors in varying weather conditions, which is essential for reliability and longevity in horticultural and agricultural applications [525,531].

The versatility of polymers allows for a wide range of customization options in garden hoses and irrigation systems. They can be designed to various specifications, including length, diameter, and wall thickness, to suit different needs and pressures related to irrigation. Additionally, polymers can be formulated to have antibacterial properties, reducing the risk of algae and bacteria buildup inside the hose, which can deteriorate the water quality and flow [532,533].

Polymers are integral to the design and functionality of garden hoses and irrigation systems, offering flexibility, durability, and resistance to environmental factors. These synthetic materials have revolutionized water delivery in horticulture and agriculture, providing efficient and adaptable irrigation solutions that conserve water and withstand harsh conditions. Through precise watering mechanisms like drip irrigation lines and sprinkler hoses, polymers contribute to water conservation by delivering water directly to plant roots while minimizing evaporation and runoff. Their flexibility and durability make them ideal for maneuvering around obstacles without kinking or breaking, while their resistance to UV radiation and chemicals ensures their long-term reliability and performance, essential for outdoor use. Furthermore, the versatility of polymers allows for customization options to meet various irrigation needs, including length, diameter, and antibacterial properties, highlighting their indispensable role in sustainable gardening practices.

### 10.6. Protective Nets

The use of polymers in the production of protective nets, especially in agrochemistry, signifies the substantial application of these materials in agriculture. Protective nets are essential in safeguarding crops against various external threats, including insects, birds, excessive sunlight, and harsh weather conditions. Polymers, with their versatile properties, play a key role in the production of these nets, ensuring they meet the required standards of durability, effectiveness, and environmental friendliness. Below, we delve into how polymers are utilized to create and function in protective agricultural nets [534,535].

Polymers such as polyethylene (PE) and polypropylene (PP) are commonly used in the manufacture of protective nets due to their high tensile strength and durability. These materials can withstand various physical loads, including stretching and tearing, common during installation and prolonged use in crop fields. The proper resilience of these polymer nets ensures crop protection over an extended period, often across several growing seasons, without the need for frequent replacement [534,536].

Protective nets made from polymers have the advantage of being both flexible and lightweight. This makes them easy to handle, install, and dismantle, a key feature for farmers and agricultural workers who may need to cover or uncover large crop areas. The flexibility of polymer nets also allows them to be laid over irregular shapes and structures without damaging the plants they are meant to protect [535,537,538]. Exposure to sunlight and changing climatic conditions can degrade many materials, but polymers used in protective nets are often treated or are inherently resistant to UV radiation. This resistance ensures that the nets maintain their structural integrity and continue to function effectively over time, even when exposed to direct sunlight for extended periods. Additionally, polymer nets can be designed to withstand various environmental conditions, such as extreme temperatures, humidity, and precipitation, making them suitable for use in different climatic zones [536,539,540]. One of the primary functions of protective nets is to deter pests and diseases. Polymer nets can be designed with specific mesh sizes to prevent insects and birds from penetrating while allowing air, light, and moisture access to the crops. This selective barrier minimizes the need for chemical pesticides, contributing to more sustainable agricultural practices. Moreover, the application of polymers can include the introduction of antimicrobial properties, further reducing the risk of disease spread among plants [541,542]. Besides providing physical protection, some polymer nets are tasked with diffusing light and moderating the temperature, creating a microclimate more favorable for plant growth. By controlling the amount and intensity of the sunlight reaching the plants, these nets can help prevent problems such as sunburn and heat stress, promoting healthier and more productive crops [543,544].

In conclusion, polymers are essential components in the production of protective agricultural nets, offering a versatile solution to crop protection challenges. By providing a physical barrier against pests and diseases, moderating environmental conditions, and promoting sustainable agricultural practices, polymer-based nets contribute significantly to enhancing the crop yield and quality.

#### 10.7. Artificial Substrates

The application of polymers in the production of artificial substrates for plants presents a fascinating utilization of these versatile materials, bridging the field of materials science with botany. Artificial substrates play a crucial role in various gardening and agricultural practices, serving as an alternative to natural soil for plant growth and support. Polymers, due to their wide range of properties and the possibility of customization through specific additives, play a significant role in the development and efficiency of these substrates. Let us delve into the key aspects of utilizing polymers in creating artificial substrates for plants [545,546].

In the subsequent stages of plastic production, various additives such as stabilizers or modifiers are often necessary. This adaptability of polymers is crucial in creating artificial substrates. By adding specific stabilizers or modifiers, manufacturers can tailor the physical properties of polymer-based substrates, such as porosity, water retention, and aeration, to meet the specific needs of different plant species. This ability to precisely tune substrate properties ensures that plant roots have access to the right amount of water, air, and nutrients, promoting healthier growth and development [546].

Another advantage of polymer-based artificial substrates is the possibility of a controlled nutrient release. By incorporating nutrients directly into the polymer matrix or coating polymer particles with slow-release fertilizers, manufacturers can create substrates that provide plants with sustained nutrition. This controlled release mechanism ensures a

steady supply of essential nutrients to plants over time, optimizing growth and reducing the likelihood of nutrients leaching into the environment [463,546].

#### 10.8. Micro- and Nanoplastics

Micro- and nanoplastics are gaining attention in various fields, including agrochemistry, where they can bring benefits, but also raise concerns about health and the environment. The application of micro- and nanoplastics in agrochemistry includes:

- Delivering nutrients and plant protection agents—micro- and nanoplastics can be used as carriers for the controlled release of nutrients and plant protection agents. Thanks to their small sizes, these particles can more easily penetrate the soil and reach plant roots, allowing for a more efficient delivery of nutrients or pesticides directly to the plant, reducing losses and limiting negative environmental impacts.
- Improving soil properties—microplastics can be added to soil to enhance its physical properties, such as water retention or structure. They can help maintain soil moisture, which is beneficial in dry regions and may reduce the need for frequent irrigation.
- Supporting plant development—some studies suggest that nanoplastics can affect plant growth and development. For example, they may support root growth or improve plant resistance to abiotic stresses, such as drought or salinity [547–549].

Micro- and nanoplastics can enter the environment in various ways, especially in the context of agrochemistry. Here are some key pathways through which these tiny particles can enter the environment.

Use in agrochemical products:

- Plant protection products and fertilizers: Micro- and nanoplastics are sometimes added to plant protection products and fertilizers as carriers of active substances or to improve product properties, such as increasing stability or the controlled release of ingredients. During their application in fields, some of these plastics can be directly introduced into the soil.
- Soil property modification: In some cases, microplastics are intentionally added to soil to improve its structure or water retention capabilities. These plastics can degrade over time into even smaller nanoplastics, which more easily penetrate the soil and groundwater [549–552].

Loss during production and transport:

- Loss during production: micro- and nanoplastics can be released into the environment during the production of agrochemicals due to leaks, breaches, or improper waste disposal.
- Loss during transport: during the transport of agrochemical products, microplastics can be accidentally released into the environment, for example, through leakage or dispersion as a result of an accident [550,551,553].

Degradation of plastic materials used in agriculture:

- Plastic covers and mulch: Various types of plastics, such as for creating polytunnels, windbreaks, or as mulch on cultivated fields, are widely used in agriculture. These materials degrade over time, leading to the formation of micro- and nanoplastics that can be carried by the wind and water.
- Irrigation systems: plastic components of irrigation systems, such as pipes and drip emitters, can erode over time, releasing microplastics into the soil and water systems.
- Washing off from cultivated fields: micro- and nanoplastics can be washed off from cultivated fields by rain or during irrigation, making their way into surface and groundwater, and from there, they can enter the wider environment, including seas and oceans.
- Impact on biota: micro- and nanoplastics can be ingested by animals, including insects, soil worms, and microorganisms, which may lead to their accumulation in food chains [356,554–556].

Despite potential benefits, there are also serious concerns about the use of micro- and nanoplastics in agrochemistry. The accumulation of micro- and nanoplastics in the environment and their potential impact on human health and ecosystems are subjects of intense research. Implementing appropriate waste management practices, developing more sustainable production and application methods for agrochemicals, and seeking biodegradable alternatives to plastics are crucial in minimizing this phenomenon [554,555,557,558]. Current research focuses on assessing the impact of micro- and nanoplastics on the environment and human health, as well as developing biodegradable alternatives that could minimize the negative effects of their use. Regulations regarding the use of these materials in agrochemistry continue to evolve as we deepen our understanding of their potential effects [557,559–561].

Polymers constitute a vast sector encompassing a range of materials with highly diverse properties. None are without flaws, yet they present a variety of advantages listed in Table 6. Researchers continue to develop new synthetic materials with innovative properties and applications. New prototypes emerge daily, and while the applications of polymers mentioned previously do not fully exhaust the subject, they provide an overview of the extensive use of plastics in today's world.

**Table 6.** Advantages and disadvantages of utilizing polymers in agriculture.

| Application                      | Advantages                                                                                                                  | Disadvantages                                                                                                               | References                                |
|----------------------------------|-----------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|
| Seeds Coating                    | Seed protection;<br>Enhanced germination;<br>Targeted delivery of nutrients and pesticides;<br>Increased sowing efficiency. | Costs;<br>Environmental concerns;<br>Potential risk to soil microflora;<br>Technology dependence.                           | [432,435–440]                             |
| Soil Erosion Control             | Soil stabilization;<br>Enhanced water retention;<br>Durability;<br>Versatility.                                             | Environmental implications;<br>Costs;<br>Effectiveness limitations;<br>Application challenges;<br>Potential removal issues. | [453,454,461–466]                         |
| Tunnel and Greenhouse Protection | Weather resistance;<br>Thermal insulation;<br>Pest and disease protection;<br>Ease of installation.                         | Costs;<br>Degradation;<br>Ventilation limitations;<br>Maintenance;<br>Challenges.                                           | [477–479,482,483,491,492,495,496,498–500] |
| Packaging                        | Lightweight;<br>Corrosion resistance;<br>Versatility;<br>Low production cost.                                               | Disposal challenges;<br>Environmental impact;<br>Degradation issues;<br>Potential health hazards.                           | [509–511,513,516]                         |
| Hoses and Irrigation Systems     | Flexibility;<br>Corrosion resistance;<br>Lightweight;<br>Mechanical durability.                                             | Environmental impact;<br>Potential health hazards;<br>Repair difficulties;<br>Temperature limitations.                      | [525–527,530–532]                         |
| Protective Nets                  | Weather resistance;<br>Flexibility;<br>Durability;<br>Ease of installation.                                                 | Costs;<br>Disposal challenges;<br>Potential animal hazards;<br>Susceptibility to damage.                                    | [534–537,540,543]                         |
| Artificial Substrates            | Control over composition and structure;<br>Durability;<br>Hygienic conditions;<br>Lightweight.                              | Costs;<br>Potential retention of chemical substances;<br>Water and air permeability limitation;<br>Environmental concerns.  | [545,546]                                 |
| Micro- and Nanoplastics          | Versatility of applications;<br>Lightweight;<br>Durability;<br>Ease of forming.                                             | Environmental pollution;<br>Bioaccumulation;<br>Public health risks;<br>Biodiversity disruption.                            | [548–550,555,556,559,560]                 |

## 11. Conclusions

In conclusion, this review highlights the significant impact of both traditional, non-degradable plastics and environmentally friendly bioplastics, such as poly(vinyl alcohol), poly(butylene adipate-co-terephthalate), poly(butylene succinate-co-adipate), poly(lactic acid), or starch-based polymers, on the agricultural sector in the face of the global plastic waste crisis. Polymers are effectively used in smart-carrier systems for agrochemicals with prolonged release, functional polymers for pest control, and super absorbents to enhance crop health under drought conditions. They are also widely utilized as mulching films, membranes, mats, non-woven fabrics, protective nets, seed coatings, agrochemical packaging, and greenhouse coverings. These applications, along with their being in artificial substrates for sustained nutrient delivery, demonstrate the essential nature of polymers in agriculture and packaging industries.

It is essential to consider that approximately 12.5 million tons of plastics, including 7.5 Mt of plastic films, are used annually in agricultural production globally, accounting for around 3.5 percent of the global plastic production (359 million tons) [1]. In Europe alone, plastic consumption in agriculture has increased from 4.3% in 2018 to 4.9% in 2022 [562]. Given their extensive use and limited sustainable alternatives, it is unlikely that polymers can be entirely eliminated in the near future to prevent soil and surface water plastic pollution, despite concerns about their toxicity and persistence.

However, some synthetic and semi-synthetic polymers, such as chitosan, nanocellulose, and  $\beta$ -cyclodextrin, exhibit high adsorption capacities for removing organophosphate pesticides (glyphosate, ethoprophos, and chlorpyrifos) and triazines (atrazine) from agricultural runoff. These materials demonstrate potential as alternatives to conventional adsorbents like charcoal and some biopolymers. The review also discusses the potential of bio-based materials as viable alternatives to conventional polyolefins and other environmentally persistent polymers.

Bio-based polymers align with innovative agricultural advancements aimed at increasing productivity while reducing plastic contamination and minimizing adverse ecotoxicological impacts on both aquatic and terrestrial ecosystems. Compostable bioplastics with their global production capacity are projected to rise from 2.2 million metric tons in 2022 to 7.4 million metric tons by 2028 [563]. The global market value of bioplastics is expected to reach USD 1353.3 billion by 2033, a significant increase from USD 96.6 billion in 2023 [564,565]. These trends highlight the need for integrating bio-based and sustainable polymers into agricultural practices to curb plastic waste. Moreover, 175 countries have agreed to negotiate a legally binding Plastics Treaty (UNEA-5.2) to address plastic pollution, reflecting global commitment towards sustainable solutions in the agricultural sector [566–568]. Despite these advancements, there is a pressing need to adopt more “green” polymers to align with ecological trends in modern agriculture. This strategic shift towards sustainable materials presents a significant opportunity to foster a more productive and environmentally responsible agricultural sector.

It is also recognized that it is necessary to undertake law-making work on the creation of uniform regulations of EU law that would guarantee environmental and climate protection on the issues discussed in the publication. In light of the considerations made, a desirable outcome would be the creation of such legal regulations that would allow conventional plastics to be replaced in whole or in part by producing them from bio-based raw materials that could decompose at the end of their useful life. All the EU actions taken so far should result in future changes to EU environmental and climate law.

**Author Contributions:** Conceptualization, P.R. and H.F.; validation, P.R., H.F. and K.L.; writing—original draft preparation, K.L., I.S., D.R., M.W., J.L., A.N.-Z., I.Z., S.C., I.P., H.F. and P.R. writing—review and editing, P.R. and H.F.; visualization, K.L., D.R. and I.S.; supervision, P.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

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

### Abbreviations and Acronyms

|        |                                                                       |               |                                                                                 |
|--------|-----------------------------------------------------------------------|---------------|---------------------------------------------------------------------------------|
| PE     | polyethylene                                                          | SCCA          | starch–chitosan–calcium alginate                                                |
| PP     | polypropylene                                                         | SCA           | starch alginate–calcium                                                         |
| PVC    | polyvinyl chloride                                                    | CCA           | chitosan–calcium alginate                                                       |
| EU     | European Union                                                        | CaA           | calcium alginate                                                                |
| EC     | European Commission                                                   | SA-L          | alginate–lignin                                                                 |
| EGD    | European Green Deal                                                   | YMP           | yerba mate powder                                                               |
| REACH  | Registration, Evaluation, Authorisation, and Restriction of Chemicals | NPK-HA/Alg    | hydroxyapatite/alginate                                                         |
| PVA    | poly(vinyl alcohol)                                                   | HA/Alg        | hydroxyapatite/alginate                                                         |
| PBAT   | poly(butylene adipate-co-terephthalate)                               | SNCs          | starch nanocrystals                                                             |
| PBSA   | poly(butylene succinate-co-adipate)                                   | TMX           | thiamethoxam                                                                    |
| PLA    | poly(lactic acid)                                                     | PEG           | polyethylene glycol                                                             |
| PCL    | poly $\epsilon$ -caprolactone                                         |               |                                                                                 |
| PBS    | polybutylene succinate                                                | GLY           | glycerol                                                                        |
| PHA    | polyhydroxy alkanates                                                 | CF-2          | composition in weight percent of the SA/PVA/GLY 55:28:17                        |
| PHB    | poly 3-hydroxybutyrate                                                | CMS/XG        | carboxymethyl starch/xanthan gum                                                |
| PET    | polyethylene terephthalate                                            | PDXE MG       | biodegradable dextrin-based microgels                                           |
| PS     | polystyrene                                                           | PDX MG        | unfunctionalized microgels                                                      |
| PTFE   | polytetrafluoroethylene                                               | PHV           | polyhydroxyvalerates                                                            |
| PU     | polyurethanes                                                         | PLGA—PEG—PLGA | poly(l-lactide-co-glycolide)—poly(ethylene glycol)—poly(l-lactide-co-glycolide) |
| PC     | polycarbonates                                                        | HV            | 3-hydroxyvalerat                                                                |
| PVDF   | polyvinylidene fluoride                                               | LC            | $\lambda$ -cyhalothrin                                                          |
| PCTFE  | polychlorotrifluoroethylene                                           | BCRNF         | biochar-based controlled-release nitrogen fertilizer                            |
| UV     | ultraviolet light                                                     | GG            | guar gum                                                                        |
| GMOs   | genetically modified organisms                                        | HNT           | halloysite nanotubes                                                            |
| PHBV   | poly 3-hydroxybutyrate-co-3-hydroxyvalerate                           | MMt           | montmorillonite clay                                                            |
| CS     | chitosan                                                              | CS-g-PCL      | poly( $\epsilon$ -caprolactone)-chitosan                                        |
| SRF    | slow-release fertilizers                                              | 2,4,6-TCP     | 2,4,6-trichlorophenol                                                           |
| CRF    | controlled-release fertilizers                                        | CS/ZA         | chitosan/zeolite-A nanocomposite                                                |
| WHO    | World Health Organization                                             | AC            | acephate                                                                        |
| NPK    | fertilizers with nitrogen, phosphorus, and potassium                  | OM            | omthosate                                                                       |
| DAP    | diammonium phosphate                                                  | MP            | methyl parathion                                                                |
| SSP    | single superphosphate                                                 | CS/Gel        | chitosan/gelatin                                                                |
| CRS    | controlled-released system                                            | (MMT)-CuO     | biopolymer-modified montmorillonite                                             |
| CR     | controlled release                                                    | PEI           | polyethyleneimine                                                               |
| SCCS   | controlled-release suspension                                         | MSNPs/PANI    | meso-sorbent silica/polyaniline                                                 |
| CAP    | chitosan-encapsulated chlorantraniliprole                             | $\beta$ -CD   | $\beta$ -cyclodextrin                                                           |
| CTS    | CAP/Chitosan                                                          | CD            | cyclodextrin                                                                    |
| DEACMS | 7-diethylaminocoumarin-4-yl)methyl succinate                          | MIP           | imprinted polymer                                                               |
| CMCS   | carboxymethyl chitosan                                                | CBL           | carbaryl                                                                        |
| 2,4-D  | 2,4-dichlorophenoxyacetic acid                                        | CBF           | carbofuran                                                                      |
| NPs    | nanoparticles                                                         | MTMC          | metolcarb                                                                       |
| Alg    | alginate                                                              | MWCNTs        | multi-walled carbon nanotubes                                                   |
| Cn     | cenosphere                                                            | OPPs          | organophosphorus pesticides                                                     |
| IMI    | imidacloprid                                                          | poly-NIPAM    | poly-N-isopropylacrylamide                                                      |
| GST    | glutaraldehyde-saturated toluene                                      | NIPAM         | N-isopropylacrylamide                                                           |

|          |                                                                                 |        |                                       |
|----------|---------------------------------------------------------------------------------|--------|---------------------------------------|
| CP/DP    | between the continuous phase and the dispersed phase                            | PM     | Pendimethalin                         |
| CsGC     | chitosan–clay composite                                                         | MBA    | N,N'-methylenebisacrylamide           |
| CA       | cellulose acetate                                                               | AC     | activated carbon                      |
| CMC      | carboxymethyl cellulose                                                         | CYM    | cymoxanil                             |
| HEC      | hydroxyethyl cellulose                                                          | IMD    | imidacloprid                          |
| EC       | ethyl cellulose                                                                 | PAN    | polyacrylonitrile                     |
| NFC      | nanofibrillated cellulose                                                       | PES    | polyethersulfone                      |
| IPDI     | isophorone diisocyanate                                                         | PSf    | polysulfone                           |
|          |                                                                                 | PVAc   | polyvinyl acetate                     |
|          |                                                                                 | TFC    | thin film composites                  |
| CS/CMC   | chitosan/carboxyme<br>thylcellulose copolymer                                   | MNPs   | micro- and nanoplastics               |
| AVM      | avermectin                                                                      | PAC    | pro-oxidant additives                 |
| DMDAAC   | diallyldimethylammonium chloride                                                | Oxo-PP | oxo-degradable polypropylene          |
| CMC-g-PD | carboxymethylcellulose/diallyl                                                  | BDM    | biodegradable mulch                   |
| MDAAC    | dimethylammonium chloride                                                       | TXG    | tamarind xyloglucan                   |
| P-Zein   | phosphorylated zein                                                             | BA     | benzoic anhydride                     |
| RS       | rosin                                                                           | TPS    | thermoplastic starch                  |
| BP       | bispiribac                                                                      | PPC    | polypropylene carbonate               |
| ECH      | epichlorohydrin                                                                 | SAH    | superabsorbent hydrogel               |
| CNF      | cellulose nanofibers                                                            | WAP    | water-absorbing polymers              |
| CMC-g    | carboxymethylcellulose-g-                                                       | WAC    | water-absorbing capacity              |
| -PAM     | polyacrylamide copolymer                                                        | SHC    | superabsorbent hydrogel composite     |
| DIN      | dinotefuran                                                                     | SHNC   | superabsorbent hydrogel nanocomposite |
| SA       | sodium alginate                                                                 | IPN    | semi-interpenetrating polymer         |
| GEL      | gelatin                                                                         | APP    | patterns of pure fertilizer           |
| PVP      | polyvinylpyrrolidone                                                            | SAP    | superabsorbent polyme                 |
| PK       | polydopamine modified kaolin                                                    | PAM    | polyacrylamide                        |
| ASO      | amino-silicone oil                                                              | EVA    | ethylene–vinyl acetate                |
| DND      | detonation nanodiamond                                                          |        |                                       |
| PNIPAm   | poly(N-isopropylacrylamide)                                                     |        |                                       |
| IPKCP    | imidacloprid/polydopamine-modified                                              | LDPE   | low-density polyethylene              |
| D-ASO    | kaolin/amino-silicone oil/detonation<br>nanodiamond/poly(N-isopropylacrylamide) | HDPE   | high-density polyethylene             |

## References

1. *Assessment of Agricultural Plastics and Their Sustainability: A Call for Action*; FAO: Rome, Italy, 2021; ISBN 978-92-5-135402-5.
2. Gao, H.; Liu, Q.; Yan, C.; Mancl, K.; Gong, D.; He, J.; Mei, X. Macro-and/or Microplastics as an Emerging Threat Effect Crop Growth and Soil Health. *Resour. Conserv. Recycl.* **2022**, *186*, 106549. [\[CrossRef\]](#)
3. Mitrano, D.M.; Wagner, M. A Sustainable Future for Plastics Considering Material Safety and Preserved Value. *Nat. Rev. Mater.* **2022**, *7*, 71–73. [\[CrossRef\]](#)
4. Penczek, S.; Pretula, J.; Lewiński, P. Polimery z odnawialnych surowców, polimery biodegradowalne. *Polimery* **2013**, *58*, 835–846. [\[CrossRef\]](#)
5. Malinowski, R. Biotworzywa jako nowe materiały przyjazne środowisku naturalnemu. *Inż. Ochr. Śr.* **2015**, *18*, 215–231.
6. Consolidated Version of the Treaty on the Functioning of the European Union, Article 11 and 191–193. 2012, 326. Available online: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:12012E/TXT> (accessed on 21 June 2024).
7. Transforming Our World: The 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs. Available online: <https://sdgs.un.org/2030agenda> (accessed on 25 June 2024).
8. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A New Circular Economy Action Plan For a Cleaner and More Competitive Europe. COM(2020) 98 Final. Brussels, 11.3.2020. 2020. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN> (accessed on 23 June 2024).
9. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions EU. Policy Framework on Biobased, Biodegradable and Compostable Plastics. COM(2022) 682 Final. Brussels, 30.11.2022. 2022. Available online: <https://Eur-Lex.Europa.Eu/Legal-Content/EN/ALL/?uri=CELEX:52022DC0682> (accessed on 23 June 2024).

10. European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions EU. The European Green Deal. COM(2019) 640 Final. Brussels, 11.12.2019. 2019. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN> (accessed on 23 June 2024).
11. European Parliament. European Parliament Resolution of 10 February 2021 on the New Circular Economy Action Plan (2020/2077(INI). 2021. Available online: [https://Www.Europarl.Europa.Eu/Doceo/Document/TA-9-2021-0040\\_EN.Html](https://Www.Europarl.Europa.Eu/Doceo/Document/TA-9-2021-0040_EN.Html) (accessed on 23 June 2024).
12. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A European Strategy for Plastics in a Circular Economy. COM(2018) 28 Final. Brussels, 16.1.2018. 2021. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2018:28:FIN> (accessed on 24 June 2024).
13. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Pathway to a Healthy Planet for All EU Action Plan: “Towards Zero Pollution for Air, Water and Soil”. COM(2021) 400 Final. Brussels, 12.5.2021. 2021. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0400> (accessed on 24 June 2024).
14. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Soil Strategy for 2030 Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate. COM/2021/699 Final. Brussels, 17.11.2021. 2020. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021DC0699> (accessed on 24 June 2024).
15. Scientific Advice Mechanism to the European Institutions. Biodegradability of Plastics in the Open Environment. Available online: <https://Scientificadvice.Eu/Advice/Biodegradability-of-Plastics-in-the-Open-Environment/> (accessed on 24 June 2024).
16. European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System. COM(2020) 381 Final. Brussels, 20.5.2020. 2020. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381> (accessed on 24 June 2024).
17. European Union. Proposal for a Regulation of the European Parliament and of the Council on the Sustainable Use of Plant Protection Products and Amending (EU) 2011/2015. COM(2022) 305 Final. Brussels, 22.6.2022. 2022. Available online: <https://Eur-Lex.Europa.Eu/Legal-Content/EN/TXT/?uri=CELEX:52022PC0305> (accessed on 24 June 2024).
18. European Council. Council of the EU. Circular Economy. Decoupling Economic Growth from Resource Use and Shifting to Circular Systems in Production and Consumption Is Key to Achieving EU Climate Neutrality by 2050. Available online: <https://www.consilium.europa.eu/en/policies/circular-economy/> (accessed on 25 June 2024).
19. European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Commission Work Programme 2018 An Agenda for a More United, Stronger and More Democratic Europe. COM(2017) 650 Final. Strasbourg, 24.10.2017. 2017. Available online: <https://Eur-Lex.Europa.Eu/Legal-Content/EN/TXT/?uri=COM:2017:650:FIN> (accessed on 24 June 2024).
20. European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop—An EU Action Plan for the Circular Economy. COM(2015) 614 Final. Brussels, 2.12.2015. 2015. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614> (accessed on 24 June 2024).
21. European Union. European Parliament and Council Directive (94/62/EC) of 20 December 1994 on Packaging and Packaging Waste. 1994, 365. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31994L0062> (accessed on 24 June 2024).
22. European Union. European Parliament and Council Directive (2008/56/EC) of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive). 2008, 164. Available online: <https://Eur-Lex.Europa.Eu/Legal-Content/EN/ALL/?uri=CELEX:32008L0056> (accessed on 24 June 2024).
23. European Union. Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment. 2021. Available online: <https://eur-lex.europa.eu/eli/dir/2019/904/oj> (accessed on 24 June 2024).
24. Montanarella, L.; Panagos, P. The Relevance of Sustainable Soil Management within the European Green Deal. *Land Use Policy* **2021**, *100*, 104950. [CrossRef]
25. The European Environment—State and Outlook 2020: Knowledge for Transition to a Sustainable Europe. Available online: [https://www.eea.europa.eu/soer/2020/copy\\_of\\_intro](https://www.eea.europa.eu/soer/2020/copy_of_intro) (accessed on 25 June 2024).
26. State of Knowledge of Soil Biodiversity—Status, Challenges and Potentialities | Policy Support and Governance | Food and Agriculture Organization of the United Nations. Available online: <https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1363310/> (accessed on 25 June 2024).
27. European Union. Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on Environmental Liability with Regard to the Prevention and Remedying of Environmental Damage. Available online: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32004L0035> (accessed on 25 June 2024).

28. European Union. Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge Is Used in Agriculture. 1986, 181. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31986L0278> (accessed on 24 June 2024).
29. European Union. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). Available online: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32010L0075> (accessed on 25 June 2024).
30. European Union. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. 2008, 312. Available online: <https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX:32008L0098> (accessed on 24 June 2024).
31. European Union. Regulation (EU) 2023/839 of the European Parliament and of the Council of 19 April 2023 Amending Regulation (EU) 2018/841 as Regards the Scope, Simplifying the Reporting and Compliance Rules, and Setting out the Targets of the Member States for 2030, and Regulation (EU) 2018/1999 as Regards Improvement in Monitoring, Reporting, Tracking of Progress and Review (LULUCEA). Available online: <https://eur-lex.europa.eu/eli/reg/2023/839/oj> (accessed on 25 June 2024).
32. European Union. Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), Establishing a European Chemicals Agency, Amending Directive 1999/45/EC and Repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as Well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02006R1907-20221217> (accessed on 25 June 2024).
33. European Agency for Safety and Health at Work. REACH—Regulation for Registration, Evaluation, Authorisation and Restriction of Chemicals. Available online: <https://osha.europa.eu/en/themes/dangerous-substances/reach> (accessed on 25 June 2024).
34. European Commission. Chemicals Strategy. The EU's Chemicals Strategy for Sustainability towards a Toxic-Free Environment. Available online: [https://environment.ec.europa.eu/strategy/chemicals-strategy\\_en](https://environment.ec.europa.eu/strategy/chemicals-strategy_en) (accessed on 25 June 2024).
35. Smreczak, B.; Ukalska-Jaruga, A.; Ciepiel, J. *Zrównoważone Użytkowanie Gleb Rolniczych w Polityce Unii Europejskiej do 2050 R*; Instytut Uprawy Nawożenia i Gleboznawstwa: Puławy, Poland, 2021; pp. 9–26, ISBN 978-83-7562-366-6.
36. Köninger, J.; Panagos, P.; Jones, A.; Briones, M.J.I.; Orgiazzi, A. In Defence of Soil Biodiversity: Towards an Inclusive Protection in the European Union. *Biol. Conserv.* **2022**, *268*, 109475. [CrossRef]
37. Hofmann, T.; Ghoshal, S.; Tufenkji, N.; Adamowski, J.F.; Bayen, S.; Chen, Q.; Demokritou, P.; Flury, M.; Hüffer, T.; Ivleva, N.P.; et al. Plastics Can Be Used More Sustainably in Agriculture. *Commun. Earth Environ.* **2023**, *4*, 332. [CrossRef]
38. Puoci, F.; Iemma, F.; Spizzirri, U.G.; Cirillo, G.; Curcio, M.; Picci, N. Polymer in Agriculture: A Review. *Am. J. Agric. Biol. Sci.* **2008**, *3*, 299–314. [CrossRef]
39. Szewczyk, P.; Lichnowski, W. Present and Prospective Use of Polyolefins and Poly(Vinyl Chloride) in Polish Agriculture. *Polimery* **1984**, *29*, 385–386. [CrossRef]
40. Yang, N.; Feng, L.; Li, K.; Feng, C.; Sun, Z.; Liu, J. The Degradable Time Evaluation of Degradable Polymer Film in Agriculture Based on Polyethylene Film Experiments. *e-Polymers* **2021**, *21*, 821–829. [CrossRef]
41. Wang, T.; Yu, C.; Chu, Q.; Wang, F.; Lan, T.; Wang, J. Adsorption Behavior and Mechanism of Five Pesticides on Microplastics from Agricultural Polyethylene Films. *Chemosphere* **2020**, *244*, 125491. [CrossRef] [PubMed]
42. Mansoor, Z.; Tchenbou-Magaia, F.; Kowalczyk, M.; Adamus, G.; Manning, G.; Parati, M.; Radecka, I.; Khan, H. Polymers Use as Mulch Films in Agriculture—A Review of History, Problems and Current Trends. *Polymers* **2022**, *14*, 5062. [CrossRef] [PubMed]
43. Zhang, G.; Zhang, S.; Xia, Z.; Wu, M.; Bai, J.; Lu, H. Effects of Biodegradable Film and Polyethylene Film Residues on Soil Moisture and Maize Productivity in Dryland. *Agriculture* **2023**, *13*, 332. [CrossRef]
44. Ghatge, S.; Yang, Y.; Ahn, J.-H.; Hur, H.-G. Biodegradation of Polyethylene: A Brief Review. *Appl. Biol. Chem.* **2020**, *63*, 27. [CrossRef]
45. Nourbakhsh, A.; Ashori, A.; Kazemi Tabrizi, A. Characterization and Biodegradability of Polypropylene Composites Using Agricultural Residues and Waste Fish. *Compos. Part B Eng.* **2014**, *56*, 279–283. [CrossRef]
46. Nor Arman, N.S.; Chen, R.S.; Ahmad, S. Review of State-of-the-Art Studies on the Water Absorption Capacity of Agricultural Fiber-Reinforced Polymer Composites for Sustainable Construction. *Constr. Build. Mater.* **2021**, *302*, 124174. [CrossRef]
47. Marasovic, P. Overview and Perspective of Nonwoven Agrotexile. *Text. Leather Rev.* **2019**, *2*, 32–45. [CrossRef]
48. Azam, F.; Ahmad, S. Fibers for Agro Textiles. In *Fibers for Technical Textiles*; Ahmad, S., Rasheed, A., Nawab, Y., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 151–168, ISBN 978-3-030-49224-3.
49. Dorugade, V.; Taye, M.; Qureshi, S.A.; Agazie, T.; Seyoum, B.; Abebe, B.; Komarabathina, S. Agrotexiles: Important Characteristics of Fibres and Their Applications—A Review. *J. Nat. Fibers* **2023**, *20*, 2211290. [CrossRef]
50. Maddah, H.A. Polypropylene as a Promising Plastic: A Review. *Am. J. Polym. Sci.* **2016**, *6*, 1–11.
51. Alsabri, A.; Tahir, F.; Al-Ghamdi, S.G. Environmental Impacts of Polypropylene (PP) Production and Prospects of Its Recycling in the GCC Region. *Mater. Today Proc.* **2022**, *56*, 2245–2251. [CrossRef]
52. Vera, P.; Canellas, E.; Nerin, C. Compounds Responsible for Off-Odors in Several Samples Composed by Polypropylene, Polyethylene, Paper and Cardboard Used as Food Packaging Materials. *Food Chem.* **2020**, *309*, 125792. [CrossRef] [PubMed]
53. Application of Plastics in Livestock Production: An Overview The Indian Journal of Animal Sciences. Available online: <https://epubs.icar.org.in/ejournal/index.php/IJAnS/article/view/114140> (accessed on 19 May 2024).

54. Borreani, G.; Tabacco, E. 9—Plastics in Animal Production. In *A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture*; Orzolek, M.D., Ed.; Plastics Design Library; Elsevier: Amsterdam, The Netherlands, 2017; pp. 145–185, ISBN 978-0-08-102170-5.
55. Zegardło, B.; Maraveas, C.; Świeczka, K.; Bombik, A. Recycling Waste Agricultural Nets as Cement Composites. *Materials* **2024**, *17*, 1828. [\[CrossRef\]](#)
56. Piehl, S.; Leibner, A.; Löder, M.G.J.; Dris, R.; Bogner, C.; Laforsch, C. Identification and Quantification of Macro- and Microplastics on an Agricultural Farmland. *Sci. Rep.* **2018**, *8*, 17950. [\[CrossRef\]](#)
57. Zhou, B.; Wang, J.; Zhang, H.; Shi, H.; Fei, Y.; Huang, S.; Tong, Y.; Wen, D.; Luo, Y.; Barceló, D. Microplastics in Agricultural Soils on the Coastal Plain of Hangzhou Bay, East China: Multiple Sources Other than Plastic Mulching Film. *J. Hazard. Mater.* **2020**, *388*, 121814. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Abdulmouti, H.; Bourezg, A.; Ranjan, R. Exploring the Applicability of Agrivoltaic System in UAE and Its Merits. In Proceedings of the 2023 Advances in Science and Engineering Technology International Conferences (ASET), Dubai, United Arab Emirates, 20–23 February 2023; pp. 1–6.
59. Agriculture | Free Full-Text | Advancement in Agriculture Approaches with Agrivoltaics Natural Cooling in Large Scale Solar PV Farms. Available online: <https://www.mdpi.com/2077-0472/13/4/854> (accessed on 19 May 2024).
60. Scarascia-Mugnozza, G.; Sica, C.; Russo, G. Plastic materials in european agriculture: Actual use and perspectives. *J. Agric. Eng.* **2011**, *42*, 15–28. [\[CrossRef\]](#)
61. Brown, R.P. *Polymers in Agriculture and Horticulture*; iSmithers Rapra Publishing: Akron, OH, USA, 2004; ISBN 978-1-85957-460-7.
62. Liu, Y.; Zhou, C.; Li, F.; Liu, H.; Yang, J. Stocks and Flows of Polyvinyl Chloride (PVC) in China: 1980–2050. *Resour. Conserv. Recycl.* **2020**, *154*, 104584. [\[CrossRef\]](#)
63. Strength and Durability of Roofing PVC Membranes in the Conditions of Climate Impacts. Available online: <https://cyberleninka.ru/article/n/strength-and-durability-of-roofing-pvc-membranes-in-the-conditions-of-climate-impacts> (accessed on 20 May 2024).
64. Ambroziak, A.; Kłosowski, P. Mechanical Properties for Preliminary Design of Structures Made from PVC Coated Fabric. *Constr. Build. Mater.* **2014**, *50*, 74–81. [\[CrossRef\]](#)
65. Garrido, M.; António, D.; Lopes, J.G.; Correia, J.R. Reparability of Aged PVC Waterproofing Membranes: Effect of Joining Method. *J. Build. Eng.* **2021**, *33*, 101569. [\[CrossRef\]](#)
66. Chen, L.; Pelton, R.E.O.; Smith, T.M. Comparative Life Cycle Assessment of Fossil and Bio-Based Polyethylene Terephthalate (PET) Bottles. *J. Clean. Prod.* **2016**, *137*, 667–676. [\[CrossRef\]](#)
67. Simon, K.; Shanbhag, R.; Slocum, A.H. Reducing Evaporative Water Losses from Irrigation Ponds through the Reuse of Polyethylene Terephthalate Bottles. *J. Irrig. Drain. Eng.* **2016**, *142*, 06015005. [\[CrossRef\]](#)
68. The Future of Polyethylene Terephthalate Bottles: Challenges and Sustainability—Tsironi—2022—Packaging Technology and Science—Wiley Online Library. Available online: [https://onlinelibrary.wiley.com/doi/full/10.1002/pts.2632?casa\\_token=n0P0gO4HRR8AAAAA:Z\\_inWv0OuvoSkhv1nGigxAPTijpsDWFKBoJ6B095EyfNT0EcPPmcJgMxdIt6lvxEaPuHCveRtAFaUtZ](https://onlinelibrary.wiley.com/doi/full/10.1002/pts.2632?casa_token=n0P0gO4HRR8AAAAA:Z_inWv0OuvoSkhv1nGigxAPTijpsDWFKBoJ6B095EyfNT0EcPPmcJgMxdIt6lvxEaPuHCveRtAFaUtZ) (accessed on 20 May 2024).
69. Abhijith, R.; Ashok, A.; Rejeesh, C.R. Sustainable Packaging Applications from Mycelium to Substitute Polystyrene: A Review. *Mater. Today Proc.* **2018**, *5*, 2139–2145. [\[CrossRef\]](#)
70. Alzubi, E.; Kassem, A.; Noche, B. A Comparative Life Cycle Assessment: Polystyrene or Polypropylene Packaging Crates to Reduce Citrus Loss and Waste in Transportation? *Sustainability* **2022**, *14*, 12644. [\[CrossRef\]](#)
71. Kratky, B.A. Growing Lettuce in Non-Aerated, Non-Circulated Hydroponic Systems. *J. Veg. Sci.* **2005**, *11*, 35–42. [\[CrossRef\]](#)
72. Kacjan Maršić, N.; Mikulič-Petkovšek, M.; Hudina, M.; Veberič, R.; Slatnar, A. Leafy Asian Vegetables Cultivated on a Floating Hydroponic System and a Substrate Culture, during the Autumn Period in Greenhouse. *Acta Hortic.* **2021**, *1320*, 413–420. [\[CrossRef\]](#)
73. Protection against Frosts by Antifreeze, Amino Acids, and Vermicompost in Phenological Stages of the Bean. Available online: [https://www.scielo.org.mx/scielo.php?pid=S2007-09342023000900303&script=sci\\_arttext&tlng=en](https://www.scielo.org.mx/scielo.php?pid=S2007-09342023000900303&script=sci_arttext&tlng=en) (accessed on 20 May 2024).
74. Krasovitski, B.; Kimmel, E.; Rozenfeld, M.; Amir, I. Aqueous Foams for Frost Protection of Plants: Stability and Protective Properties. *J. Agric. Eng. Res.* **1999**, *72*, 177–185. [\[CrossRef\]](#)
75. Dhanumalayan, E.; Joshi, G.M. Performance Properties and Applications of Polytetrafluoroethylene (PTFE)—A Review. *Adv. Compos. Hybrid Mater.* **2018**, *1*, 247–268. [\[CrossRef\]](#)
76. Wang, R.; Xu, G.; He, Y. Structure and Properties of Polytetrafluoroethylene (PTFE) Fibers. *e-Polymers* **2017**, *17*, 215–220. [\[CrossRef\]](#)
77. Puts, G.J.; Crouse, P.; Ameduri, B.M. Polytetrafluoroethylene: Synthesis and Characterization of the Original Extreme Polymer. *Chem. Rev.* **2019**, *119*, 1763–1805. [\[CrossRef\]](#)
78. Yin, M.H.; Zhang, Y.C.; Zhou, R.M.; Zhai, Z.Y.; Wang, J.L.; Cui, Y.H.; Li, D.S. Friction Mechanism and Application of PTFE Coating in Finger Seals. *Tribol. Trans.* **2022**, *65*, 260–269. [\[CrossRef\]](#)
79. Jeong, D.-Y.; Cho, J.-H. Nanoceramic and Polytetrafluoroethylene Polymer Composites for Mechanical Seal Application at Low Temperature. *Bull. Korean Chem. Soc.* **2013**, *34*, 1345–1348. [\[CrossRef\]](#)
80. Rujnić Havstad, M.; Tucman, I.; Katančić, Z.; Pilipović, A. Influence of Ageing on Optical, Mechanical, and Thermal Properties of Agricultural Films. *Polymers* **2023**, *15*, 3638. [\[CrossRef\]](#) [\[PubMed\]](#)

81. Salapare, H.S., III; Guittard, F.; Noblin, X.; Givenchy, E.T.D.; Celestini, F.; Ramos, H.J. Stability of the Hydrophilic and Superhydrophobic Properties of Oxygen Plasma-Treated Poly(Tetrafluoroethylene) (PTFE) Surfaces. *J. Colloid Interface Sci.* **2013**, *396*, 287–292. [CrossRef] [PubMed]
82. Huber, S.; Moe, M.K.; Schmidbauer, N.; Hansen, G.H.; Herzke, D. *Emissions from Incineration of Fluoropolymer Materials*; Norwegian Institute for Air Research: Kjeller, Norway, 2009.
83. Akinay, A.E.; Tinçer, T.  $\gamma$ -Irradiated Poly(Tetrafluoroethylene) Particle-Filled Low-Density Polyethylene. II. UV Stability of LDPE in the Presence of 2°-PTFE Powder and Silane Coupling Agents. *J. Appl. Polym. Sci.* **1999**, *74*, 877–888. [CrossRef]
84. Jia, W.; Karapetrova, A.; Zhang, M.; Xu, L.; Li, K.; Huang, M.; Wang, J.; Huang, Y. Automated Identification and Quantification of Invisible Microplastics in Agricultural Soils. *Sci. Total Environ.* **2022**, *844*, 156853. [CrossRef] [PubMed]
85. Sung, W.B.; Seung, S.I. Physical Properties and Doping Characteristics of Polyaniline-Nylon 6 Composite Films. *Polymer* **1998**, *39*, 485–489. [CrossRef]
86. Water | Free Full-Text | Normal and Tangential Drag Forces of Nylon Nets, Clean and with Fouling, in Fish Farming. An Experimental Study. Available online: <https://www.mdpi.com/2073-4441/12/8/2238> (accessed on 20 May 2024).
87. Walsh, T. 34—The Plastic Piping Industry in North America. In *Applied Plastics Engineering Handbook*; Kutz, M., Ed.; Plastics Design Library; William Andrew Publishing: Oxford, UK, 2011; pp. 585–602, ISBN 978-1-4377-3514-7.
88. Shirzadi, M.H.; Arvin, M.J.; Abootalebi, A.; Hasandokht, M.R. Effect of Nylon Mulch and Some Plant Growth Regulators on Water Use Efficiency and Some Quantitative Traits in Onion (*Allium cepa* Cv.) under Water Deficit Stress. *Cogent Food Agric.* **2020**, *6*, 1779562. [CrossRef]
89. Babatunde, K.M.; Shittu, K.A.; Adekanmbi, O.A.; Asimi, M.A. The Influence of Colour and Thickness of Nylon Mulch on Soil Temperature, Moisture, Percent Germination and Some Growth Parameters of Cucumber (*Cucumis sativus* L.) Seedlings. *Land Sci.* **2020**, *2*, p13. [CrossRef]
90. Calibration of Soil Moisture Sensing with Subsurface Heated Fiber Optics Using Numerical Simulation—Benítez-Buelga—2016—Water Resources Research—Wiley Online Library. Available online: <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015WR017897> (accessed on 20 May 2024).
91. Huh, D.S.; Cooper, S.L. Dynamic Mechanical Properties of Polyurethane Block Polymers. *Polym. Eng. Sci.* **1971**, *11*, 369–376. [CrossRef]
92. Noreen, A.; Zia, K.M.; Zuber, M.; Tabasum, S.; Zahoor, A.F. Bio-Based Polyurethane: An Efficient and Environment Friendly Coating Systems: A Review. *Prog. Org. Coat.* **2016**, *91*, 25–32. [CrossRef]
93. Ghosh, A.; Chowdhury, S.R.; Dutta, R.; Babu, R.; Rumbo, C.; Dasgupta, N.; Mukherjee, P.; Das, N.C.; Ranjan, S. Polyurethane Chemistry for the Agricultural Applications—Recent Advancement and Future Prospects. In *Polyurethanes: Preparation, Properties, and Applications Volume 3: Emerging Applications*; ACS Symposium Series; American Chemical Society: Washington, DC, USA, 2023; Volume 1454, pp. 1–36.
94. Kaur, R.; Sharma, R.; Chahal, G.K. Synthesis of Lignin-Based Hydrogels and Their Applications in Agriculture: A Review. *Chem. Pap.* **2021**, *75*, 4465–4478. [CrossRef]
95. Tanasić, J.; Erceg, T.; Tanasić, L.; Baloš, S.; Klisurić, O.; Ristić, I. The Influence of Reaction Conditions on Structural Properties and Swelling Kinetics of Polyurethane Hydrogels Intended for Agricultural Purposes. *React. Funct. Polym.* **2021**, *169*, 105085. [CrossRef]
96. Kwon, J.K.; Khoshimkhujaev, B.; Lee, J.H.; Yu, I.H.; Park, K.S.; Choi, H.G. Growth and Yield of Tomato and Cucumber Plants in Polycarbonate or Glass Greenhouses. *Hortic. Sci. Technol.* **2017**, *35*, 79–87. [CrossRef]
97. Development of Procedure for Determination of Characteristics of Heated Polycarbonate Greenhouses. Available online: <https://cyberleninka.ru/article/n/development-of-procedure-for-determination-of-characteristics-of-heated-polycarbonate-greenhouses> (accessed on 20 May 2024).
98. Gohil, M.; Joshi, G. Chapter 18—Perspective of Polycarbonate Composites and Blends Properties, Applications, and Future Development: A Review. In *Green Sustainable Process for Chemical and Environmental Engineering and Science*; Altalhi, T., Inamuddin, Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 393–424, ISBN 978-0-323-99643-3.
99. Itoh, M.; Iwasaki, Y. Control of *Ralstonia Solanacearum* in Tomato Hydroponics Using a Polyvinylidene Fluoride Ultrafiltration Membrane. *Acta Hortic.* **2018**, *1227*, 299–304. [CrossRef]
100. Huang, F.Y.C.; Arning, A. Performance Comparison between Polyvinylidene Fluoride and Polytetrafluoroethylene Hollow Fiber Membranes for Direct Contact Membrane Distillation. *Membranes* **2019**, *9*, 52. [CrossRef]
101. Ghahramani, P.; Eldyasti, A.; Leung, S.N. Open-Cell Polyvinylidene Fluoride Foams as Carriers to Promote Biofilm Growth for Biological Wastewater Treatment. *Polym. Eng. Sci.* **2021**, *61*, 2161–2171. [CrossRef]
102. Engliman, N.S.; Jahim, J.M.; Abdul, P.M.; Ling, T.P.; Tan, J.P.; Ong, C.B. Effectiveness of Fouling Mechanism for Bacterial Immobilization in Polyvinylidene Fluoride Membranes for Biohydrogen Fermentation. *Food Bioprod. Process.* **2020**, *120*, 48–57. [CrossRef]
103. Saha, N.C.; Ghosh, A.K.; Garg, M.; Sadhu, S.D. Flexible Packaging Material—Manufacturing Processes and Its Application. In *Food Packaging: Materials, Techniques and Environmental Issues*; Saha, N.C., Ghosh, A.K., Garg, M., Sadhu, S.D., Eds.; Springer Nature: Singapore, 2022; pp. 47–87, ISBN 9789811642333.
104. Gardiner, J. Fluoropolymers: Origin, Production, and Industrial and Commercial Applications. *Aust. J. Chem.* **2014**, *68*, 13–22. [CrossRef]

105. Verma, K.; Sarkar, C.; Adam, S. Biodegradable Polymers for Agriculture. In *Biodegradable Polymers and Their Emerging Applications*; Saha, S., Sarkar, C., Eds.; Materials Horizons: From Nature to Nanomaterials; Springer: Berlin/Heidelberg, Germany, 2023; pp. 191–212. [\[CrossRef\]](#)
106. Agarwal, S. Biodegradable Polymers: Present Opportunities and Challenges in Providing a Microplastic-Free Environment. *Macromol. Chem. Phys.* **2020**, *221*, 2000017. [\[CrossRef\]](#)
107. Valdés García, A.; Ramos Santonja, M.; Sanahuja, A.B.; Selva, M.D.C.G. Characterization and Degradation Characteristics of Poly( $\epsilon$ -Caprolactone)-Based Composites Reinforced with Almond Skin Residues. *Polym. Degrad. Stab.* **2014**, *108*, 269–279. [\[CrossRef\]](#)
108. Yamamoto-Tamura, K.; Hiradate, S.; Watanabe, T.; Koitabashi, M.; Sameshima-Yamashita, Y.; Yarimizu, T.; Kitamoto, H. Contribution of Soil Esterase to Biodegradation of Aliphatic Polyester Agricultural Mulch Film in Cultivated Soils. *AMB Express* **2015**, *5*, 10. [\[CrossRef\]](#)
109. Li, N.; Sun, C.; Jiang, J.; Wang, A.; Wang, C.; Shen, Y.; Huang, B.; An, C.; Cui, B.; Zhao, X.; et al. Advances in Controlled-Release Pesticide Formulations with Improved Efficacy and Targetability. *J. Agric. Food Chem.* **2021**, *69*, 12579–12597. [\[CrossRef\]](#) [\[PubMed\]](#)
110. Kwiecien, I.; Adamus, G.; Jiang, G.; Radecka, I.; Baldwin, T.C.; Khan, H.R.; Johnston, B.; Pennetta, V.; Hill, D.; Bretz, I.; et al. Biodegradable PBAT/PLA Blend with Bioactive MCPA-PHBV Conjugate Suppresses Weed Growth. *Biomacromolecules* **2018**, *19*, 511–520. [\[CrossRef\]](#) [\[PubMed\]](#)
111. Jandas, P.J.; Mohanty, S.; Nayak, S.K. Sustainability, Compostability, and Specific Microbial Activity on Agricultural Mulch Films Prepared from Poly(Lactic Acid). *Ind. Eng. Chem. Res.* **2013**, *52*, 17714–17724. [\[CrossRef\]](#)
112. Sun, Y.; Mi, W.; Su, L.; Shan, Y.; Wu, L. Controlled-Release Fertilizer Enhances Rice Grain Yield and N Recovery Efficiency in Continuous Non-Flooding Plastic Film Mulching Cultivation System. *Field Crop. Res.* **2019**, *231*, 122–129. [\[CrossRef\]](#)
113. Merlini, C.; Lacotte, V.; Castro, V.O.; Perli, G.; Da Silva, P.; Livi, S. Novel Aphid-Repellent Fiber Mats Based on Poly(Lactic Acid)-Containing Ionic Liquids. *ACS Omega* **2024**, *9*, 5406–5417. [\[CrossRef\]](#)
114. Gowda, V.; Shivakumar, S. Agrowaste-Based Polyhydroxyalkanoate (PHA) Production Using Hydrolytic Potential of *Bacillus Thuringiensis* IAM 12077. *Braz. Arch. Biol. Technol.* **2014**, *57*, 55–61. [\[CrossRef\]](#)
115. Kalia, V.C. (Ed.) *Biotechnological Applications of Polyhydroxyalkanoates*; Springer: Singapore, 2019; ISBN 9789811337581.
116. Malinconico, M. (Ed.) *Soil Degradable Bioplastics for a Sustainable Modern Agriculture*; Green Chemistry and Sustainable Technology; Springer: Berlin/Heidelberg, Germany, 2017; ISBN 978-3-662-54128-9.
117. Matei, E.; Predescu, A.M.; Răpă, M.; Țurcanu, A.A.; Mateș, I.; Constantin, N.; Predescu, C. Natural Polymers and Their Nanocomposites Used for Environmental Applications. *Nanomaterials* **2022**, *12*, 1707. [\[CrossRef\]](#)
118. Singh, A.; Dhiman, N.; Kar, A.K.; Singh, D.; Purohit, M.P.; Ghosh, D.; Patnaik, S. Advances in Controlled Release Pesticide Formulations: Prospects to Safer Integrated Pest Management and Sustainable Agriculture. *J. Hazard. Mater.* **2020**, *385*, 121525. [\[CrossRef\]](#)
119. Philibert, T.; Lee, B.H.; Fabien, N. Current Status and New Perspectives on Chitin and Chitosan as Functional Biopolymers. *Appl. Biochem. Biotechnol.* **2017**, *181*, 1314–1337. [\[CrossRef\]](#)
120. Zhang, Z.; Yang, N.; Yu, J.; Jin, S.; Shen, G.; Chen, H.; Yuzhen, N.; Xiang, D.; Qian, K. Research Progress of a Pesticide Polymer-Controlled Release System Based on Polysaccharides. *Polymers* **2023**, *15*, 2810. [\[CrossRef\]](#)
121. Smola-Dmochowska, A.; Lewicka, K.; Macyk, A.; Rychter, P.; Pamuła, E.; Dobrzyński, P. Biodegradable Polymers and Polymer Composites with Antibacterial Properties. *Int. J. Mol. Sci.* **2023**, *24*, 7473. [\[CrossRef\]](#) [\[PubMed\]](#)
122. Rychter, P. Chitosan/Glyphosate Formulation as a Potential, Environmental Friendly Herbicide with Prolonged Activity. *J. Environ. Sci. Health Part B* **2019**, *54*, 681–692. [\[CrossRef\]](#) [\[PubMed\]](#)
123. Kumaraswamy, R.V.; Kumari, S.; Choudhary, R.C.; Pal, A.; Raliya, R.; Biswas, P.; Saharan, V. Engineered Chitosan Based Nanomaterials: Bioactivities, Mechanisms and Perspectives in Plant Protection and Growth. *Int. J. Biol. Macromol.* **2018**, *113*, 494–506. [\[CrossRef\]](#) [\[PubMed\]](#)
124. Kashyap, P.L.; Xiang, X.; Heiden, P. Chitosan Nanoparticle Based Delivery Systems for Sustainable Agriculture. *Int. J. Biol. Macromol.* **2015**, *77*, 36–51. [\[CrossRef\]](#) [\[PubMed\]](#)
125. Kwak, S.-Y.; Lew, T.T.S.; Sweeney, C.J.; Koman, V.B.; Wong, M.H.; Bohmert-Tatarev, K.; Snell, K.D.; Seo, J.S.; Chua, N.-H.; Strano, M.S. Chloroplast-Selective Gene Delivery and Expression in Planta Using Chitosan-Complexed Single-Walled Carbon Nanotube Carriers. *Nat. Nanotechnol.* **2019**, *14*, 447–455. [\[CrossRef\]](#) [\[PubMed\]](#)
126. Morin-Crini, N.; Lichtfouse, E.; Torri, G.; Crini, G. Applications of Chitosan in Food, Pharmaceuticals, Medicine, Cosmetics, Agriculture, Textiles, Pulp and Paper, Biotechnology, and Environmental Chemistry. *Environ. Chem. Lett.* **2019**, *17*, 1667–1692. [\[CrossRef\]](#)
127. Stoffolano, J.; Wong, R.; Lo, T.; Ford, B.; Geden, C.J. Effect of Chitosan on Adult Longevity When Fed, in No-Choice Experiments, to *Musca domestica* L., *Tabanus nigrovittatus* Macquart, and *Phormia regina* (Meigen) Adults and Its Consumption in Adult *Musca domestica* L. *Pest Manag. Sci.* **2020**, *76*, 4293–4300. [\[CrossRef\]](#)
128. Sathiyabama, M.; Muthukumar, S. Chitosan Guar Nanoparticle Preparation and Its in Vitro Antimicrobial Activity towards Phytopathogens of Rice. *Int. J. Biol. Macromol.* **2020**, *153*, 297–304. [\[CrossRef\]](#)
129. Hidangmayum, A.; Dwivedi, P.; Katiyar, D.; Hemantaranjan, A. Application of Chitosan on Plant Responses with Special Reference to Abiotic Stress. *Physiol. Mol. Biol. Plants* **2019**, *25*, 313–326. [\[CrossRef\]](#)

130. Neri-Badang, M.C.; Chakraborty, S. Carbohydrate Polymers as Controlled Release Devices for Pesticides. *J. Carbohydr. Chem.* **2019**, *38*, 67–85. [\[CrossRef\]](#)
131. Gamage, A.; Liyanapathirana, A.; Manamperi, A.; Gunathilake, C.; Mani, S.; Merah, O.; Madhujith, T. Applications of Starch Biopolymers for a Sustainable Modern Agriculture. *Sustainability* **2022**, *14*, 6085. [\[CrossRef\]](#)
132. Zarski, A.; Bajer, K.; Kapuśniak, J. Review of the Most Important Methods of Improving the Processing Properties of Starch toward Non-Food Applications. *Polymers* **2021**, *13*, 832. [\[CrossRef\]](#) [\[PubMed\]](#)
133. Ojogbo, E.; Ogunsona, E.O.; Mekonnen, T.H. Chemical and Physical Modifications of Starch for Renewable Polymeric Materials. *Mater. Today Sustain.* **2020**, *7–8*, 100028. [\[CrossRef\]](#)
134. Yadav, A.; Yadav, K.; Abd-Elsalam, K.A. Nanofertilizers: Types, Delivery and Advantages in Agricultural Sustainability. *Agrochemicals* **2023**, *2*, 296–336. [\[CrossRef\]](#)
135. Zanino, A.; Pizzetti, F.; Masi, M.; Rossi, F. Polymers as Controlled Delivery Systems in Agriculture: The Case of Atrazine and Other Pesticides. *Eur. Polym. J.* **2024**, *203*, 112665. [\[CrossRef\]](#)
136. Adel, A.M.; El-Gendy, A.A.; Diab, M.A.; Abou-Zeid, R.E.; El-Zawawy, W.K.; Dufresne, A. Microfibrillated Cellulose from Agricultural Residues. Part I: Papermaking Application. *Ind. Crop. Prod.* **2016**, *93*, 161–174. [\[CrossRef\]](#)
137. Zainul Armir, N.A.; Zulkifli, A.; Gunaseelan, S.; Palanivelu, S.D.; Salleh, K.M.; Che Othman, M.H.; Zakaria, S. Regenerated Cellulose Products for Agricultural and Their Potential: A Review. *Polymers* **2021**, *13*, 3586. [\[CrossRef\]](#)
138. Saberi Riseh, R. Advancing Agriculture through Bioresource Technology: The Role of Cellulose-Based Biodegradable Mulches. *Int. J. Biol. Macromol.* **2024**, *255*, 128006. [\[CrossRef\]](#)
139. Urbina, L.; Corcuera, M.Á.; Gabilondo, N.; Eceiza, A.; Retegi, A. A Review of Bacterial Cellulose: Sustainable Production from Agricultural Waste and Applications in Various Fields. *Cellulose* **2021**, *28*, 8229–8253. [\[CrossRef\]](#)
140. Demitri, C.; Scalera, F.; Madaghiele, M.; Sannino, A.; Maffezzoli, A. Potential of Cellulose-Based Superabsorbent Hydrogels as Water Reservoir in Agriculture. *Int. J. Polym. Sci.* **2013**, *2013*, 435073. [\[CrossRef\]](#)
141. Firmanda, A.; Fahma, F.; Syamsu, K.; Suryanegara, L.; Wood, K. Controlled Slow-release Fertilizer Based on Cellulose Composite and Its Impact. *Biofuels Bioprod. Biorefining* **2022**, *16*, 1909–1930. [\[CrossRef\]](#)
142. Ibrahim, M.M.; Abdahim, M.M.; Abou im, M.N.H. Lignocellulosic Biomass for the Preparation of Cellulose-based Hydrogel and Its. *J. Appl. Polym. Sci.* **2015**, *132*, 42652. [\[CrossRef\]](#)
143. Roy, A.; Singh, S.; Bajpai, J.; Bajpai, A. Controlled Pesticide Release from Biodegradable Polymers. *Open Chem.* **2014**, *12*, 453–469. [\[CrossRef\]](#)
144. Campos, E.V.R.; de Oliveira, J.L.; Fraceto, L.F. Applications of Controlled Release Systems for Fungicides, Herbicides, Acaricides, Nutrients, and Plant Growth Hormones: A Review. *Adv. Sci. Eng. Med.* **2014**, *6*, 373–387. [\[CrossRef\]](#)
145. Kalia, A.; Sharma, S.P.; Kaur, H.; Kaur, H. Chapter 5—Novel Nanocomposite-Based Controlled-Release Fertilizer and Pesticide Formulations: Prospects and Challenges. In *Multifunctional Hybrid Nanomaterials for Sustainable Agri-Food and Ecosystems*; Abd-Elsalam, K.A., Ed.; Micro and Nano Technologies; Elsevier: Amsterdam, The Netherlands, 2020; pp. 99–134, ISBN 978-0-12-821354-4.
146. Akelah, A. Polymers in the Controlled Release of Agrochemicals. In *Functionalized Polymeric Materials in Agriculture and the Food Industry*; Akelah, A., Ed.; Springer: Boston, MA, USA, 2013; pp. 133–192, ISBN 978-1-4614-7061-8.
147. Khatib, I.; Rychter, P.; Falfushynska, H. Pesticide Pollution: Detrimental Outcomes and Possible Mechanisms of Fish Exposure to Common Organophosphates and Triazines. *J. Xenobiotics* **2022**, *12*, 236–265. [\[CrossRef\]](#)
148. Falfushynska, H.; Khatib, I.; Kasianchuk, N.; Lushchak, O.; Horyn, O.; Sokolova, I.M. Toxic Effects and Mechanisms of Common Pesticides (Roundup and Chlorpyrifos) and Their Mixtures in a Zebrafish Model (*Danio rerio*). *Sci. Total Environ.* **2022**, *833*, 155236. [\[CrossRef\]](#)
149. Khatib, I.; Horyn, O.; Bodnar, O.; Lushchak, O.; Rychter, P.; Falfushynska, H. Molecular and Biochemical Evidence of the Toxic Effects of Terbutylazine and Malathion in Zebrafish. *Animals* **2023**, *13*, 1029. [\[CrossRef\]](#)
150. Cherwoo, L.; Gupta, I.; Bhatia, R.; Setia, H. Improving Agricultural Practices: Application of Polymers in Agriculture. *Energy Ecol. Environ.* **2023**, *9*, 25–41. [\[CrossRef\]](#)
151. Zheng, L.; Deng, L.; Zhong, Y.; Wang, Y.; Fan, X. Molluscicides against the Snail-Intermediate Host of Schistosoma: A Review. *Parasitol. Res.* **2021**, *120*, 3355–3393. [\[CrossRef\]](#)
152. Jothimani, B.; Venkatachalapathy, B.; Karthikeyan, N.S.; Ravichandran, C. A Review on Versatile Applications of Degradable Polymers. In *Green Biopolymers and Their Nanocomposites*; Gnanasekaran, D., Ed.; Springer: Singapore, 2019; pp. 403–422, ISBN 9789811380631.
153. Yamamoto, C.F.; Pereira, E.I.; Mattoso, L.H.C.; Matsunaka, T.; Ribeiro, C. Slow Release Fertilizers Based on Urea/Urea-Formaldehyde Polymer Nanocomposites. *Chem. Eng. J.* **2016**, *287*, 390–397. [\[CrossRef\]](#)
154. Duhan, J.S.; Kumar, R.; Kumar, N.; Kaur, P.; Nehra, K.; Duhan, S. Nanotechnology: The New Perspective in Precision Agriculture. *Biotechnol. Rep.* **2017**, *15*, 11–23. [\[CrossRef\]](#) [\[PubMed\]](#)
155. Agrawal, S.; Rathore, P. Review Article Nanotechnology Pros and Cons to Agriculture: A Review. *Int. J. Curr. Microbiol. Appl. Sci.* **2014**, *3*, 43–55. [\[CrossRef\]](#)
156. Guha, T.; Gopal, G.; Kundu, R.; Mukherjee, A. Nanocomposites for Delivering Agrochemicals: A Comprehensive Review. *J. Agric. Food Chem.* **2020**, *68*, 3691–3702. [\[CrossRef\]](#)
157. El-Ghamry, A.; Mosa, A.A.; Alshaal, T.; El-Ramady, H. Nanofertilizers vs. Biofertilizers: New Insights. *Environ. Biodivers. Soil Secur.* **2018**, *2*, 51–72. [\[CrossRef\]](#)
158. Popp, J.; Pető, K.; Nagy, J. Pesticide Productivity and Food Security. A Review. *Agron. Sustain. Dev.* **2013**, *33*, 243–255. [\[CrossRef\]](#)

159. Mani, P.K.; Mondal, S. Agri-Nanotechniques for Plant Availability of Nutrients. In *Plant Nanotechnology: Principles and Practices*; Kole, C., Kumar, D.S., Khodakovskaya, M.V., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 263–303, ISBN 978-3-319-42154-4.
160. Singh, G.; Ramadass, K.; Sooriyakumar, P.; Hettithanthri, O.; Vithange, M.; Bolan, N.; Tavakkoli, E.; Van Zwieten, L.; Vinu, A. Nanoporous Materials for Pesticide Formulation and Delivery in the Agricultural Sector. *J. Control. Release* **2022**, *343*, 187–206. [\[CrossRef\]](#)
161. Pietrzak, D.; Kania, J.; Malina, G.; Kmiecik, E.; Wątor, K. Pesticides from the EU First and Second Watch Lists in the Water Environment. *CLEAN–Soil Air Water* **2019**, *47*, 1800376. [\[CrossRef\]](#)
162. Mihou, A.P.; Michaelakis, A.; Krokos, F.D.; Mazomenos, B.E.; Couladouros, E.A. Prolonged Slow Release of (Z)-11-Hexadecenyl Acetate Employing Polyurea Microcapsules. *J. Appl. Entomol.* **2007**, *131*, 128–133. [\[CrossRef\]](#)
163. Lee, C.-S.; Hwang, H.S. Starch-Based Hydrogels as a Drug Delivery System in Biomedical Applications. *Gels* **2023**, *9*, 951. [\[CrossRef\]](#)
164. Raval, A.; Parikh, J.; Engineer, C. Mechanism of Controlled Release Kinetics from Medical Devices. *Braz. J. Chem. Eng.* **2010**, *27*, 211–225. [\[CrossRef\]](#)
165. Deka, R.; Boruah, P.; Ali, A.A.; Dutta, R.; Gogoi, P.; Sarmah, J.K. Smart Hydrogel with Rapid Self-Healing and Controlled Release Attributes for Biomedical Applications. *Smart Mater. Struct.* **2022**, *31*, 095039. [\[CrossRef\]](#)
166. Adepu, S.; Ramakrishna, S. Controlled Drug Delivery Systems: Current Status and Future Directions. *Molecules* **2021**, *26*, 5905. [\[CrossRef\]](#) [\[PubMed\]](#)
167. Lee, J.H.; Yeo, Y. Controlled Drug Release from Pharmaceutical Nanocarriers. *Chem. Eng. Sci.* **2015**, *125*, 75–84. [\[CrossRef\]](#)
168. Bhowmik, D.; Gopinath, H.; Kumar, B.P.; Duraivel, S.; Kumar, K.P.S. Controlled Release Drug Delivery Systems. *Pharma Innov.* **2012**, *1*, 24–32.
169. Heng, P.W.S. Controlled Release Drug Delivery Systems. *Pharm. Dev. Technol.* **2018**, *23*, 833. [\[CrossRef\]](#)
170. Yenilmez, E.; Başaran, E.; Yazan, Y. Release Characteristics of Vitamin E Incorporated Chitosan Microspheres and in Vitro–in Vivo Evaluation for Topical Application. *Carbohydr. Polym.* **2011**, *84*, 807–811. [\[CrossRef\]](#)
171. Odrobińska, J.; Neugebauer, D. Retinol derivative as bioinitiator in the synthesis of hydroxyl-functionalized polymethacrylates for micellar delivery systems. *Express Polym. Lett.* **2019**, *13*, 806. [\[CrossRef\]](#)
172. Boostani, S.; Jafari, S.M. A Comprehensive Review on the Controlled Release of Encapsulated Food Ingredients; Fundamental Concepts to Design and Applications. *Trends Food Sci. Technol.* **2021**, *109*, 303–321. [\[CrossRef\]](#)
173. Zaitoon, A.; Lim, L.-T. Triggered and Controlled Release of Bioactives in Food Applications. *Adv. Food Nutr. Res.* **2022**, *100*, 49–107. [\[CrossRef\]](#)
174. Morales-Medina, R.; Drusch, S.; Acevedo, F.; Castro-Alvarez, A.; Benie, A.; Poncelet, D.; Dragosavac, M.M.; Tesoriero, M.V.D.; Löwenstein, P.; Yonaha, V.; et al. Structure, Controlled Release Mechanisms and Health Benefits of Pectins as an Encapsulation Material for Bioactive Food Components. *Food Funct.* **2022**, *13*, 10870–10881. [\[CrossRef\]](#)
175. Cota-Arriola, O.; Onofre Cortez-Rocha, M.; Burgos-Hernández, A.; Marina Ezquerro-Brauer, J.; Plascencia-Jatomea, M. Controlled Release Matrices and Micro/Nanoparticles of Chitosan with Antimicrobial Potential: Development of New Strategies for Microbial Control in Agriculture. *J. Sci. Food Agric.* **2013**, *93*, 1525–1536. [\[CrossRef\]](#) [\[PubMed\]](#)
176. Memarizadeh, N.; Ghadamyari, M.; Adeli, M.; Talebi, K. Preparation, Characterization and Efficiency of Nanoencapsulated Imidacloprid under Laboratory Conditions. *Ecotoxicol. Environ. Saf.* **2014**, *107*, 77–83. [\[CrossRef\]](#) [\[PubMed\]](#)
177. Neubauer, M.P.; Poehlmann, M.; Fery, A. Microcapsule Mechanics: From Stability to Function. *Adv. Colloid Interface Sci.* **2014**, *207*, 65–80. [\[CrossRef\]](#)
178. Ngwuluka, N.C.; Abu-Thabit, N.Y.; Uwaezuoke, O.J.; Erebor, J.O.; Ilomuanya, M.O.; Mohamed, R.R.; Soliman, S.M.A.; Elella, M.H.A.; Ebrahim, N.A.A.; Ngwuluka, N.C.; et al. Natural Polymers in Micro- and Nanoencapsulation for Therapeutic and Diagnostic Applications: Part I: Lipids and Fabrication Techniques. In *Nano- and Microencapsulation—Techniques and Applications*; IntechOpen: London, UK, 2020; ISBN 978-1-83968-349-7.
179. Bremer-Hoffmann, S.; Halamoda-Kenzaoui, B.; Borgos, S.E. Identification of Regulatory Needs for Nanomedicines. *J. Interdiscip. Nanomedicine* **2018**, *3*, 4–15. [\[CrossRef\]](#)
180. Slattey, M.; Harper, B.; Harper, S. Pesticide Encapsulation at the Nanoscale Drives Changes to the Hydrophobic Partitioning and Toxicity of an Active Ingredient. *Nanomaterials* **2019**, *9*, 81. [\[CrossRef\]](#) [\[PubMed\]](#)
181. Iavicoli, I.; Leso, V.; Beezhold, D.H.; Shvedova, A.A. Nanotechnology in Agriculture: Opportunities, Toxicological Implications, and Occupational Risks. *Toxicol. Appl. Pharmacol.* **2017**, *329*, 96–111. [\[CrossRef\]](#)
182. Wang, P.; Lombi, E.; Zhao, F.-J.; Kopittke, P.M. Nanotechnology: A New Opportunity in Plant Sciences. *Trends Plant Sci.* **2016**, *21*, 699–712. [\[CrossRef\]](#)
183. Karny, A.; Zinger, A.; Kajal, A.; Shainsky-Roitman, J.; Schroeder, A. Therapeutic Nanoparticles Penetrate Leaves and Deliver Nutrients to Agricultural Crops. *Sci. Rep.* **2018**, *8*, 7589. [\[CrossRef\]](#)
184. Fischer, J.; Beckers, S.J.; Yiamsawas, D.; Thines, E.; Landfester, K.; Wurm, F.R. Targeted Drug Delivery in Plants: Enzyme-Responsive Lignin Nanocarriers for the Curative Treatment of the Worldwide Grapevine Trunk Disease Esca. *Adv. Sci.* **2019**, *6*, 1802315. [\[CrossRef\]](#)
185. Singh, M.N.; Hemant, K.S.Y.; Ram, M.; Shivakumar, H.G. Microencapsulation: A Promising Technique for Controlled Drug Delivery. *Res. Pharm. Sci.* **2010**, *5*, 65–77.

186. Sanopoulou, M.; Papadokostaki, K.G. Controlled Drug Release Systems: Mechanisms and Kinetics. In *Biomedical Membranes and (Bio)Artificial Organs*; World Scientific: Singapore, 2018; pp. 1–33, ISBN 978-981-322-175-8.
187. Nollet, L.M.L.; Rathore, H.S. (Eds.) *Handbook of Pesticides: Methods of Pesticide Residues Analysis*; CRC Press: Boca Raton, FL, USA, 2009; ISBN 978-0-429-14116-4.
188. Machado, T.O.; Grabow, J.; Sayer, C.; de Araújo, P.H.H.; Ehrenhard, M.L.; Wurm, F.R. Biopolymer-Based Nanocarriers for Sustained Release of Agrochemicals: A Review on Materials and Social Science Perspectives for a Sustainable Future of Agri- and Horticulture. *Adv. Colloid Interface Sci.* **2022**, *303*, 102645. [[CrossRef](#)] [[PubMed](#)]
189. Lechenet, M.; Dessaint, F.; Py, G.; Makowski, D.; Munier-Jolain, N. Reducing Pesticide Use While Preserving Crop Productivity and Profitability on Arable Farms. *Nat. Plants* **2017**, *3*, 17008. [[CrossRef](#)] [[PubMed](#)]
190. Abdalla, Z.F.; El-Sawy, S.; El-Bassiony, A.E.-M.; Jun, H.; Shedeed, S.; Okasha, A.M.; Bayoumi, Y.; El-Ramady, H.; Prokisch, J. Smart Fertilizers vs. Nano-Fertilizers: A Pictorial Overview. *Environ. Biodivers. Soil Secur.* **2022**, *6*, 191–204. [[CrossRef](#)]
191. Liu, R.; Lal, R. Potentials of Engineered Nanoparticles as Fertilizers for Increasing Agronomic Productions. *Sci. Total Environ.* **2015**, *514*, 131–139. [[CrossRef](#)]
192. Babu, S.; Singh, R.; Yadav, D.; Rathore, S.S.; Raj, R.; Avasthe, R.; Yadav, S.K.; Das, A.; Yadav, V.; Yadav, B.; et al. Nanofertilizers for Agricultural and Environmental Sustainability. *Chemosphere* **2022**, *292*, 133451. [[CrossRef](#)]
193. Milani, P.; França, D.; Balieiro, A.G.; Faez, R. Polymers and Its Applications in Agriculture. *Polímeros* **2017**, *27*, 256–266. [[CrossRef](#)]
194. Sampathkumar, K.; Tan, K.X.; Loo, S.C.J. Developing Nano-Delivery Systems for Agriculture and Food Applications with Nature-Derived Polymers. *iScience* **2020**, *23*, 101055. [[CrossRef](#)]
195. Afrin, S.; Karim, Z. 1—Polysaccharides. In *Polysaccharide-Based Nanocomposites for Gene Delivery and Tissue Engineering*; Bhawani, S.A., Karim, Z., Jawaid, M., Eds.; Woodhead Publishing Series in Biomaterials; Woodhead Publishing: Cambridge, UK, 2021; pp. 1–14, ISBN 978-0-12-821230-1.
196. Vinzant, K.; Rashid, M.; Khodakovskaya, M.V. Advanced Applications of Sustainable and Biological Nano-Polymers in Agricultural Production. *Front. Plant Sci.* **2023**, *13*, 1081165. [[CrossRef](#)]
197. Agarwal, M.; Nagar, D.P.; Srivastava, N.; Agarwal, M. Chitosan Nanoparticles Based Drug Delivery: An Update. *Int. J. Adv. Multidiscip. Res.* **2015**, *2*, 1–13.
198. Maluin, F.N.; Hussein, M.Z. Chitosan-Based Agronanochemicals as a Sustainable Alternative in Crop Protection. *Molecules* **2020**, *25*, 1611. [[CrossRef](#)]
199. Campos, E.V.R.; De Oliveira, J.L.; Fraceto, L.F.; Singh, B. Polysaccharides as Safer Release Systems for Agrochemicals. *Agron. Sustain. Dev.* **2015**, *35*, 47–66. [[CrossRef](#)]
200. Dudhani, A.R.; Kosaraju, S.L. Bioadhesive Chitosan Nanoparticles: Preparation and Characterization. *Carbohydr. Polym.* **2010**, *81*, 243–251. [[CrossRef](#)]
201. Grillo, R.; Pereira, A.E.S.; Nishisaka, C.S.; de Lima, R.; Oehlke, K.; Greiner, R.; Fraceto, L.F. Chitosan/Tripolyphosphate Nanoparticles Loaded with Paraquat Herbicide: An Environmentally Safer Alternative for Weed Control. *J. Hazard. Mater.* **2014**, *278*, 163–171. [[CrossRef](#)]
202. Choudhary, R.C.; Kumaraswamy, R.V.; Kumari, S.; Sharma, S.S.; Pal, A.; Raliya, R.; Biswas, P.; Saharan, V. Zinc Encapsulated Chitosan Nanoparticle to Promote Maize Crop Yield. *Int. J. Biol. Macromol.* **2019**, *127*, 126–135. [[CrossRef](#)]
203. Saharan, V.; Kumaraswamy, R.V.; Choudhary, R.C.; Kumari, S.; Pal, A.; Raliya, R.; Biswas, P. Cu-Chitosan Nanoparticle Mediated Sustainable Approach To Enhance Seedling Growth in Maize by Mobilizing Reserved Food. *J. Agric. Food Chem.* **2016**, *64*, 6148–6155. [[CrossRef](#)]
204. Wang, J.; Wang, M.; Li, G.-B.; Zhang, B.-H.; Lü, H.; Luo, L.; Kong, X.-P. Evaluation of a Spinosad Controlled-Release Formulation Based on Chitosan Carrier: Insecticidal Activity against *Plutella xylostella* (L.) Larvae and Dissipation Behavior in Soil. *ACS Omega* **2021**, *6*, 30762–30768. [[CrossRef](#)]
205. Wang, M.; Kong, X.-P.; Li, H.; Ge, J.-C.; Han, X.-Z.; Liu, J.-H.; Yu, S.-L.; Li, W.; Li, D.-L.; Wang, J. Coprecipitation-Based Synchronous Chlorantraniliprole Encapsulation with Chitosan: Carrier–Pesticide Interactions and Release Behavior. *Pest Manag. Sci.* **2023**, *79*, 3757–3766. [[CrossRef](#)]
206. Xu, Q.; Long, S.; Zhu, G.; Li, J.; Zhou, Y. Preparation and Pesticide Release Performance of Carboxymethyl Chitosan Film. *J. Phys. Conf. Ser.* **2024**, *2679*, 012027. [[CrossRef](#)]
207. Feng, S.; Wang, J.; Zhang, L.; Chen, Q.; Yue, W.; Ke, N.; Xie, H. Coumarin-Containing Light-Responsive Carboxymethyl Chitosan Micelles as Nanocarriers for Controlled Release of Pesticide. *Polymers* **2020**, *12*, 2268. [[CrossRef](#)]
208. Maan, S.; Jatrana, A.; Kumar, V.; Sindhu, M.; Mondal, S. Controlled Release of Chlorpyrifos through Crosslinked Chitosan–Guargum Biopolymer Based Nano-Formulation. *Sustain. Chem. Pharm.* **2024**, *37*, 101378. [[CrossRef](#)]
209. Singh, A.; Kar, A.K.; Singh, D.; Verma, R.; Shraogi, N.; Zehra, A.; Gautam, K.; Anbumani, S.; Ghosh, D.; Patnaik, S. pH-Responsive Eco-Friendly Chitosan Modified Cenosphere/Alginate Composite Hydrogel Beads as Carrier for Controlled Release of Imidacloprid towards Sustainable Pest Control. *Chem. Eng. J.* **2022**, *427*, 131215. [[CrossRef](#)]
210. Mujtaba, M.; Khawar, K.M.; Camara, M.C.; Carvalho, L.B.; Fraceto, L.F.; Morsi, R.E.; Elsabee, M.Z.; Kaya, M.; Labidi, J.; Ullah, H.; et al. Chitosan-Based Delivery Systems for Plants: A Brief Overview of Recent Advances and Future Directions. *Int. J. Biol. Macromol.* **2020**, *154*, 683–697. [[CrossRef](#)]
211. dos Santos Pereira, T.; França, D.; Souza, C.F.; Faez, R. Chitosan-Sugarcane Bagasse Microspheres as Fertilizer Delivery: On/Off Water Availability System. *J. Polym. Environ.* **2020**, *28*, 2977–2987. [[CrossRef](#)]

212. Suratman, A.; Purwaningsih, D.R.; Kunarti, E.S.; Kuncaka, A. Controlled Release Fertilizer Encapsulated by Glutaraldehyde-Crosslinked Chitosan Using Freeze-Drying Method. *Indones. J. Chem.* **2020**, *20*, 1414. [\[CrossRef\]](#)
213. Siri, J.G.S.; Fernando, C.A.N.; De Silva, S.N.T. A Green Control Release NPK Fertilizer Based on Micro/Nanoparticle of Chitosan Impregnated Activated Coir Fiber. *Nanosci. Nanotechnol.-Asia* **2021**, *11*, 54–64. [\[CrossRef\]](#)
214. Jayanudin, J.; Lestari, R.S.D.; Kustiningsih, I.; Irawanto, D.; Bahaudin, R.; Wardana, R.L.A.; Muhammad, F.; Suyuti, M.; Luthfi, M. Preparation of Chitosan Microspheres as Carrier Material to Controlled Release of Urea Fertilizer. *S. Afr. J. Chem. Eng.* **2021**, *38*, 70–77. [\[CrossRef\]](#)
215. Eddarai, E.M.; El Mouzahim, M.; Ragaoui, B.; El Addaoui, S.; Boussen, R.; Warad, I.; Bellaouchou, A.; Zarrouk, A. Chitosan/Kaolin Clay Biocomposite as a Sustainable and Environmentally Eco-Friendly Coating Material for Slow Release NPK Fertilizers: Effect on Soil Nutrients and Tomato Growth. *Int. J. Biol. Macromol.* **2023**, *242*, 125019. [\[CrossRef\]](#)
216. Ma, J.; Faqir, Y.; Chai, Y.; Wu, S.; Luo, T.; Liao, S.; Kaleri, A.R.; Tan, C.; Qing, Y.; Kalhor, M.T.; et al. Chitosan Microspheres-Based Controlled Release Nitrogen Fertilizers Enhance the Growth, Antioxidant, and Metabolite Contents of Chinese Cabbage. *Sci. Hortic.* **2023**, *308*, 111542. [\[CrossRef\]](#)
217. Quirós, J.; Gonzalo, S.; Jalvo, B.; Boltes, K.; Perdígón-Melón, J.A.; Rosal, R. Electrospun Cellulose Acetate Composites Containing Supported Metal Nanoparticles for Antifungal Membranes. *Sci. Total Environ.* **2016**, *563–564*, 912–920. [\[CrossRef\]](#)
218. Pang, L.; Gao, Z.; Feng, H.; Wang, S.; Wang, Q. Cellulose Based Materials for Controlled Release Formulations of Agrochemicals: A Review of Modifications and Applications. *J. Control. Release* **2019**, *316*, 105–115. [\[CrossRef\]](#) [\[PubMed\]](#)
219. Yang, Y.; Guo, Y.; Sun, R.; Wang, X. Self-Assembly and  $\beta$ -Carotene Loading Capacity of Hydroxyethyl Cellulose-Graft-Linoleic Acid Nanomicelles. *Carbohydr. Polym.* **2016**, *145*, 56–63. [\[CrossRef\]](#) [\[PubMed\]](#)
220. Gold, G.T.; Varma, D.M.; Taub, P.J.; Nicoll, S.B. Development of Crosslinked Methylcellulose Hydrogels for Soft Tissue Augmentation Using an Ammonium Persulfate-Ascorbic Acid Redox System. *Carbohydr. Polym.* **2015**, *134*, 497–507. [\[CrossRef\]](#) [\[PubMed\]](#)
221. Li, Y.; Zhen, D.; Liao, S.; Zhu, D.; Yang, X. Controlled-Release Urea Encapsulated by Ethyl Cellulose/Butyl Acrylate/Vinyl Acetate Hybrid Latex. *Pol. J. Chem. Technol.* **2018**, *20*, 108–112. [\[CrossRef\]](#)
222. Mahfoudhi, N. Poly (Acrylic Acid-Co-Acrylamide)/Cellulose Nanofibrils Nanocomposite Hydrogels: Effects of CNFs Content on the Hydrogel Properties. *Cellulose* **2016**, *23*, 3691–3701. [\[CrossRef\]](#)
223. Yusnaidar, Y.; Wirjosentono, B.; Thamrin, T.; Eddiyanto, E. Synthesized Superabsorbent Based on Cellulose from Rice Straw for Controlled-Release of Urea. *Orient. J. Chem.* **2017**, *33*, 1905–1913. [\[CrossRef\]](#)
224. Pang, L.; Gao, Z.; Feng, H.; Wang, S.; Ma, R.; Zhou, B.; Hu, S.; Jin, K. Synthesis of a Fluorescent Ethyl Cellulose Membrane with Application in Monitoring 1-Naphthylacetic Acid from Controlled Release Formula. *Carbohydr. Polym.* **2017**, *176*, 160–166. [\[CrossRef\]](#)
225. Pang, L.; Gao, Z.; Zhang, S.; Li, Y.; Hu, S.; Ren, X. Preparation and Anti-UV Property of Modified Cellulose Membranes for Biopesticides Controlled Release. *Ind. Crop. Prod.* **2016**, *89*, 176–181. [\[CrossRef\]](#)
226. Senna, A.M.; Botaro, V.R. Biodegradable Hydrogel Derived from Cellulose Acetate and EDTA as a Reduction Substrate of Leaching NPK Compound Fertilizer and Water Retention in Soil. *J. Control. Release Off. J. Control. Release Soc.* **2017**, *260*, 194–201. [\[CrossRef\]](#)
227. Li, X.; Li, Q.; Xu, X.; Su, Y.; Yue, Q.; Gao, B. Characterization, Swelling and Slow-Release Properties of a New Controlled Release Fertilizer Based on Wheat Straw Cellulose Hydrogel. *J. Taiwan Inst. Chem. Eng.* **2016**, *60*, 564–572. [\[CrossRef\]](#)
228. Essawy, H.A.; Ghazy, M.B.M.; El-Hai, F.A.; Mohamed, M.F. Superabsorbent Hydrogels via Graft Polymerization of Acrylic Acid from Chitosan-Cellulose Hybrid and Their Potential in Controlled Release of Soil Nutrients. *Int. J. Biol. Macromol.* **2016**, *89*, 144–151. [\[CrossRef\]](#)
229. Işiklan, N. Controlled Release of Insecticide Carbaryl from Sodium Alginate, Sodium Alginate/Gelatin, and Sodium Alginate/Sodium Carboxymethyl Cellulose Blend Beads Crosslinked with Glutaraldehyde. *J. Appl. Polym. Sci.* **2006**, *99*, 1310–1319. [\[CrossRef\]](#)
230. Mphateng, T.N.; Mapossa, A.B.; Wesley-Smith, J.; Ramjee, S.; Focke, W.W. Cellulose Acetate/Organoclay Nanocomposites as Controlled Release Matrices for Pest Control Applications. *Cellulose* **2022**, *29*, 3915–3933. [\[CrossRef\]](#)
231. Xiao, D.; Liang, W.; Xie, Z.; Cheng, J.; Du, Y.; Zhao, J. A Temperature-Responsive Release Cellulose-Based Microcapsule Loaded with Chlorpyrifos for Sustainable Pest Control. *J. Hazard. Mater.* **2021**, *403*, 123654. [\[CrossRef\]](#) [\[PubMed\]](#)
232. Saberi Riseh, R.; Gholizadeh Vazvani, M.; Hassanisaadi, M.; Skorik, Y.A. Micro-/Nano-Carboxymethyl Cellulose as a Promising Biopolymer with Prospects in the Agriculture Sector: A Review. *Polymers* **2023**, *15*, 440. [\[CrossRef\]](#) [\[PubMed\]](#)
233. Ma, H.; Zhao, Y.; Lu, Z.; Xing, R.; Yao, X.; Jin, Z.; Wang, Y.; Yu, F. Citral-Loaded Chitosan/Carboxymethyl Cellulose Copolymer Hydrogel Microspheres with Improved Antimicrobial Effects for Plant Protection. *Int. J. Biol. Macromol.* **2020**, *164*, 986–993. [\[CrossRef\]](#)
234. Hao, L.; Lin, G.; Lian, J.; Chen, L.; Zhou, H.; Chen, H.; Xu, H.; Zhou, X. Carboxymethyl Cellulose Capsulated Zein as Pesticide Nano-Delivery System for Improving Adhesion and Anti-UV Properties. *Carbohydr. Polym.* **2020**, *231*, 115725. [\[CrossRef\]](#)
235. Zhao, M.; Zhou, H.; Hao, L.; Chen, H.; Zhou, X. Natural Rosin Modified Carboxymethyl Cellulose Delivery System with Lowered Toxicity for Long-Term Pest Control. *Carbohydr. Polym.* **2021**, *259*, 117749. [\[CrossRef\]](#)
236. Mohd Sharif, S.N.; Hashim, N.; Md Isa, I.; Abu Bakar, S.; Idris Saidin, M.; Syahrizal Ahmad, M.; Mamat, M.; Zobir Hussein, M.; Zainul, R. Carboxymethyl Cellulose Hydrogel Based Formulations of Zinc Hydroxide Nitrate-Sodium Dodecylsulphate-

- Bispyribac Nanocomposite: Advancements in Controlled Release Formulation of Herbicide. *J. Nanosci. Nanotechnol.* **2021**, *21*, 5867–5880. [[CrossRef](#)]
237. Ahmad, D.F.B.A.; Wasli, M.E.; Tan, C.S.Y.; Musa, Z.; Chin, S.-F. Eco-Friendly Cellulose-Based Hydrogels Derived from Wastepapers as a Controlled-Release Fertilizer. *Chem. Biol. Technol. Agric.* **2023**, *10*, 36. [[CrossRef](#)]
  238. Sharma, N.; Allardyce, B.J.; Rajkhowa, R.; Agrawal, R. Controlled Release Fertilizer Delivery System Derived from Rice Straw Cellulose Nanofibres: A Circular Economy Based Solution for Sustainable Development. *Bioengineered* **2023**, *14*, 2242124. [[CrossRef](#)]
  239. Priya, E.; Jha, A.; Sarkar, S.; Maji, P.K. A Urea-Loaded Hydrogel Comprising of Cellulose Nanofibers and Carboxymethyl Cellulose: An Effective Slow-Release Fertilizer. *J. Clean. Prod.* **2024**, *434*, 140215. [[CrossRef](#)]
  240. Sultan, M.; Taha, G. Sustained-Release Nitrogen Fertilizer Delivery Systems Based on Carboxymethyl Cellulose-Grafted Polyacrylamide: Swelling and Release Kinetics. *Int. J. Biol. Macromol.* **2024**, *266*, 131184. [[CrossRef](#)] [[PubMed](#)]
  241. Artusio, F.; Casà, D.; Granetto, M.; Tosco, T.; Pisano, R. Alginate Nanohydrogels as a Biocompatible Platform for the Controlled Release of a Hydrophilic Herbicide. *Processes* **2021**, *9*, 1641. [[CrossRef](#)]
  242. Du, Y.; Zhang, Q.; Yu, M.; Jiao, B.; Chen, F.; Yin, M. Sodium Alginate-Based Composite Microspheres for Controlled Release of Pesticides and Reduction of Adverse Effects of Copper in Agricultural Soils. *Chemosphere* **2023**, *313*, 137539. [[CrossRef](#)]
  243. Gao, X.; Guo, C.; Hao, J.; Zhao, Z.; Long, H.; Li, M. Adsorption of Heavy Metal Ions by Sodium Alginate Based Adsorbent—a Review and New Perspectives. *Int. J. Biol. Macromol.* **2020**, *164*, 4423–4434. [[CrossRef](#)]
  244. Zheng, D.; Bai, B.; Zhao, H.; Xu, X.; Hu, N.; Wang, H. Stimuli-Responsive Ca-Alginate-Based Photothermal System with Enhanced Foliar Adhesion for Controlled Pesticide Release. *Colloids Surf. B Biointerfaces* **2021**, *207*, 112004. [[CrossRef](#)]
  245. Xie, Y.-L.; Jiang, W.; Li, F.; Zhang, Y.; Liang, X.-Y.; Wang, M.; Zhou, X.; Wu, S.-Y.; Zhang, C.-H. Controlled Release of Spirotetramat Using Starch–Chitosan–Alginate-Encapsulation. *Bull. Environ. Contam. Toxicol.* **2020**, *104*, 149–155. [[CrossRef](#)]
  246. El Bouchtaoui, F.-Z.; Ablouh, E.-H.; Kassem, I.; Kassab, Z.; Sehaqui, H.; El Achaby, M. Slow-Release Fertilizers Based on Lignin–Sodium Alginate Biopolymeric Blend for Sustained N–P Nutrients Release. *J. Coat. Technol. Res.* **2022**, *19*, 1551–1565. [[CrossRef](#)]
  247. Llive, L.M.; Perullini, M.; Santagapita, P.R.; Schneider-Teixeira, A.; Deladino, L. Controlled Release of Fertilizers from Ca(II)-Alginate Matrix Modified by Yerba Mate (*Ilex paraguariensis*) Waste. *Eur. Polym. J.* **2020**, *138*, 109955. [[CrossRef](#)]
  248. Nooeaid, P.; Cha-aim, K.; Chuysinuan, P.; Pengsuk, C.; Thanyacharoern, T.; Sophonputtanaphoca, S.; Techasakul, S. Nutrient Controlled Release Behaviors and Plant Growth of NPK Encapsulated Hydroxyapatite/Alginate Biocomposite toward Agricultural and Environmental Sustainability. *Mater. Res. Express* **2024**, *11*, 035310. [[CrossRef](#)]
  249. Stanley, N.; Mahanty, B. Preparation and Characterization of Biogenic CaCO<sub>3</sub>-Reinforced Polyvinyl Alcohol–Alginate Hydrogel as Controlled-Release Urea Formulation. *Polym. Bull.* **2020**, *77*, 529–540. [[CrossRef](#)]
  250. Lewicka, K.; Rychter, P.; Pastusiak, M.; Janeczek, H.; Dobrzynski, P. Biodegradable Blends of Grafted Dextrin with PLGA-Block-PEG Copolymer as a Carrier for Controlled Release of Herbicides into Soil. *Materials* **2020**, *13*, 832. [[CrossRef](#)] [[PubMed](#)]
  251. Liu, T.; Qian, K.; Fan, J.; Qin, Z.; Yi, L.; Wang, J.; Dou, W. Nano-Based Smart Pesticide Formulations Utilizing Starch Nanocrystals: Achieving High Stability and Extended Effective Duration. *Ind. Crop. Prod.* **2024**, *214*, 118470. [[CrossRef](#)]
  252. Dong, X.; Bai, Y.; Ma, X.; Xue, P.; Zhang, Y.; Bian, L. Adsorption and Sustained-Release Capacity of Glyphosate on Microporous Corn Starch. *Starch-Stärke* **2021**, *73*, 2000224. [[CrossRef](#)]
  253. Fabiyi, O.A.; Saliu, O.D.; Claudius-cole, A.O.; Olaniyi, I.O.; Oguntebi, O.V.; Olatunji, G.A. Porous Starch Citrate Biopolymer for Controlled Release of Carbofuran in the Management of Root Knot Nematode *Meloidogyne Incognita*. *Biotechnol. Rep.* **2020**, *25*, e00428. [[CrossRef](#)]
  254. Versino, F.; Urriza, M.; García, M.A. Eco-Compatible Cassava Starch Films for Fertilizer Controlled-Release. *Int. J. Biol. Macromol.* **2019**, *134*, 302–307. [[CrossRef](#)]
  255. Sofyane, A.; Ablouh, E.; Lahcini, M.; Elmeziane, A.; Khoulood, M.; Kaddami, H.; Raihane, M. Slow-Release Fertilizers Based on Starch Acetate/Glycerol/Polyvinyl Alcohol Biocomposites for Sustained Nutrient Release. *Mater. Today Proc.* **2021**, *36*, 74–81. [[CrossRef](#)]
  256. Lü, S.; Gao, C.; Wang, X.; Xu, X.; Bai, X.; Gao, N.; Feng, C.; Wei, Y.; Wu, L.; Liu, M. Synthesis of a Starch Derivative and Its Application in Fertilizer for Slow Nutrient Release and Water-Holding. *RSC Adv.* **2014**, *4*, 51208–51214. [[CrossRef](#)]
  257. Dhiman, A.; Thaper, P.; Bhardwaj, D.; Agrawal, G. Biodegradable Dextrin-Based Microgels for Slow Release of Dual Fertilizers for Sustainable Agriculture. *ACS Appl. Mater. Interfaces* **2024**, *16*, 11860–11871. [[CrossRef](#)]
  258. Da Costa, D.; Exbrayat-Héritier, C.; Rambaud, B.; Megy, S.; Terreux, R.; Verrier, B.; Primard, C. Surface Charge Modulation of Rifampicin-Loaded PLA Nanoparticles to Improve Antibiotic Delivery in *Staphylococcus Aureus* Biofilms. *J. Nanobiotechnol.* **2021**, *19*, 12. [[CrossRef](#)]
  259. Tao, R.; You, C.; Qu, Q.; Zhang, X.; Deng, Y.; Ma, W.; Huang, C. Recent Advances in the Design of Controlled- and Sustained-Release Micro/Nanocarriers of Pesticide. *Environ. Sci. Nano* **2023**, *10*, 351–371. [[CrossRef](#)]
  260. Sikorska, W.; Musioł, M.; Rydz, J.; Zięba, M.; Rychter, P.; Lewicka, K.; Šišková, A.; Mosnáčková, K.; Kowalczyk, M.; Adamus, G. Prediction Studies of Environment-Friendly Biodegradable Polymeric Packaging Based on PLA. Influence of Specimens' Thickness on the Hydrolytic Degradation Profile. *Waste Manag.* **2018**, *78*, 938–947. [[CrossRef](#)] [[PubMed](#)]
  261. Rychter, P.; Lewicka, K.; Rogacz, D. Environmental Usefulness of PLA/PEG Blends for Controlled-Release Systems of Soil-Applied Herbicides. *J. Appl. Polym. Sci.* **2019**, *136*, 47856. [[CrossRef](#)]

262. Rychter, P.; Lewicka, K.; Pastusiak, M.; Domański, M.; Dobrzyński, P. PLGA–PEG Terpolymers as a Carriers of Bioactive Agents, Influence of PEG Blocks Content on Degradation and Release of Herbicides into Soil. *Polym. Degrad. Stab.* **2019**, *161*, 95–107. [\[CrossRef\]](#)
263. Boyandin, A.N.; Kazantseva, E.A. Constructing Slow-Release Formulations of Herbicide Metribuzin Using Its Co-Extrusion with Biodegradable Polyester Poly- $\epsilon$ -Caprolactone. *J. Environ. Sci. Health Part B* **2021**, *56*, 467–476. [\[CrossRef\]](#)
264. Abedalwafa, M.; Wang, F.; Wang, L.; Li, C. Biodegradable poly-epsilon-caprolactone (PCL) for tissue engineering applications: A review. *Rev. Adv. Mater. Sci* **2013**, *34*, 123–140.
265. Khoshtinat, S. State-of-the-Art Review of Aliphatic Polyesters and Polyolefins Biodeterioration by Microorganisms: From Mechanism to Characterization. *Corros. Mater. Degrad.* **2023**, *4*, 542–572. [\[CrossRef\]](#)
266. Strangis, G.; Rossi, D.; Cinelli, P.; Seggiani, M. Seawater Biodegradable Poly(Butylene Succinate-co-Adipate)—Wheat Bran Biocomposites. *Materials* **2023**, *16*, 2593. [\[CrossRef\]](#)
267. Liu, B.; Wang, Y.; Yang, F.; Wang, X.; Shen, H.; Cui, H.; Wu, D. Construction of a Controlled-Release Delivery System for Pesticides Using Biodegradable PLA-Based Microcapsules. *Colloids Surf. B Biointerfaces* **2016**, *144*, 38–45. [\[CrossRef\]](#)
268. Roshani, B.; Tavanai, H.; Morshed, M.; Khajehali, J. Controlled Release of Thiram Pesticide from Poly (L-Lactic Acid) Nanofibers. *J. Text. Inst.* **2016**, *108*, 1504–1509. [\[CrossRef\]](#)
269. Takei, T.; Yoshida, M.; Hatate, Y.; Shiomi, K.; Kiyoyama, S. Preparation of Polylactide/Poly( $\epsilon$ -Caprolactone) Microspheres Enclosing Acetamiprid and Evaluation of Release Behavior. *Polym. Bull.* **2008**, *61*, 391–397. [\[CrossRef\]](#)
270. Suave, J.; Dall'Agnol, E.C.; Pezzin, A.P.T.; Meier, M.M.; Silva, D.A.K. Biodegradable Microspheres of Poly(3-Hydroxybutyrate)/Poly( $\epsilon$ -Caprolactone) Loaded with Malathion Pesticide: Preparation, Characterization, and in Vitro Controlled Release Testing. *J. Appl. Polym. Sci.* **2010**, *117*, 3419–3427. [\[CrossRef\]](#)
271. Kiselev, E.G.; Boyandin, A.N.; Zhila, N.O.; Prudnikova, S.V.; Shumilova, A.A.; Baranovskiy, S.V.; Shishatskaya, E.I.; Thomas, S.; Volova, T.G. Constructing Sustained-Release Herbicide Formulations Based on Poly-3-Hydroxybutyrate and Natural Materials as a Degradable Matrix. *Pest Manag. Sci.* **2020**, *76*, 1772–1785. [\[CrossRef\]](#) [\[PubMed\]](#)
272. Prudnikova, S.V.; Volova, T.G. Design and Application of Slow-Release Pesticide Formulations Embedded in a Biodegradable Matrix Based on Poly(3-Hydroxybutyrate). *J. Sib. Fed. Univ. Biol.* **2019**, *12*, 329–336. [\[CrossRef\]](#)
273. Wang, Y.; Li, C.; Wang, Y.; Zhang, Y.; Li, X. Compound Pesticide Controlled Release System Based on the Mixture of Poly(Butylene Succinate) and PLA. *J. Microencapsul.* **2018**, *35*, 494–503. [\[CrossRef\]](#)
274. Liu, Y.; Guo, B. Preparation and Characterisation of Poly(Butylene Succinate) Microcarriers Containing Pesticide. *Micro Nano Lett.* **2019**, *14*, 81–85. [\[CrossRef\]](#)
275. Cen, Z.; Wei, L.; Muthukumarappan, K.; Sobhan, A.; McDaniel, R. Assessment of a Biochar-Based Controlled Release Nitrogen Fertilizer Coated with Polylactic Acid. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 2007–2019. [\[CrossRef\]](#)
276. El Assimi, T.; Blažic, R.; Vidović, E.; Raihane, M.; El Meziane, A.; Baouab, M.H.V.; Khoulood, M.; Beniazza, R.; Kricheldorf, H.; Lahcini, M. Polylactide/Cellulose Acetate Biocomposites as Potential Coating Membranes for Controlled and Slow Nutrients Release from Water-Soluble Fertilizers. *Prog. Org. Coat.* **2021**, *156*, 106255. [\[CrossRef\]](#)
277. El Assimi, T.; Chaib, M.; Raihane, M.; El Meziane, A.; Khoulood, M.; Benhida, R.; Beniazza, R.; Lahcini, M. Poly( $\epsilon$ -Caprolactone)-g-Guar Gum and Poly( $\epsilon$ -Caprolactone)-g-Halloysite Nanotubes as Coatings for Slow-Release DAP Fertilizer. *J. Polym. Environ.* **2020**, *28*, 2078–2090. [\[CrossRef\]](#)
278. Boutrouia, E.H.; El Assimi, T.; Qayouh, H.; Raihane, M.; El Meziane, A.; Baouab, M.H.V.; Youcef, H.B.; El Kadib, A.; Lahcini, M. Poly( $\epsilon$ -Caprolactone)-Grafted-Chitosan Copolymers: Synthesis and Use as Tunable and Biodegradable Coating for Water Soluble Fertilizers. *React. Funct. Polym.* **2024**, *198*, 105887. [\[CrossRef\]](#)
279. Souza, J.L.; de Campos, A.; França, D.; Faez, R. PHB and Montmorillonite Clay Composites as KNO<sub>3</sub> and NPK Support for a Controlled Release. *J. Polym. Environ.* **2019**, *27*, 2089–2097. [\[CrossRef\]](#)
280. Baldanza, V.A.R.; Souza, F.G., Jr.; Filho, S.T.; Franco, H.A.; Oliveira, G.E.; Caetano, R.M.J.; Hernandez, J.A.R.; Ferreira Leite, S.G.; Furtado Sousa, A.M.; Nazareth Silva, A.L. Controlled-Release Fertilizer Based on Poly(Butylene Succinate)/Urea/Clay and Its Effect on Lettuce Growth. *J. Appl. Polym. Sci.* **2018**, *135*, 46858. [\[CrossRef\]](#)
281. Singh, N.K.; Sanghvi, G.; Yadav, M.; Padhiyar, H.; Christian, J.; Singh, V. Fate of Pesticides in Agricultural Runoff Treatment Systems: Occurrence, Impacts and Technological Progress. *Environ. Res.* **2023**, *237*, 117100. [\[CrossRef\]](#) [\[PubMed\]](#)
282. Tang, Z.; Wood, J.; Smith, D.; Thapa, A.; Aryal, N. A Review on Constructed Treatment Wetlands for Removal of Pollutants in the Agricultural Runoff. *Sustainability* **2021**, *13*, 13578. [\[CrossRef\]](#)
283. Marican, A.; Durán-Lara, E.F. A Review on Pesticide Removal through Different Processes. *Environ. Sci. Pollut. Res.* **2018**, *25*, 2051–2064. [\[CrossRef\]](#)
284. El Harmoudi, H.; El Gaini, L.; Daoudi, E.; Rhazi, M.; Boughaleb, Y.; El Mhammedi, M.A.; Migalska-Zalas, A.; Bakasse, M. Removal of 2,4-D from Aqueous Solutions by Adsorption Processes Using Two Biopolymers: Chitin and Chitosan and Their Optical Properties. *Opt. Mater.* **2014**, *36*, 1471–1477. [\[CrossRef\]](#)
285. Rissouli, L.; Benicha, M.; Chafik, T.; Chabbi, M. Decontamination of Water Polluted with Pesticide Using Biopolymers: Adsorption of Glyphosate by Chitin and Chitosan. *J. Mater. Environ. Sci.* **2017**, *8*, 4544–4549. [\[CrossRef\]](#)
286. Rissouli, L.; Benicha, M.; Chabbi, M. Contribution to the Elimination of Linuron by the Adsorption Process Using Chitin and Chitosan Biopolymers. *J. Mater. Environ. Sci.* **2016**, *7*, 531–540.

287. Abdeen, Z.; Mohammad, S.G. Study of the Adsorption Efficiency of an Eco-Friendly Carbohydrate Polymer for Contaminated Aqueous Solution by Organophosphorus Pesticide. *Open J. Org. Polym. Mater.* **2014**, *4*, 16–28. [[CrossRef](#)]
288. Moradeeya, P.G.; Kumar, M.A.; Thorat, R.B.; Rathod, M.; Khambhaty, Y.; Basha, S. Nanocellulose for Biosorption of Chlorpyrifos from Water: Chemometric Optimization, Kinetics and Equilibrium. *Cellulose* **2017**, *24*, 1319–1332. [[CrossRef](#)]
289. Alsbaiee, A.; Smith, B.J.; Xiao, L.; Ling, Y.; Helbling, D.E.; Dichtel, W.R. Rapid Removal of Organic Micropollutants from Water by a Porous  $\beta$ -Cyclodextrin Polymer. *Nature* **2016**, *529*, 190–194. [[CrossRef](#)] [[PubMed](#)]
290. Hu, X.; Xu, G.; Zhang, H.; Li, M.; Tu, Y.; Xie, X.; Zhu, Y.; Jiang, L.; Zhu, X.; Ji, X.; et al. Multifunctional  $\beta$ -Cyclodextrin Polymer for Simultaneous Removal of Natural Organic Matter and Organic Micropollutants and Detrimental Microorganisms from Water. *ACS Appl. Mater. Interfaces* **2020**, *12*, 12165–12175. [[CrossRef](#)] [[PubMed](#)]
291. Mostafa, M.; Bin Jumah, M.N.; Othman, S.I.; Alruhaimi, R.S.; Salama, Y.F.; Allam, A.A.; Abukhadra, M.R. Effective Removal of Different Species of Organophosphorus Pesticides (Acephate, Omthosate, and Methyl Parathion) Using Chitosan/Zeolite-A as Multifunctional Adsorbent. *Environ. Technol. Innov.* **2021**, *24*, 101875. [[CrossRef](#)]
292. Attallah, O.A.; Wafa, M.M.A.; Al-Ghobashy, M.A.; Nebesen, M.; Monir, H.H. Adsorptive Removal of Pesticides from Aqueous Solutions Using Chitosan/Gelatin Polymeric Composite: Process Monitoring and Optimization. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 8183–8194. [[CrossRef](#)]
293. Zhang, C.; Zhang, R.Z.; Ma, Y.Q.; Guan, W.B.; Wu, X.L.; Liu, X.; Li, H.; Du, Y.L.; Pan, C.P. Preparation of Cellulose/Graphene Composite and Its Applications for Triazine Pesticides Adsorption from Water. *ACS Sustain. Chem. Eng.* **2015**, *3*, 396–405. [[CrossRef](#)]
294. Sahithya, K.; Das, D.; Das, N. Effective Removal of Dichlorvos from Aqueous Solution Using Biopolymer Modified MMT–CuO Composites: Equilibrium, Kinetic and Thermodynamic Studies. *J. Mol. Liq.* **2015**, *211*, 821–830. [[CrossRef](#)]
295. Sahithya, K.; Das, D.; Das, N. Adsorptive Removal of Monocrotophos from Aqueous Solution Using Biopolymer Modified Montmorillonite–CuO Composites: Equilibrium, Kinetic and Thermodynamic Studies. *Process Saf. Environ. Prot.* **2016**, *99*, 43–54. [[CrossRef](#)]
296. Pal, J.; Deb, M.K.; Sircar, J.K.; Agnihotri, P.K. Microwave Green Synthesis of Biopolymer-Stabilized Silver Nanoparticles and Their Adsorption Behavior for Atrazine. *Appl. Water Sci.* **2015**, *5*, 181–190. [[CrossRef](#)]
297. Etcheverry, M.; Cappa, V.; Trelles, J.; Zanini, G. Montmorillonite-Alginate Beads: Natural Mineral and Biopolymers Based Sorbent of Paraquat Herbicides. *J. Environ. Chem. Eng.* **2017**, *5*, 5868–5875. [[CrossRef](#)]
298. Narayanan, N.; Gajbhiye, V.; Gupta, S.; Manjaiah, K.M. Novel Biopolymer-Nanoorganoclay Composites for the Decontamination of Pesticides from Water. *Pestic. Res. J.* **2016**, *28*, 25–34.
299. Narayanan, N.; Gupta, S.; Gajbhiye, V.T.; Manjaiah, K.M. Optimization of Isotherm Models for Pesticide Sorption on Biopolymer-Nanoclay Composite by Error Analysis. *Chemosphere* **2017**, *173*, 502–511. [[CrossRef](#)] [[PubMed](#)]
300. Bilici, Z.; Ozay, Y.; Yuzer, A.; Ince, M.; Ocakoglu, K.; Dizge, N. Fabrication and Characterization of Polyethersulfone Membranes Functionalized with Zinc Phthalocyanines Embedding Different Substitute Groups. *Colloids Surf. Physicochem. Eng. Asp.* **2021**, *617*, 126288. [[CrossRef](#)]
301. Bhalerao, T.; Puranik, P. Microbial Degradation of Monocrotophos by *Aspergillus Oryzae*. *Int. Biodeterior. Biodegrad.* **2009**, *63*, 503–508. [[CrossRef](#)]
302. Abdelhameed, R.; El-Zawahry, M.; Emam, H. Efficient Removal of Organophosphorus Pesticides from Wastewater Using Polyethylenimine-Modified Fabrics. *Polymer* **2018**, *155*, 225–234. [[CrossRef](#)]
303. El-Said, W.; El-Khouly, M.; Ali, M.; Rashad, R.; Elshehy, E.; Al-Bogami, A. Synthesis of Mesoporous Silica-Polymer Composite for the Chloridazon Pesticide Removal from Aqueous Media. *J. Environ. Chem. Eng.* **2018**, *6*, 2214–2221. [[CrossRef](#)]
304. Mlynáriková, H.; Legáth, J.; Guzy, J.; Kovalkovicová, N.; Ivanko, S. Effect of Chloridazone on the Animal Organism. *Gen. Physiol. Biophys.* **1999**, *18*, 99–104.
305. Liber, K.; Solomon, K.R. Acute and Chronic Toxicity of 2,3,4,6-Tetrachlorophenol and Pentachlorophenol to *Daphnia* and Rotifers. *Arch. Environ. Contam. Toxicol.* **1994**, *26*, 212–221. [[CrossRef](#)]
306. Salazar, S.; Guerra, D.; Yutronic, N.; Jara, P. Removal of Aromatic Chlorinated Pesticides from Aqueous Solution Using  $\beta$ -Cyclodextrin Polymers Decorated with  $\text{Fe}_3\text{O}_4$  Nanoparticles. *Polymers* **2018**, *10*, 1038. [[CrossRef](#)]
307. So, J.; Pang, C.; Dong, H.; Jang, P.; Juhyok, U.; Ri, K.; Yun, C. Adsorption of 1-Naphthyl Methyl Carbamate in Water by Utilizing a Surface Molecularly Imprinted Polymer. *Chem. Phys. Lett.* **2018**, *699*, 199–207. [[CrossRef](#)]
308. Sathishkumar, M.; Choi, J.G.; Ku, C.S.; Vijayaraghavan, K.; Binupriya, A.R.; Yun, S.E. Carbaryl Sorption by Porogen-Treated Banana Pith Carbon. *Adsorpt. Sci. Technol.* **2008**, *26*, 679–686. [[CrossRef](#)]
309. Youssef, A.; El-Naggar, M.; Malhat, F.; Sharkawi, H. Efficient Removal of Pesticides and Heavy Metals from Wastewater and the Antimicrobial Activity of the Synthesized F-MWCNTs/PVA Nanocomposite Film. *J. Clean. Prod.* **2018**, *206*, 315–325. [[CrossRef](#)]
310. Shahnazi, A.; Nabid, M.R.; Sedghi, R.; Heidari, B. A Thermosensitive Molecularly Imprinted Poly-NIPAM Coated MWCNTs/TiO<sub>2</sub> Photocatalyst for the Preferential Removal of Pendimethalin Pesticide from Wastewater. *J. Photochem. Photobiol. Chem.* **2020**, *402*, 112802. [[CrossRef](#)]
311. Dimitrov, B.D.; Gadeva, P.G.; Benova, D.K.; Bineva, M.V. Comparative Genotoxicity of the Herbicides Roundup, Stomp and Reglone in Plant and Mammalian Test Systems. *Mutagenesis* **2006**, *21*, 375–382. [[CrossRef](#)] [[PubMed](#)]

312. Sharma, G.; Thakur, B.; Kumar, A.; Sharma, S.; Naushad, M.; Stadler, F.J. Atrazine Removal Using Chitin-Cl-Poly(Acrylamide-Co-Itaconic Acid) Nanohydrogel: Isotherms and pH Responsive Nature. *Carbohydr. Polym.* **2020**, *241*, 116258. [[CrossRef](#)] [[PubMed](#)]
313. Clausen, L.; Fabricius, I. Atrazine, Isoproturon, Mecoprop, 2,4-D, and Bentazone Adsorption onto Iron Oxides. *J. Environ. Qual.* **2001**, *30*, 858–869. [[CrossRef](#)]
314. Fayette, J.; Roberts, P.D.; Pernezny, K.L.; Jones, J.B. The Role of Cymoxanil and Famoxadone in the Management of Bacterial Spot on Tomato and Pepper and Bacterial Leaf Spot on Lettuce. *Crop Prot.* **2012**, *31*, 107–112. [[CrossRef](#)]
315. Tonietto, B.D.; Laurentino, A.O.M.; Costa-Valle, M.T.; Cestonaro, L.V.; Antunes, B.P.; Sates, C.; Dos Santos, N.G.; Dallegrave, E.; Garcia, S.C.; Leal, M.B.; et al. Imidacloprid-Based Commercial Pesticide Causes Behavioral, Biochemical, and Hematological Impairments in Wistar Rats. *Environ. Toxicol. Pharmacol.* **2022**, *94*, 103924. [[CrossRef](#)]
316. Utzeri, G.; Verissimo, L.; Murtinho, D.; Pais, A.A.C.C.; Perrin, F.X.; Ziarelli, F.; Iordache, T.-V.; Sarbu, A.; Valente, A.J.M. Poly( $\beta$ -Cyclodextrin)-Activated Carbon Gel Composites for Removal of Pesticides from Water. *Molecules* **2021**, *26*, 1426. [[CrossRef](#)]
317. Drioli, E.; Macedonio, F.; Tocci, E. Membrane Science and Membrane Engineering for a Sustainable Industrial Development. *Sep. Purif. Technol.* **2021**, *275*, 119196. [[CrossRef](#)]
318. Esfahani, M.R.; Aktij, S.A.; Dabaghian, Z.; Firouzjaei, M.D.; Rahimpour, A.; Eke, J.; Escobar, I.C.; Abolhassani, M.; Greenlee, L.F.; Esfahani, A.R.; et al. Nanocomposite Membranes for Water Separation and Purification: Fabrication, Modification, and Applications. *Sep. Purif. Technol.* **2019**, *213*, 465–499. [[CrossRef](#)]
319. Kadirkhan, F.; Goh, P.S.; Ismail, A.F.; Wan Mustapa, W.N.F.; Halim, M.H.M.; Soh, W.K.; Yeo, S.Y. Recent Advances of Polymeric Membranes in Tackling Plasticization and Aging for Practical Industrial CO<sub>2</sub>/CH<sub>4</sub> Applications—A Review. *Membranes* **2022**, *12*, 71. [[CrossRef](#)] [[PubMed](#)]
320. Saleh, T.A.; Parthasarathy, P.; Irfan, M. Advanced Functional Polymer Nanocomposites and Their Use in Water Ultra-Purification. *Trends Environ. Anal. Chem.* **2019**, *24*, e00067. [[CrossRef](#)]
321. María Arsuaga, J.; Sotto, A.; Del Rosario, G.; Martínez, A.; Molina, S.; Teli, S.B.; De Abajo, J. Influence of the Type, Size, and Distribution of Metal Oxide Particles on the Properties of Nanocomposite Ultrafiltration Membranes. *J. Membr. Sci.* **2013**, *428*, 131–141. [[CrossRef](#)]
322. Deng, Y.-F.; Zhang, D.; Zhang, N.; Huang, T.; Lei, Y.-Z.; Wang, Y. Electrospun Stereocomplex Polylactide Porous Fibers toward Highly Efficient Oil/Water Separation. *J. Hazard. Mater.* **2021**, *407*, 124787. [[CrossRef](#)]
323. Alam, J.; Alhoshan, M.; Shukla, A.K.; Aldalbahi, A.; Ali, F.A.A. K-Carrageenan—A Versatile Biopolymer for the Preparation of a Hydrophilic PVDF Composite Membrane. *Eur. Polym. J.* **2019**, *120*, 109219. [[CrossRef](#)]
324. Momina, K.A. Study of Different Polymer Nanocomposites and Their Pollutant Removal Efficiency: Review. *Polymer* **2021**, *217*, 123453. [[CrossRef](#)]
325. Kotobuki, M.; Gu, Q.; Zhang, L.; Wang, J. Ceramic-Polymer Composite Membranes for Water and Wastewater Treatment: Bridging the Big Gap between Ceramics and Polymers. *Molecules* **2021**, *26*, 3331. [[CrossRef](#)]
326. Benavente, L.; Coetsier, C.; Venault, A.; Chang, Y.; Causserand, C.; Bacchin, P.; Aimar, P. FTIR Mapping as a Simple and Powerful Approach to Study Membrane Coating and Fouling. *J. Membr. Sci.* **2016**, *520*, 477–489. [[CrossRef](#)]
327. Lawrence Arockiasamy, D.; Alhoshan, M.; Alam, J.; Muthumareeswaran, M.; Figoli, A.; Arun Kumar, S. Separation of Proteins and Antifouling Properties of Polyphenylsulfone Based Mixed Matrix Hollow Fiber Membranes. *Sep. Purif. Technol.* **2017**, *174*, 529–543. [[CrossRef](#)]
328. Othman, N.H.; Alias, N.H.; Fuzil, N.S.; Marpani, F.; Shahrudin, M.Z.; Chew, C.M.; David Ng, K.M.; Lau, W.J.; Ismail, A.F. A Review on the Use of Membrane Technology Systems in Developing Countries. *Membranes* **2021**, *12*, 30. [[CrossRef](#)]
329. Asif, M.B.; Zhang, Z. Ceramic Membrane Technology for Water and Wastewater Treatment: A Critical Review of Performance, Full-Scale Applications, Membrane Fouling and Prospects. *Chem. Eng. J.* **2021**, *418*, 129481. [[CrossRef](#)]
330. Qalyoubi, L.; Al-Othman, A.; Al-Asheh, S. Recent Progress and Challenges of Adsorptive Membranes for the Removal of Pollutants from Wastewater. Part II: Environmental Applications. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100102. [[CrossRef](#)]
331. Zhao, C.; Xue, J.; Ran, F.; Sun, S. Modification of Polyethersulfone Membranes—A Review of Methods. *Prog. Mater. Sci.* **2013**, *58*, 76–150. [[CrossRef](#)]
332. Khademian, E.; Salehi, E.; Sanaeepur, H.; Galiano, F.; Figoli, A. A Systematic Review on Carbohydrate Biopolymers for Adsorptive Remediation of Copper Ions from Aqueous Environments-Part A: Classification and Modification Strategies. *Sci. Total Environ.* **2020**, *738*, 139829. [[CrossRef](#)]
333. Salehi, E.; Daraei, P.; Arabi Shamsabadi, A. A Review on Chitosan-Based Adsorptive Membranes. *Carbohydr. Polym.* **2016**, *152*, 419–432. [[CrossRef](#)]
334. Adam, M.R.; Hubadillah, S.K.; Esham, M.I.M.; Othman, M.H.D.; Rahman, M.A.; Ismail, A.F.; Jaafar, J. Adsorptive Membranes for Heavy Metals Removal From Water. In *Membrane Separation Principles and Applications*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 361–400, ISBN 978-0-12-812815-2.
335. Alias, M.S.; Kamarudin, S.K.; Zainoodin, A.M.; Masdar, M.S. Active Direct Methanol Fuel Cell: An Overview. *Int. J. Hydrogen Energy* **2020**, *45*, 19620–19641. [[CrossRef](#)]
336. Anwar, F.; Arthanareeswaran, G. Silver Nano-Particle Coated Hydroxyapatite Nano-Composite Membrane for the Treatment of Palm Oil Mill Effluent. *J. Water Process Eng.* **2019**, *31*, 100844. [[CrossRef](#)]

337. Lalia, B.S.; Kochkodan, V.; Hashaiekh, R.; Hilal, N. A Review on Membrane Fabrication: Structure, Properties and Performance Relationship. *Desalination* **2013**, *326*, 77–95. [\[CrossRef\]](#)
338. Sundarrajan, S.; Balamurugan, R.; Kaur, S.; Ramakrishna, S. Potential of Engineered Electrospun Nanofiber Membranes for Nanofiltration Applications. *Dry. Technol.* **2013**, *31*, 163–169. [\[CrossRef\]](#)
339. Tijing, L.D.; Choi, J.-S.; Lee, S.; Kim, S.-H.; Shon, H.K. Recent Progress of Membrane Distillation Using Electrospun Nanofibrous Membrane. *J. Membr. Sci.* **2014**, *453*, 435–462. [\[CrossRef\]](#)
340. Ahmed, F.E.; Lalia, B.S.; Hashaiekh, R. A Review on Electrospinning for Membrane Fabrication: Challenges and Applications. *Desalination* **2015**, *356*, 15–30. [\[CrossRef\]](#)
341. Hai, F.I. Biocatalytic Membrane Reactors for the Removal of Recalcitrant and Emerging Pollutants from Wastewater. In *Handbook of Membrane Reactors*; Elsevier: Amsterdam, The Netherlands, 2013.
342. Tarchoun, A.F.; Trache, D.; Klapötke, T.M.; Krumm, B.; Kofen, M. Synthesis and Characterization of New Insensitive and High-Energy Dense Cellulosic Biopolymers. *Fuel* **2021**, *292*, 120347. [\[CrossRef\]](#)
343. Cheng, J.; Zhan, C.; Wu, J.; Cui, Z.; Si, J.; Wang, Q.; Peng, X.; Turng, L.-S. Highly Efficient Removal of Methylene Blue Dye from an Aqueous Solution Using Cellulose Acetate Nanofibrous Membranes Modified by Polydopamine. *ACS Omega* **2020**, *5*, 5389–5400. [\[CrossRef\]](#)
344. Esmaeili, N.; Boyd, S.E.; Brown, C.L.; Mac A Gray, E.; Webb, C.J. Improving the Gas-Separation Properties of PVAc-Zeolite 4A Mixed-Matrix Membranes through Nano-Sizing and Silanation of the Zeolite. *Chemphyschem Eur. J. Chem. Phys. Phys. Chem.* **2019**, *20*, 1590–1606. [\[CrossRef\]](#)
345. Ma, H.; Burger, C.; Hsiao, B.S.; Chu, B. Fabrication and Characterization of Cellulose Nanofiber Based Thin-Film Nanofibrous Composite Membranes. *J. Membr. Sci.* **2014**, *454*, 272–282. [\[CrossRef\]](#)
346. Kaur, S.; Sundarrajan, S.; Rana, D.; Matsuura, T.; Ramakrishna, S. Influence of Electrospun Fiber Size on the Separation Efficiency of Thin Film Nanofiltration Composite Membrane. *J. Membr. Sci.* **2012**, *392*–393, 101–111. [\[CrossRef\]](#)
347. Tian, M.; Qiu, C.; Liao, Y.; Chou, S.; Wang, R. Preparation of Polyamide Thin Film Composite Forward Osmosis Membranes Using Electrospun Polyvinylidene Fluoride (PVDF) Nanofibers as Substrates. *Sep. Purif. Technol.* **2013**, *118*, 727–736. [\[CrossRef\]](#)
348. Riaz, T.; Ahmad, A.; Saleemi, S.; Adrees, M.; Jamshed, F.; Hai, A.M.; Jamil, T. Synthesis and Characterization of Polyurethane-Cellulose Acetate Blend Membrane for Chromium (VI) Removal. *Carbohydr. Polym.* **2016**, *153*, 582–591. [\[CrossRef\]](#)
349. Nambikkattu, J.; Kaleekkal, N.J.; Jacob, J.P. Metal Ferrite Incorporated Polysulfone Thin-Film Nanocomposite Membranes for Wastewater Treatment. *Environ. Sci. Pollut. Res.* **2021**, *28*, 11915–11927. [\[CrossRef\]](#)
350. Mohammad, A.W.; Teow, Y.H.; Ang, W.L.; Chung, Y.T.; Oatley-Radcliffe, D.L.; Hilal, N. Nanofiltration Membranes Review: Recent Advances and Future Prospects. *Desalination* **2015**, *356*, 226–254. [\[CrossRef\]](#)
351. Kader, M.A.; Senge, M.; Mojid, M.A.; Ito, K. Recent Advances in Mulching Materials and Methods for Modifying Soil Environment. *Soil Tillage Res.* **2017**, *168*, 155–166. [\[CrossRef\]](#)
352. Wang, Z.; Zhao, X.; Wu, P.; Chen, X. Effects of Water Limitation on Yield Advantage and Water Use in Wheat (*Triticum aestivum* L.)/Maize (*Zea mays* L.) Strip Intercropping. *Eur. J. Agron.* **2015**, *71*, 149–159. [\[CrossRef\]](#)
353. Somanathan, H.; Sathasivam, R.; Sivaram, S.; Mariappan Kumaresan, S.; Muthuraman, M.S.; Park, S.U. An Update on Polyethylene and Biodegradable Plastic Mulch Films and Their Impact on the Environment. *Chemosphere* **2022**, *307*, 135839. [\[CrossRef\]](#) [\[PubMed\]](#)
354. Kasirajan, S.; Ngouajio, M. Polyethylene and Biodegradable Mulches for Agricultural Applications: A Review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [\[CrossRef\]](#)
355. Zhang, H.; Chen, M.; Qiao, R.; Ding, F.; Feng, H.; Jiang, R. Agronomic Performances of Biodegradable and Non-Biodegradable Plastic Film Mulching on a Maize Cropping System in the Semi-Arid Loess Plateau, China. *Pedosphere* **2024**, *34*, 88–96. [\[CrossRef\]](#)
356. Steinmetz, Z.; Wollmann, C.; Schaefer, M.; Buchmann, C.; David, J.; Tröger, J.; Muñoz, K.; Frör, O.; Schaumann, G.E. Plastic Mulching in Agriculture. Trading Short-Term Agronomic Benefits for Long-Term Soil Degradation? *Sci. Total Environ.* **2016**, *550*, 690–705. [\[CrossRef\]](#)
357. Tan, Q.; Yang, L.; Wei, F.; Chen, Y.; Li, J. Comparative Life Cycle Assessment of Polyethylene Agricultural Mulching Film and Alternative Options Including Different End-of-Life Routes. *Renew. Sustain. Energy Rev.* **2023**, *178*, 113239. [\[CrossRef\]](#)
358. Aa, H. Effect of Polyethylene Mulching Type on the Growth, Yield and Fruits Quality of *Physalis Pubescens*. *Adv. Plants Agric. Res.* **2017**, *6*, 00229. [\[CrossRef\]](#)
359. Malińska, K.; Pudelko, A.; Postawa, P.; Stachowiak, T.; Drózd, D. Performance of Biodegradable Biochar-Added and Bio-Based Plastic Clips for Growing Tomatoes. *Materials* **2022**, *15*, 7205. [\[CrossRef\]](#)
360. Berger, S.; Kim, Y.; Kettering, J.; Gebauer, G. Plastic Mulching in Agriculture—Friend or Foe of N<sub>2</sub>O Emissions? *Agric. Ecosyst. Environ.* **2013**, *167*, 43–51. [\[CrossRef\]](#)
361. El-Beltagi, H.S.; Basit, A.; Mohamed, H.I.; Ali, I.; Ullah, S.; Kamel, E.A.R.; Shalaby, T.A.; Ramadan, K.M.A.; Alkhateeb, A.A.; Ghazzawy, H.S. Mulching as a Sustainable Water and Soil Saving Practice in Agriculture: A Review. *Agronomy* **2022**, *12*, 1881. [\[CrossRef\]](#)
362. Dvorak, P.; Hajšlová, J.; Hamouz, K.; Schulzová, V.; Kuchtová, P.; Tomasek, J. Black Polypropylene Mulch Textile in Organic Agriculture. Available online: <https://orprints.org/id/eprint/20582/> (accessed on 19 May 2024).
363. Selke, S.; Auras, R.; Nguyen, T.A.; Castro Aguirre, E.; Cheruvathur, R.; Liu, Y. Evaluation of Biodegradation-Promoting Additives for Plastics. *Environ. Sci. Technol.* **2019**, *49*, 3769–3777. [\[CrossRef\]](#) [\[PubMed\]](#)

364. Ahmed, T.; Shahid, M.; Azeem, F.; Rasul, I.; Shah, A.A.; Noman, M.; Hameed, A.; Manzoor, N.; Manzoor, I.; Muhammad, S. Biodegradation of Plastics: Current Scenario and Future Prospects for Environmental Safety. *Environ. Sci. Pollut. Res.* **2018**, *25*, 7287–7298. [\[CrossRef\]](#)
365. López-Tolentino, G.; Ibarra-Jiménez, L.; Méndez-Prieto, A.; Río, A.J.L.; Lira-Saldivar, R.H.; Valenzuela-Soto, J.H.; Lozano-Cavazos, C.J.; Torres-Olivar, V. Photosynthesis, Growth, and Fruit Yield of Cucumber in Response to Oxo-Degradable Plastic Mulches. *Acta Agric. Scand. Sect. B—Soil Plant Sci.* **2017**, *67*, 77–84. [\[CrossRef\]](#)
366. Yang, Y.; Li, Z.; Yan, C.; Chadwick, D.; Jones, D.L.; Liu, E.; Liu, Q.; Bai, R.; He, W. Kinetics of Microplastic Generation from Different Types of Mulch Films in Agricultural Soil. *Sci. Total Environ.* **2022**, *814*, 152572. [\[CrossRef\]](#)
367. Hayes, D.G.; Anunciado, M.B.; DeBruyn, J.M.; Bandopadhyay, S.; Schaeffer, S.; English, M.; Ghimire, S.; Miles, C.; Flury, M.; Sintim, H.Y. Biodegradable Plastic Mulch Films for Sustainable Specialty Crop Production. In *Polymers for Agri-Food Applications*; Gutiérrez, T.J., Ed.; Springer International Publishing: Cham, Switzerland, 2019; pp. 183–213, ISBN 978-3-030-19416-1.
368. *Cellulose Fibers: Bio- and Nano-Polymer Composites: Green Chemistry and Technology*; Kalia, S.; Kaith, B.S.; Kaur, I. (Eds.) Springer: Berlin/Heidelberg, Germany, 2011; ISBN 978-3-642-17369-1.
369. Rosenboom, J.-G.; Langer, R.; Traverso, G. Bioplastics for a Circular Economy. *Nat. Rev. Mater.* **2022**, *7*, 117–137. [\[CrossRef\]](#) [\[PubMed\]](#)
370. Finkenstadt, V.L.; Tisserat, B. Poly(Lactic Acid) and Osage Orange Wood Fiber Composites for Agricultural Mulch Films. *Ind. Crop. Prod.* **2010**, *31*, 316–320. [\[CrossRef\]](#)
371. Yamamoto-Tamura, K.; Hoshino, Y.T.; Tsuboi, S.; Huang, C.; Kishimoto-Mo, A.W.; Sameshima-Yamashita, Y.; Kitamoto, H. Fungal Community Dynamics during Degradation of Poly(Butylene Succinate-Co-Adipate) Film in Two Cultivated Soils in Japan. *Biosci. Biotechnol. Biochem.* **2020**, *84*, 1077–1087. [\[CrossRef\]](#)
372. Ning, R.; Liu, C.; Cheng, X.; Lei, F.; Zhang, F.; Xu, W.; Zhu, L.; Jiang, J. Fabrication of Multi-Functional Biodegradable Liquid Mulch Utilizing Xyloglucan Derived from Tamarind Waste for Agricultural Application. *Int. J. Biol. Macromol.* **2024**, *257*, 128627. [\[CrossRef\]](#)
373. Wang, K.; Sun, X.; Long, B.; Li, F.; Yang, C.; Chen, J.; Ma, C.; Xie, D.; Wei, Y. Green Production of Biodegradable Mulch Films for Effective Weed Control. *ACS Omega* **2021**, *6*, 32327–32333. [\[CrossRef\]](#)
374. Corrêa, A.C.; De Campos, A.; Claro, P.I.C.; Guimarães, G.G.F.; Mattoso, L.H.C.; Marconcini, J.M. Biodegradability and Nutrients Release of Thermoplastic Starch and Poly( $\epsilon$ -Caprolactone) Blends for Agricultural Uses. *Carbohydr. Polym.* **2022**, *282*, 119058. [\[CrossRef\]](#) [\[PubMed\]](#)
375. Bartnikowski, M.; Dargaville, T.R.; Ivanovski, S.; Huttmacher, D.W. Degradation Mechanisms of Polycaprolactone in the Context of Chemistry, Geometry and Environment. *Prog. Polym. Sci.* **2019**, *96*, 1–20. [\[CrossRef\]](#)
376. Szymanek, I.; Cvek, M.; Rogacz, D.; Źarski, A.; Lewicka, K.; Sedlarik, V.; Rychter, P. Degradation of Polylactic Acid/Polypropylene Carbonate Films in Soil and Phosphate Buffer and Their Potential Usefulness in Agriculture and Agrochemistry. *Int. J. Mol. Sci.* **2024**, *25*, 653. [\[CrossRef\]](#)
377. Gu, X.-B.; Li, Y.-N.; Du, Y.-D. Biodegradable Film Mulching Improves Soil Temperature, Moisture and Seed Yield of Winter Oilseed Rape (*Brassica napus* L.). *Soil Tillage Res.* **2017**, *171*, 42–50. [\[CrossRef\]](#)
378. Kijchavengkul, T.; Auras, R.; Rubino, M.; Alvarado, E.; Camacho Montero, J.R.; Rosales, J.M. Atmospheric and Soil Degradation of Aliphatic–Aromatic Polyester Films. *Polym. Degrad. Stab.* **2010**, *95*, 99–107. [\[CrossRef\]](#)
379. Souza, P.M.S.; Sommaggio, L.R.D.; Marin-Morales, M.A.; Morales, A.R. PBAT Biodegradable Mulch Films: Study of Ecotoxicological Impacts Using Allium Cepa, Lactuca Sativa and HepG2/C3A Cell Culture. *Chemosphere* **2020**, *256*, 126985. [\[CrossRef\]](#)
380. Michalik, R.; Wandzik, I. A Mini-Review on Chitosan-Based Hydrogels with Potential for Sustainable Agricultural Applications. *Polymers* **2020**, *12*, 2425. [\[CrossRef\]](#)
381. Supare, K.; Mahanwar, P.A. Starch-Derived Superabsorbent Polymers in Agriculture Applications: An Overview. *Polym. Bull.* **2022**, *79*, 5795–5824. [\[CrossRef\]](#)
382. Gan, J.; Zhu, Y.; Wilen, C.; Pittenger, D.; Crowley, D. Effect of Planting Covers on Herbicide Persistence in Landscape Soils. *Environ. Sci. Technol.* **2003**, *37*, 2775–2779. [\[CrossRef\]](#)
383. Kader, M.A.; Singha, A.; Begum, M.A.; Jewel, A.; Khan, F.H.; Khan, N.I. Mulching as Water-Saving Technique in Dryland Agriculture: Review Article. *Bull. Natl. Res. Cent.* **2019**, *43*, 147. [\[CrossRef\]](#)
384. Haider, T.P.; Völker, C.; Kramm, J.; Landfester, K.; Wurm, F.R. Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society. *Angew. Chem. Int. Ed.* **2019**, *58*, 50–62. [\[CrossRef\]](#) [\[PubMed\]](#)
385. Saha, A.; Sekharan, S.; Manna, U. Superabsorbent Hydrogel (SAH) as a Soil Amendment for Drought Management: A Review. *Soil Tillage Res.* **2020**, *204*, 104736. [\[CrossRef\]](#)
386. Feng, D.; Bai, B.; Ding, C.; Wang, H.; Suo, Y. Synthesis and Swelling Behaviors of Yeast- g -Poly(Acrylic Acid) Superabsorbent Co-Polymer. *Ind. Eng. Chem. Res.* **2014**, *53*, 12760–12769. [\[CrossRef\]](#)
387. Saha, A.; Rattan, B.; Sekharan, S.; Manna, U. Quantifying the Interactive Effect of Water Absorbing Polymer (WAP)-Soil Texture on Plant Available Water Content and Irrigation Frequency. *Geoderma* **2020**, *368*, 114310. [\[CrossRef\]](#)
388. Buchmann, C.; Bentz, J.; Schaumann, G.E. Intrinsic and Model Polymer Hydrogel-Induced Soil Structural Stability of a Silty Sand Soil as Affected by Soil Moisture Dynamics. *Soil Tillage Res.* **2015**, *154*, 22–33. [\[CrossRef\]](#)
389. Ullah, F.; Othman, M.B.H.; Javed, F.; Ahmad, Z.; Md Akil, H. Classification, Processing and Application of Hydrogels: A Review. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2015**, *57*, 414–433. [\[CrossRef\]](#)

390. Guilherme, M.R.; Aouada, F.A.; Fajardo, A.R.; Martins, A.F.; Paulino, A.T.; Davi, M.F.T.; Rubira, A.F.; Muniz, E.C. Superabsorbent Hydrogels Based on Polysaccharides for Application in Agriculture as Soil Conditioner and Nutrient Carrier: A Review. *Eur. Polym. J.* **2015**, *72*, 365–385. [\[CrossRef\]](#)
391. Ahmed, E.M. Hydrogel: Preparation, Characterization, and Applications: A Review. *J. Adv. Res.* **2015**, *6*, 105–121. [\[CrossRef\]](#)
392. Xu, J.; Liu, X.; Ren, X.; Gao, G. The Role of Chemical and Physical Crosslinking in Different Deformation Stages of Hybrid Hydrogels. *Eur. Polym. J.* **2018**, *100*, 86–95. [\[CrossRef\]](#)
393. Xiao, X.; Yu, L.; Xie, F.; Bao, X.; Liu, H.; Ji, Z.; Chen, L. One-Step Method to Prepare Starch-Based Superabsorbent Polymer for Slow Release of Fertilizer. *Chem. Eng. J.* **2017**, *309*, 607–616. [\[CrossRef\]](#)
394. Zhang, Y.; Zhao, L.; Chen, Y. Synthesis and Characterization of Starch-g-Poly(Acrylic Acid)/Organo-Zeolite 4A Superabsorbent Composites with Respect to Their Water-Holding Capacities and Nutrient-Release Behavior. *Polym. Compos.* **2017**, *38*, 1838–1848. [\[CrossRef\]](#)
395. Chibac-Scutaru, A.L.; Coseri, S. Advances in the Use of Cellulose-Based Proton Exchange Membranes in Fuel Cell Technology: A Review. *Int. J. Biol. Macromol.* **2023**, *247*, 125810. [\[CrossRef\]](#) [\[PubMed\]](#)
396. Duceac, I.A.; Coseri, S. Biopolymers and Their Derivatives: Key Components of Advanced Biomedical Technologies. *Biotechnol. Adv.* **2022**, *61*, 108056. [\[CrossRef\]](#) [\[PubMed\]](#)
397. Culica, M.E.; Chibac-Scutaru, A.-L.; Mohan, T.; Coseri, S. Cellulose-Based Biogenic Supports, Remarkably Friendly Biomaterials for Proteins and Biomolecules. *Biosens. Bioelectron.* **2021**, *182*, 113170. [\[CrossRef\]](#) [\[PubMed\]](#)
398. Duceac, I.A.; Vereștiuc, L.; Coroaba, A.; Arotăritei, D.; Coseri, S. All-Polysaccharide Hydrogels for Drug Delivery Applications: Tunable Chitosan Beads Surfaces via Physical or Chemical Interactions, Using Oxidized Pullulan. *Int. J. Biol. Macromol.* **2021**, *181*, 1047–1062. [\[CrossRef\]](#)
399. Duceac, I.A.; Coseri, S. Chitosan Schiff-Base Hydrogels—A Critical Perspective Review. *Gels* **2022**, *8*, 779. [\[CrossRef\]](#)
400. Dragan, E.S.; Ghiorghita, C.-A.; Dinu, M.; Duceac, I.; Coseri, S. Fabrication of Self-Antibacterial Chitosan/Oxidized Starch Polyelectrolyte Complex Sponges for Controlled Delivery of Curcumin. *Food Hydrocoll.* **2022**, *135*, 108147. [\[CrossRef\]](#)
401. Baron, R.I.; Bercea, M.; Avadanei, M.; Lisa, G.; Biliuta, G.; Coseri, S. Green Route for the Fabrication of Self-Healable Hydrogels Based on Tricarboxy Cellulose and Poly(Vinyl Alcohol). *Int. J. Biol. Macromol.* **2019**, *123*, 744–751. [\[CrossRef\]](#)
402. Biliuta, G.; Suteu, D.; Malutan, T.; Chirculescu, A.-I.; Nica, I.; Coseri, S. Valorization of tempo-oxidized cellulosic fractions for efficient dye removal from wastewaters. *Cellul. Chem. Technol.* **2018**, *52*, 609–618.
403. Coseri, S.; Biliuta, G.; Simionescu, B.C. Selective Oxidation of Cellulose, Mediated by N-Hydroxyphthalimide, under a Metal-Free Environment. *Polym. Chem.* **2018**, *9*, 961–967. [\[CrossRef\]](#)
404. Culica, M.; Biliuta, G.; Rotaru, R.; Lisa, G.; Baron, R.; Coseri, S. New Electromagnetic Shielding Materials Based on Viscose-carbon Nanotubes Composites. *Polym. Eng. Sci.* **2019**, *59*, 1499–1506. [\[CrossRef\]](#)
405. Biliuta, G.; Sacarescu, L.; Socoliuc, V.; Iacob, M.; Gheorghe, L.; Negru, D.; Coseri, S. Carboxylated Polysaccharides Decorated with Ultrasmall Magnetic Nanoparticles with Antibacterial and MRI Properties. *Macromol. Chem. Phys.* **2017**, *218*, 1700062. [\[CrossRef\]](#)
406. Zhang, Z.; Abidi, N.; Lucia, L.; Chabi, S.; Denny, C.T.; Parajuli, P.; Rumi, S.S. Cellulose/Nanocellulose Superabsorbent Hydrogels as a Sustainable Platform for Materials Applications: A Mini-Review and Perspective. *Carbohydr. Polym.* **2023**, *299*, 120140. [\[CrossRef\]](#) [\[PubMed\]](#)
407. Wang, W.; Yang, Z.; Zhang, A.; Yang, S. Water Retention and Fertilizer Slow Release Integrated Superabsorbent Synthesized from Millet Straw and Applied in Agriculture. *Ind. Crop. Prod.* **2021**, *160*, 113126. [\[CrossRef\]](#)
408. Zhang, M.; Yang, J. Preparation and Characterization of Multifunctional Slow Release Fertilizer Coated with Cellulose Derivatives. *Int. J. Polym. Mater. Polym. Biomater.* **2020**, *70*, 774–781. [\[CrossRef\]](#)
409. Barajas-Ledesma, R.M.; Patti, A.F.; Wong, V.N.L.; Raghuwanshi, V.S.; Garnier, G. Engineering Nanocellulose Superabsorbent Structure by Controlling the Drying Rate. *Colloids Surf. Physicochem. Eng. Asp.* **2020**, *600*, 124943. [\[CrossRef\]](#)
410. Barajas-Ledesma, R.M.; Wong, V.N.L.; Little, K.; Patti, A.F.; Garnier, G. Carboxylated Nanocellulose Superabsorbent: Biodegradation and Soil Water Retention Properties. *J. Appl. Polym. Sci.* **2022**, *139*, 51495. [\[CrossRef\]](#)
411. Tanpichai, S.; Phoothong, F.; Boonmahitthisud, A. Superabsorbent Cellulose-Based Hydrogels Cross-Liked with Borax. *Sci. Rep.* **2022**, *12*, 8920. [\[CrossRef\]](#)
412. Kim, B.; Kim, T.-H.; Lee, B. Optimal Synthesis of Carboxymethylcellulose-Based Composite Superabsorbents. *Korean J. Chem. Eng.* **2021**, *38*, 215–225. [\[CrossRef\]](#)
413. Das, D.; Prakash, P.; Rout, P.K.; Bhaladhare, S. Synthesis and Characterization of Superabsorbent Cellulose-Based Hydrogel for Agriculture Application. *Starch-Stärke* **2021**, *73*, 1900284. [\[CrossRef\]](#)
414. Ajmeri, J.R.; Ajmeri, C.J. Developments in Nonwovens as Agrotexiles. In *Advances in Technical Nonwovens*; Woodhead Publishing: Sawston, UK, 2016; pp. 365–384, ISBN 978-0-08-100575-0.
415. Šišková, A.O.; Peer, P.; Andicsová, A.E.; Jordanov, I.; Rychter, P. Circulatory Management of Polymer Waste: Recycling into Fine Fibers and Their Applications. *Materials* **2021**, *14*, 4694. [\[CrossRef\]](#) [\[PubMed\]](#)
416. Shi, L.; Li, Z.; Zhang, Y.; Ren, Z.; Zhang, Y.; Li, S.; Weng, W. Electrospun Starch-Based Nanofiber Mats for Odor Adsorption of Oyster Peptides: Recyclability and Structural Characterization. *Food Hydrocoll.* **2024**, *147*, 109408. [\[CrossRef\]](#)
417. Liu, X.; Chen, C.; Sun, J.; Wang, X. Development of Natural Fiber-Based Degradable Nonwoven Mulch from Recyclable Mill Waste. *Waste Manag.* **2021**, *121*, 432–440. [\[CrossRef\]](#) [\[PubMed\]](#)

418. Yang, T.; Xiong, X.; Petrů, M.; Tan, X.; Kaneko, H.; Militký, J.; Sakuma, A. Theoretical and Experimental Studies on Thermal Properties of Polyester Nonwoven Fibrous Material. *Materials* **2020**, *13*, 2882. [\[CrossRef\]](#)
419. Chizhov, A.S.; Ol'khov, A.A.; Monakhova, T.V.; Shibryaeva, L.S.; Iordanskii, A.L. Thermooxidation and Biodegradation of Nonwoven Biopolymer Fibrous Materials. *Polym. Sci. Ser. D* **2018**, *11*, 339–343. [\[CrossRef\]](#)
420. Marczak, D.; Lejcuś, K.; Grzybowska-Pietras, J.; Biniaś, W.; Lejcuś, I.; Misiewicz, J. Biodegradation of Sustainable Nonwovens Used in Water Absorbing Geocomposites Supporting Plants Vegetation. *Sustain. Mater. Technol.* **2020**, *26*, e00235. [\[CrossRef\]](#)
421. Hablot, E.; Dharmalingam, S.; Hayes, D.; Wadsworth, L.; Blazy, C.; Narayan, R. Effect of Simulated Weathering on Physicochemical Properties and Inherent Biodegradation of PLA/PHA Nonwoven Mulches. *J. Polym. Environ.* **2014**, *22*, 417–429. [\[CrossRef\]](#)
422. Dharmalingam, S.; Hayes, D.; Wadsworth, L.; Dunlap, R.; DeBruyn, J.; Lee, J.; Wszelaki, A. Soil Degradation of Polylactic Acid/Polyhydroxyalkanoate-Based Nonwoven Mulches. *J. Polym. Environ.* **2015**, *23*, 302–315. [\[CrossRef\]](#)
423. Gaminian, H.; Ahvazi, B.; Vidmar, J.J.; Ekuere, U.; Regan, S. Revolutionizing Sustainable Nonwoven Fabrics: The Potential Use of Agricultural Waste and Natural Fibres for Nonwoven Fabric. *Biomass* **2024**, *4*, 363–401. [\[CrossRef\]](#)
424. Anand, S.C.; Brunnschweiler, D.; Swarbrick, G.; Russell, S.J. Chapter 8—Mechanical Bonding. In *Handbook of Nonwovens*, 2nd ed.; Russell, S.J., Ed.; The Textile Institute Book Series; Woodhead Publishing: Cambridge, UK, 2022; pp. 301–393, ISBN 978-0-12-818912-2.
425. Yan, Y. 2—Developments in Fibers for Technical Nonwovens. In *Advances in Technical Nonwovens*; Kellie, G., Ed.; Woodhead Publishing Series in Textiles; Woodhead Publishing: Cambridge, UK, 2016; pp. 19–96, ISBN 978-0-08-100575-0.
426. Böhme, M.; Pinker, I.; Grueneberg, H.; Herfort, S. Sheep Wool as Fertiliser for Vegetables and Flowers in Organic Farming. *Acta Hortic.* **2012**, *933*, 195–202. [\[CrossRef\]](#)
427. Broda, J.; Gawłowski, A.; Grzybowska-Pietras, J.; Rom, M.; Przybyło, S.; Laszczak, R. Application of geotextiles for the stabilization of steep slopes in gravel pits. *Inż. Ekol.* **2017**, *18*, 71–77. [\[CrossRef\]](#)
428. Zheljazkov, V.D.; Stratton, G.W.; Pincok, J.; Butler, S.; Jeliaskova, E.A.; Nedkov, N.K.; Gerard, P.D. Wool-Waste as Organic Nutrient Source for Container-Grown Plants. *Waste Manag.* **2009**, *29*, 2160–2164. [\[CrossRef\]](#) [\[PubMed\]](#)
429. Gabryś, T.; Fryczkowska, B.; Grzybowska-Pietras, J.; Biniaś, D. Modification and Properties of Cellulose Nonwoven Fabric—Multifunctional Mulching Material for Agricultural Applications. *Materials* **2021**, *14*, 4335. [\[CrossRef\]](#)
430. Gao, Y.; Truong, Y.B.; Cacioli, P.; Butler, P.; Kyratzis, I.L. Bioremediation of Pesticide Contaminated Water Using an Organophosphate Degrading Enzyme Immobilized on Nonwoven Polyester Textiles. *Enzyme Microb. Technol.* **2014**, *54*, 38–44. [\[CrossRef\]](#)
431. Ingmar, O.; Setiyono, S.; Savitri, D.A.; Novijanto, N. Effect of Seed Coating and Packaging Material on Viability and Vigor of Soybean Seed in Room Temperature Storage. *J. Appl. Agric. Sci. Technol.* **2023**, *7*, 109–118. [\[CrossRef\]](#)
432. Zhang, K.; Khan, Z.; Yu, Q.; Qu, Z.; Liu, J.; Luo, T.; Zhu, K.; Bi, J.; Hu, L.; Luo, L. Biochar Coating Is a Sustainable and Economical Approach to Promote Seed Coating Technology, Seed Germination, Plant Performance, and Soil Health. *Plants* **2022**, *11*, 2864. [\[CrossRef\]](#)
433. Samarah, N.H.; Aldahadha, A. Effect of Polymer Coating on Seed Germination and the Emergence of Squash (*Cucurbita pepo* Zucchini). *J. Appl. Hortic.* **2023**, *24*, 288–292. [\[CrossRef\]](#)
434. Zeng, D.; Fan, Z.; Tian, X.; Wang, W.; Zhou, M.; Li, H. Preparation and Mechanism Analysis of an Environment-Friendly Maize Seed Coating Agent. *J. Sci. Food Agric.* **2018**, *98*, 2889–2897. [\[CrossRef\]](#)
435. Giroto, A.S.; Valle, S.F.; Guimarães, G.G.F.; Ohrem, B.; Bresolin, J.; Lücke, A.; Wissel, H.; Hungria, M.; Ribeiro, C.; Mattoso, L.H.C.; et al. Polyglycerol Citrate: A Novel Coating and Inoculation Material for Soybean Seeds. *Environ. Technol. Innov.* **2024**, *34*, 103627. [\[CrossRef\]](#)
436. Akhter, M.; Shah, G.A.; Niazi, M.B.K.; Mir, S.; Jahan, Z.; Rashid, M.I. Novel Water-Soluble Polymer Coatings Control NPK Release Rate, Improve Soil Quality and Maize Productivity. *J. Appl. Polym. Sci.* **2021**, *138*, 51239. [\[CrossRef\]](#)
437. Kumar, N. Polysaccharide-Based Component and Their Relevance in Edible Film/Coating: A Review. *Nutr. Food Sci.* **2019**, *49*, 793–823. [\[CrossRef\]](#)
438. Campos de Melo, A.P.; de Melo e Silva-Neto, C.; Seleguini, A.; Marçal Fernandes, P. Does Fruit Cooling and Seed Film Coating Affect the Germination Potential of Physalis? *Sci. Agropecu.* **2015**, *6*, 325–328. [\[CrossRef\]](#)
439. Afzal, I.; Javed, T.; Amirkhani, M.; Taylor, A.G. Modern Seed Technology: Seed Coating Delivery Systems for Enhancing Seed and Crop Performance. *Agriculture* **2020**, *10*, 526. [\[CrossRef\]](#)
440. do Espírito Santo Pereira, A.; Caixeta Oliveira, H.; Fernandes Fraceto, L.; Santaella, C. Nanotechnology Potential in Seed Priming for Sustainable Agriculture. *Nanomaterials* **2021**, *11*, 267. [\[CrossRef\]](#)
441. Ludwig, E.J.; Nunes, U.R.; Prestes, O.D.; Fagundes, L.K.; Fernandes, T.S.; Saibt, N. Polymer Coating in Soybean Seed Treatment and Their Relation to Leaching of Chemicals. *Rev. Ambiente Água* **2020**, *15*, e2602. [\[CrossRef\]](#)
442. Rakesh, P.; Prasad, R.D.; Devi, G.U.; Bhat, B.N. In Vitro Assessment of Seedling Growth and Management of Castor Wilt and Groundnut Collar Rot through the Combination of Seed Coat Polymers, Fungicides and Bioagents. *Bull. Environ. Pharmacol. Life Sci.* **2017**, *6*, 147–153.
443. Kumar, S.; Gangwar, C.B.; Gupta, H.; Yadav, G.; Singh, S.; Yadav, S.K. Influence of Seed Coating with Polymer Coat and Chemical on Pigeon Pea Seed Quality during Storage. *Pharma Innov. J.* **2022**, *11*, 2222–2224. [\[CrossRef\]](#)
444. Robani, H. Film-Coating of Horticultural Seed. *HortTechnology* **1994**, *4*, 104–105. [\[CrossRef\]](#)
445. Accinelli, C.; Abbas, H.K.; Shier, W.T.; Vicari, A.; Little, N.S.; Aloise, M.R.; Giacomini, S. Degradation of Microplastic Seed Film-Coating Fragments in Soil. *Chemosphere* **2019**, *226*, 645–650. [\[CrossRef\]](#)

446. Vercelheze, A.E.S.; Marim, B.M.; Oliveira, A.L.M.; Mali, S. Development of Biodegradable Coatings for Maize Seeds and Their Application for Azospirillum Brasilense Immobilization. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 2193–2203. [\[CrossRef\]](#)
447. Lee, S.; Hong, J.-Y.; Jang, J. Synthesis and Electrical Response of Polyaniline/Poly(Styrene Sulfonate)-Coated Silica Spheres Prepared by Seed-Coating Method. *J. Colloid Interface Sci.* **2013**, *398*, 33–38. [\[CrossRef\]](#) [\[PubMed\]](#)
448. Abd El-Aziz, M.E.; Salama, D.M.; Morsi, S.M.M.; Youssef, A.M.; El-Sakhawy, M. Development of Polymer Composites and Encapsulation Technology for Slow-Release Fertilizers. *Rev. Chem. Eng.* **2022**, *38*, 603–616. [\[CrossRef\]](#)
449. Korbecka-Glinka, G.; Wiśniewska-Wrona, M.; Kopania, E. Zastosowanie Polimerów Naturalnych Do Uszlachetniania Materiału Siewnego. *Polimery* **2021**, *66*, 11–20. [\[CrossRef\]](#)
450. Turco, R.; Ortega-Toro, R.; Tesser, R.; Mallardo, S.; Collazo-Bigliardi, S.; Chiralt Boix, A.; Malinconico, M.; Rippa, M.; Di Serio, M.; Santagata, G. Poly (Lactic Acid)/Thermoplastic Starch Films: Effect of Cardoon Seed Epoxidized Oil on Their Chemicophysical, Mechanical, and Barrier Properties. *Coatings* **2019**, *9*, 574. [\[CrossRef\]](#)
451. Pathak, V.; Ambrose, R.P.K. Starch-Based Biodegradable Hydrogel as Seed Coating for Corn to Improve Early Growth under Water Shortage. *J. Appl. Polym. Sci.* **2020**, *137*, 48523. [\[CrossRef\]](#)
452. Dogaru, B.-I.; Stoleru, V.; Mihalache, G.; Yonsel, S.; Popescu, M.-C. Gelatin Reinforced with CNCs as Nanocomposite Matrix for Trichoderma Harzianum KUEN 1585 Spores in Seed Coatings. *Molecules* **2021**, *26*, 5755. [\[CrossRef\]](#)
453. Yakupoglu, T.; Rodrigo-Comino, J.; Cerdà, A. Potential Benefits of Polymers in Soil Erosion Control for Agronomical Plans: A Laboratory Experiment. *Agronomy* **2019**, *9*, 276. [\[CrossRef\]](#)
454. Donayre, A.; Sanchez, L.F.; Kim, S.; Aguilar, R.; Nakamatsu, J. Eco-Friendly Improvement of Water Erosion Resistance of Unstable Soils with Biodegradable Polymers. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *416*, 012044. [\[CrossRef\]](#)
455. Larson, S.; Newman, J.K.; O Connor, G.; Griggs, C.; Martin, A.; Nijak, G.; Lord, E.; Duggar, R.; Leeson, A. *Biopolymer as an Alternative to Petroleum-Based Polymers to Control Soil Erosion: Iowa Army Ammunition Plant*; Defense Technical Information Center: Fort Belvoir, VA, USA, 2013.
456. Algadwi, M.B.; Spyropoulos, E.; Nawaz, B.A. Erosion Protection by Polymer Additive. In Proceedings of the 2nd International Conference on Civil Engineering Fundamentals and Applications (ICCEFA'21), Seoul, Republic of Korea, 21–23 November 2021.
457. CSIRO PUBLISHING | Soil Research. Available online: <https://www.publish.csiro.au/SR/SR05175> (accessed on 14 April 2024).
458. Effect of Polyacrylamide Polymer on Wind Erosion Control of Sandy Soil in Azadegan Plain. Available online: [https://jsw.um.ac.ir/article\\_38575\\_en.html](https://jsw.um.ac.ir/article_38575_en.html) (accessed on 14 April 2024).
459. Flanagan, D.C.; Norton, L.D.; Peterson, J.R.; Chaudhari, K. Using Polyacrylamide to Control Erosion on Agricultural and Disturbed Soils in Rainfed Areas. *J. Soil Water Conserv.* **2003**, *58*, 301–311.
460. Koerner, R.M.; Okrasinski, T.A. Erosion Control of Granular Soils Using PVA. *J. Constr. Div.* **1978**, *104*, 279–294. [\[CrossRef\]](#)
461. Zhang, W.; Liu, Q.; Xu, Y.; Mu, X.; Zhang, H.; Lei, Z. Waste Cabbage-Integrated Nutritional Superabsorbent Polymers for Water Retention and Absorption Applications. *Langmuir* **2022**, *38*, 14869–14878. [\[CrossRef\]](#) [\[PubMed\]](#)
462. Huang, W.; Zhou, C.; Liu, Z. Model Test Study on the Enhancement of Ecological Self-Repairing Ability of Surface Slope Soil by New Polymer Composites. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9933. [\[CrossRef\]](#) [\[PubMed\]](#)
463. Panova, I.; Drobyazko, A.; Spiridonov, V.; Sybachin, A.; Kydraliev, K.; Jorobekova, S.; Yaroslavov, A. Humics-Based Interpolyelectrolyte Complexes for Antierosion Protection of Soil: Model Investigation. *Land Degrad. Dev.* **2019**, *30*, 337–347. [\[CrossRef\]](#)
464. Wali, S.; Khattak, M.I.K. and M.I. Synthesis, Characterization and Application of Karak Bentonite Clay-Graft-Poly (Acrylamide/Co- Acrylic Acid) Superabsorbent Composite and Its Adsorption Study for Selected Heavy Metals. *J. Chem. Soc. Pak.* **2023**, *45*, 226.
465. Tian, H.; Cheng, S.; Zhen, J.; Lei, Z. Superabsorbent Polymer with Excellent Water/Salt Absorbency and Water Retention, and Fast Swelling Properties for Preventing Soil Water Evaporation. *J. Polym. Environ.* **2023**, *31*, 812–824. [\[CrossRef\]](#)
466. Khudhair, H.H.; Basim, K.N.; Al-Baidhani, J.H. Experimental Study of the Effect on Soil Erosion of Using Tiny Gravel as Bedding for Defective Sewer Pipes. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1067*, 012008. [\[CrossRef\]](#)
467. Doroftei, B.-I.; Degeratu, M.; Bandoc, G. Numerical tests for soil erosion reduction solutions under the action of the wind. *Ann. Acad. Rom. Sci. Ser. Eng. Sci.* **2022**, *14*, 62–72. [\[CrossRef\]](#)
468. Misiewicz, J.; Datta, S.S.; Lejcuś, K.; Marczak, D. The Characteristics of Time-Dependent Changes of Coefficient of Permeability for Superabsorbent Polymer-Soil Mixtures. *Materials* **2022**, *15*, 4465. [\[CrossRef\]](#)
469. Kou, H.; Jia, H.; Chu, J.; Zheng, P.; Liu, A. Effect of Polymer on Strength and Permeability of Marine Clay. *Mar. Georesources Geotechnol.* **2021**, *39*, 234–240. [\[CrossRef\]](#)
470. Shaheen, A.; Turaib Ali Bukhari, S. Potential of Sawdust and Corn Cobs Derived Biochar to Improve Soil Aggregate Stability, Water Retention, and Crop Yield of Degraded Sandy Loam Soil. *J. Plant Nutr.* **2018**, *41*, 2673–2682. [\[CrossRef\]](#)
471. Jinger, D.; Kumar, R.; Kakade, V.; Dinesh, D.; Singh, G.; Pande, V.C.; Bhatnagar, P.R.; Rao, B.K.; Vishwakarma, A.K.; Kumar, D.; et al. Agroforestry for Controlling Soil Erosion and Enhancing System Productivity in Ravine Lands of Western India under Climate Change Scenario. *Environ. Monit. Assess.* **2022**, *194*, 267. [\[CrossRef\]](#) [\[PubMed\]](#)
472. de Carvalho, I.V.; Camilloto, G.P. Polímeros biodegradáveis na agricultura. *An. Semin. Iniciaç. Científica* **2021**, *25*. [\[CrossRef\]](#)
473. Ben-Hur, M. Using Synthetic Polymers as Soil Conditioners to Control Runoff and Soil Loss in Arid and Semi-Arid Regions—A Review. *Soil Res.* **2006**, *44*, 191–204. [\[CrossRef\]](#)

474. Haghighat, P.H.; Torabi, A.M. Preparation of biodegradable low density polyethylene by starch—Urea composition for agricultural applications. *Iran. J. Chem. Chem. Eng.* **2004**, *23*, 7–11.
475. Thiagamani, S.M.K.; Krishnasamy, S.; Siengchin, S. Challenges of Biodegradable Polymers: An Environmental Perspective. *Appl. Sci. Eng. Prog.* **2024**, *12*, 149. [\[CrossRef\]](#)
476. Khan, M.; Zaheer, M.H.; Kakar, H.K.; Ullah, Z.; Bukhsh, K. Reuse of Non-Degradable Waste Polyethylene Bottles for Ground Improvement. *J. ICT Des. Eng. Technol. Sci.* **2023**, *7*, 1–5. [\[CrossRef\]](#)
477. Tyagi, P.; Agate, S.; Velez, O.D.; Lucia, L.; Pal, L. A Critical Review of the Performance and Soil Biodegradability Profiles of Biobased Natural and Chemically Synthesized Polymers in Industrial Applications. *Environ. Sci. Technol.* **2022**, *56*, 2071–2095. [\[CrossRef\]](#)
478. Sun, B.; Guo, C.; Chen, Y.; Chu, X.; Ma, X. Study on Spraying Construction Method of a Non-Water Reacting Polymer Layer in the Tunnel. *Materials* **2022**, *15*, 4138. [\[CrossRef\]](#)
479. Guo, C.; Wang, F. Research on Polymer Injection Technology for Quick Tunnel Repairment. In Proceedings of the Road Pavement Material Characterization and Rehabilitation: Selected Papers from the 2009 GeoHunan International Conference, Changsha, China, 3–6 August 2012; pp. 110–117. [\[CrossRef\]](#)
480. Shokodko, E.; Bobrova, E.Y.; Zinoveva, E.A.; Zhukov, A.D. Dome House Insulation Systems. *Mater. Sci. Forum* **2020**, *992*, 48–53. [\[CrossRef\]](#)
481. Plank, J. Polymere für die Tiefbohrzementierung. *Nachrichten Aus Chem.* **2011**, *59*, 510–515. [\[CrossRef\]](#)
482. Nirman, P. Polyimide Nanocomposites and Its Application. *Int. J. Res. Appl. Sci. Eng. Technol.* **2018**, *6*, 2448–2851. [\[CrossRef\]](#)
483. Tan, J.; Wang, Q.; Liu, Y.; Zeng, Y.; Ding, Q.; Wu, R.; Liu, Y.; Xiang, X. Synthesis, Gas Barrier and Thermal Properties of Polyimide Containing Rigid Planar Fluorene Moieties. *J. Macromol. Sci. Part A* **2018**, *55*, 75–84. [\[CrossRef\]](#)
484. Yoshida, M.; Hoshino, K.; Taino, T.; Myoren, H.; Takada, S.; Kikuchi, K.; Nakagawa, H.; Aoyagi, M.; Sato, H.; Shimizu, H.M. X-Ray Detection Using Superconducting Tunnel Junctions with Polyimide Insulation Layer. *IEEE Trans. Appl. Supercond.* **2005**, *15*, 606–608. [\[CrossRef\]](#)
485. Iwamoto, M.; Kubota, T. Elastic and Inelastic Tunneling through Polyimide LB Films. In Proceedings of the 1994 4th International Conference on Properties and Applications of Dielectric Materials (ICPADM), Brisbane, Australia, 3–8 July 1994; Volume 1, pp. 197–200.
486. Dhamaniya, S.; Gupta, V.; Kakatkar, R. Recent Advances in Biodegradable Polymers. *J. Res. Updat. Polym. Sci.* **2018**, *7*. [\[CrossRef\]](#)
487. Zhang, W. Analysis on the Development and Application of Biodegradable Polymers. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *647*, 012156. [\[CrossRef\]](#)
488. Vroman, I.; Tighzert, L. Biodegradable Polymers. *Materials* **2009**, *2*, 307–344. [\[CrossRef\]](#)
489. Dehbi, A.; Youssef, B.; Mourad, A.-H.I.; Chappey, C.; Picuno, P.; Statuto, D. Physical and Gas Permeation Properties of Five-Layer Polyethylene Film Used as Greenhouse Roof. *J. Agric. Eng.* **2018**, *49*, 124–129. [\[CrossRef\]](#)
490. Cabrera, G.; Li, J.; Maazouz, A.; Lamnawar, K. A Journey from Processing to Recycling of Multilayer Waste Films: A Review of Main Challenges and Prospects. *Polymers* **2022**, *14*, 2319. [\[CrossRef\]](#)
491. Ma, J.Q. Application of Spray-on Waterproofing Membrane in Tunnels. *Adv. Mater. Res.* **2011**, *168–170*, 822–826. [\[CrossRef\]](#)
492. Gong, C.; Wang, Y.; Ding, W.; Lei, M.; Shi, C. Waterproof Performance of Sealing Gasket in Shield Tunnel: A Review. *Appl. Sci.* **2022**, *12*, 4556. [\[CrossRef\]](#)
493. Jiang, Y.; He, B.; Zhao, J.; Pei, H.; Liu, J.; Wang, H. Influence of Novel Polymer Waterproofing Membrane on Mechanical Properties of Tunnel Lining Structure. *Constr. Build. Mater.* **2022**, *360*, 129579. [\[CrossRef\]](#)
494. Tengilimoglu, O.; Akyuz, U. Experimental Study on Hybrid Precast Tunnel Segments Reinforced by Macro-Synthetic Fibres and Glass Fibre Reinforced Polymer Bars. *Tunn. Undergr. Space Technol.* **2020**, *106*, 103612. [\[CrossRef\]](#)
495. Markovičová, L.; Zatkalíková, V.; Hanusová, P. Carbon Fiber Polymer Composites. *Conf. Qual. Prod. Improv.-CQPI* **2019**, *1*, 276–280. [\[CrossRef\]](#)
496. Radford, D.W.; Grabher, A.; Bridge, J. Inorganic Polymer Matrix Composite Strength Related to Interface Condition. *Materials* **2009**, *2*, 2216–2227. [\[CrossRef\]](#)
497. Reis, J.M.; Ferreira, A. Fracture Energy of Polymer Concrete Reinforced with Short Carbon and Glass Fibers. *Mater. Sci. Forum* **2004**, *455–456*, 810–813. [\[CrossRef\]](#)
498. Deshpande, P.P.; Jadhav, N.G.; Gelling, V.J.; Sazou, D. Conducting Polymers for Corrosion Protection: A Review. *J. Coat. Technol. Res.* **2014**, *11*, 473–494. [\[CrossRef\]](#)
499. Ghafari, N. Corrosion Control in Underground Concrete Structures Using Double Waterproofing Shield System (DWS). *Int. J. Min. Sci. Technol.* **2013**, *23*, 603–611. [\[CrossRef\]](#)
500. Hu, X.; He, C.; Feng, K.; Liu, S.; Walton, G. Effects of Polypyrrole Coated Rebar on Corrosion Behavior of Tunnel Lining with the Combination Effect of Sustained Loading and Pre-Existing Cracks When Exposed to Chlorides. *Constr. Build. Mater.* **2019**, *221*, 318–331. [\[CrossRef\]](#)
501. Maraveas, C. Environmental Sustainability of Greenhouse Covering Materials. *Sustainability* **2019**, *11*, 6129. [\[CrossRef\]](#)
502. Abdel-Ghany, A.M.; Al-Helal, I.M.; Alzahrani, S.M.; Alsadon, A.A.; Ali, I.M.; Elleithy, R.M. Covering Materials Incorporating Radiation-Preventing Techniques to Meet Greenhouse Cooling Challenges in Arid Regions: A Review. *Sci. World J.* **2012**, *2012*, e906360. [\[CrossRef\]](#)

503. Lamnatou, C.; Chemisana, D. Solar Radiation Manipulations and Their Role in Greenhouse Claddings: Fresnel Lenses, NIR- and UV-Blocking Materials. *Renew. Sustain. Energy Rev.* **2013**, *18*, 271–287. [\[CrossRef\]](#)
504. Espejo, C.; Arribas, A.; Monzó, F.; Díez, P.P. Nanocomposite Films with Enhanced Radiometric Properties for Greenhouse Covering Applications. *J. Plast. Film Sheeting* **2012**, *28*, 336–350. [\[CrossRef\]](#)
505. Maraveas, C.; Kotzabasaki, M.I.; Bayer, I.S.; Bartzanas, T. Sustainable Greenhouse Covering Materials with Nano- and Micro-Particle Additives for Enhanced Radiometric and Thermal Properties and Performance. *AgriEngineering* **2023**, *5*, 1347–1377. [\[CrossRef\]](#)
506. Kavga, A.; Souliotis, M.; Koumoulos, E.P.; Fokaides, P.A.; Charitidis, C.A. Environmental and Nanomechanical Testing of an Alternative Polymer Nanocomposite Greenhouse Covering Material. *Sol. Energy* **2018**, *159*, 1–9. [\[CrossRef\]](#)
507. Peteu, S.F.; Oancea, F.; Siciua, O.A.; Constantinescu, F.; Dinu, S. Responsive Polymers for Crop Protection. *Polymers* **2010**, *2*, 229–251. [\[CrossRef\]](#)
508. Elshafie, H.S.; Camele, I. Applications of Absorbent Polymers for Sustainable Plant Protection and Crop Yield. *Sustainability* **2021**, *13*, 3253. [\[CrossRef\]](#)
509. Mangaraj, S.; Yadav, A.; Bal, L.M.; Dash, S.K.; Mahanti, N.K. Application of Biodegradable Polymers in Food Packaging Industry: A Comprehensive Review. *J. Packag. Technol. Res.* **2019**, *3*, 77–96. [\[CrossRef\]](#)
510. Twede, D. History of Packaging. In *The Routledge Companion to Marketing History*; Routledge: London, UK, 2016; ISBN 978-1-315-88285-7.
511. Веремейчик, О.В.; Якимович, Е.Б. *Packaging. History. Packaging Materials. Bionic Design*; БНТУ: Minskaja Voblasć, Belarus, 2014; ISBN 978-985-550-225-9.
512. Meena, P.L.; Goel, A.; Rai, V.; Barwa, M.S. Packaging Material and Need of Biodegradable Polymers: A Review. *Int. J. Appl. Res.* **2017**, *3*, 886–896.
513. Bharadwaj, A.; Yadav, D.; Varshney, S. Non-biodegradable waste—Its impact & safe disposal. *Int. J. Adv. Technol. Eng. Sci.* **2015**, *3*, 184–191.
514. Composites for Environmental Engineering | Wiley Online Books. Available online: <https://onlinelibrary.wiley.com/doi/book/10.1002/9781119555346#page=112> (accessed on 15 April 2024).
515. Wu, F.; Misra, M.; Mohanty, A.K. Challenges and New Opportunities on Barrier Performance of Biodegradable Polymers for Sustainable Packaging. *Prog. Polym. Sci.* **2021**, *117*, 101395. [\[CrossRef\]](#)
516. Swetha, T.A.; Bora, A.; Mohanrasu, K.; Balaji, P.; Raja, R.; Ponnuchamy, K.; Muthusamy, G.; Arun, A. A Comprehensive Review on Polylactic Acid (PLA)—Synthesis, Processing and Application in Food Packaging. *Int. J. Biol. Macromol.* **2023**, *234*, 123715. [\[CrossRef\]](#) [\[PubMed\]](#)
517. Bastarrachea, L.; Dhawan, S.; Sablani, S.S. Engineering Properties of Polymeric-Based Antimicrobial Films for Food Packaging: A Review. *Food Eng. Rev.* **2011**, *3*, 79–93. [\[CrossRef\]](#)
518. Zhong, Y.; Godwin, P.; Jin, Y.; Xiao, H. Biodegradable Polymers and Green-Based Antimicrobial Packaging Materials: A Mini-Review. *Adv. Ind. Eng. Polym. Res.* **2020**, *3*, 27–35. [\[CrossRef\]](#)
519. Lyashenko, V.; Sotnik, S.; Babker, A.M. Features of Packaging from Polymers in Pharmaceuticals. *Saudi J. Med. Pharm. Sci.* **2018**, *4*, 166–174.
520. Kaiser, K.; Schmid, M.; Schlummer, M. Recycling of Polymer-Based Multilayer Packaging: A Review. *Recycling* **2018**, *3*, 1. [\[CrossRef\]](#)
521. Yamada, K.; Tomonaga, F.; Kamimura, A. Improved Preparation of Recycled Polymers in Chemical Recycling of Fiber-Reinforced Plastics and Molding of Test Product Using Recycled Polymers. *J. Mater. Cycles Waste Manag.* **2010**, *12*, 271–274. [\[CrossRef\]](#)
522. Achilias, D.S.; Giannoulis, A.; Papageorgiou, G.Z. Recycling of Polymers from Plastic Packaging Materials Using the Dissolution–Reprecipitation Technique. *Polym. Bull.* **2009**, *63*, 449–465. [\[CrossRef\]](#)
523. Vouvoudi, E.C.; Achilias, D.S. Polymer Packaging Waste Recycling: Study of the Pyrolysis of Two Blends via TGA. *J. Therm. Anal. Calorim.* **2020**, *142*, 1891–1895. [\[CrossRef\]](#)
524. Shahid, M.K.; Kashif, A.; Choi, Y. Advances in the Recycling of Polymer-Based Plastic Materials. In *Urban Mining for Waste Management and Resource Recovery*; CRC Press: Boca Raton, FL, USA, 2021; ISBN 978-1-00-320107-6.
525. Mahala, V. Madhuca indica: An Overview of Tree. *Agric. Food E-Newsl.* **2022**, *4*.
526. Stelescu, M.D. Polymer Composites Based on Plasticized PVC and Vulcanized Nitrile Rubber Waste Powder for Irrigation Pipes. *Int. Sch. Res. Not.* **2013**, *2013*, e726121. [\[CrossRef\]](#)
527. Bouchenafa, W.; Dewals, B.; Lefevre, A.; Mignot, E. Water Soluble Polymers as a Means to Increase Flow Capacity: Field Experiment of Drag Reduction by Polymer Additives in an Irrigation Canal. *J. Hydraul. Eng.* **2021**, *147*, 05021003. [\[CrossRef\]](#)
528. Borsato, E.; Martello, M.; Marinello, F.; Bortolini, L. Environmental and Economic Sustainability Assessment for Two Different Sprinkler and A Drip Irrigation Systems: A Case Study on Maize Cropping. *Agriculture* **2019**, *9*, 187. [\[CrossRef\]](#)
529. Al-Taey, D.K.A.; Hussain, A.J. Drought’s Impact on Growth and Strategies to Mitigate Its Effects on Potato Cultivation: A Review. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1262*, 042070. [\[CrossRef\]](#)
530. Guo, K.; Zhang, Z.H.; Zhou, H. The Research on Wear Resistant Polyurethane Hose Capable of Being Flat. *Adv. Mater. Res.* **2012**, *535–537*, 1378–1381. [\[CrossRef\]](#)
531. Sadeghzadeh, M.A.; Jannati, M.; Melekinezhad, H. Solar-Thermophysical Irrigation Instrument for Container Plants. *J. Irrig. Drain. Eng.* **2022**, *148*, 04022019. [\[CrossRef\]](#)

532. Zhou, B.; Wang, T.; Li, Y.; Bralts, V. Effects of Microbial Community Variation on Bio-Clogging in Drip Irrigation Emitters Using Reclaimed Water. *Agric. Water Manag.* **2017**, *194*, 139–149. [\[CrossRef\]](#)
533. Huang, Y.-W.; Wang, Z.-M.; Yan, X.; Chen, J.; Guo, Y.-J.; Lang, W.-Z. Versatile Polyvinylidene Fluoride Hybrid Ultrafiltration Membranes with Superior Antifouling, Antibacterial and Self-Cleaning Properties for Water Treatment. *J. Colloid Interface Sci.* **2017**, *505*, 38–48. [\[CrossRef\]](#)
534. Vismara, E.; Ajmi, K.; Arrigoni, P.; Starace, G.; Torri, G. Innovative Polyethylene Nets for Agricultural and Environmental Applications. In Proceedings of the 262nd ACS National Meeting & Exposition, Atlanta, GA, USA, 22–26 August 2021.
535. La Mantia, F.P.; Ceraulo, M.; Testa, P.; Morreale, M. Biodegradable Polymers for the Production of Nets for Agricultural Product Packaging. *Materials* **2021**, *14*, 323. [\[CrossRef\]](#)
536. Sustainability | Free Full-Text | The Sustainability of Plastic Nets in Agriculture. Available online: <https://www.mdpi.com/2071-1050/12/9/3625> (accessed on 15 April 2024).
537. Sica, C.; Picuno, P. Spectro-radiometrical characterization of plastic nets for protected cultivation. *Acta Hortic.* **2008**, *801*, 245–252. [\[CrossRef\]](#)
538. SciELO—Brazil—Polymers and Its Applications in Agriculture Polymers and Its Applications in Agriculture. Available online: <https://www.scielo.br/j/po/a/Y94k4QmMfsKGqqfHgzbdcLj/?lang=en> (accessed on 15 April 2024).
539. Sánchez-Solís, A.; Padilla, A. Effect of Sands on Poly(Vinyl Chloride) Resistance to Ultraviolet Light. *Polym. Bull.* **1996**, *36*, 753–758. [\[CrossRef\]](#)
540. Mourad, M.M.; Abdou, Y.; Berber, M.R.; Elhussiny, F. Using nano tungsten oxide polymer composite as a gamma radiation shielding. *Delta J. Sci.* **2021**, *43*, 126–132. [\[CrossRef\]](#)
541. Laboratory Efficacy of HaNPV against Pod Borer, *Helicoverpa Armigera* (Hubner) Infesting Chickpea—MedCrave Online. Available online: <https://medcraveonline.com/APAR/laboratory-efficacy-of-hanpv-against-pod-borer-helicoverpa-armigera-hubner-infesting-chickpea.html> (accessed on 15 April 2024).
542. Das, P.K.; Panda, G.; Patra, K.; Jena, N.; Dash, M. The Role of Polyplexes in Developing a Green Sustainable Approach in Agriculture. *RSC Adv.* **2022**, *12*, 34463–34481. [\[CrossRef\]](#) [\[PubMed\]](#)
543. Ay, C.; Fong, S.W.; Lee, M.T. Study on Polymer Matrix Composites Used as Greenhouse Coverings: Optical Properties. *Appl. Mech. Mater.* **2017**, *863*, 15–19. [\[CrossRef\]](#)
544. Wang, X.; Jiang, H.; Wang, Y.; Dong, L. Generation of Temperature Gradient on Microfluidic Plant Chip for High-Throughput Plant Phenotyping. In Proceedings of the 2017 IEEE 12th International Conference on Nano/Micro Engineered and Molecular Systems (NEMS), Los Angeles, CA, USA, 9–12 April 2017; pp. 398–401.
545. Panova, G.G.; Krasnopeeveva, E.L.; Laishevskina, S.G.; Kuleshova, T.E.; Udalova, O.R.; Khomyakov, Y.V.; Mirskaya, G.V.; Vertebny, V.E.; Zhuravleva, A.S.; Shevchenko, N.N.; et al. Polymer Gel Substrate: Synthesis and Application in the Intensive Light Artificial Culture of Agricultural Plants. *Gels* **2023**, *9*, 937. [\[CrossRef\]](#)
546. McCabe, K.G.; Schrader, J.A.; Currey, C.J.; Grewell, D.; Graves, W.R. Soy-Composite Biocontainers Allow for Reduced Fertilizer Inputs during Container-Crop Production. *HortScience* **2016**, *51*, 927–934. [\[CrossRef\]](#)
547. de Souza Machado, A.A.; Lau, C.W.; Kloas, W.; Bergmann, J.; Bachelier, J.B.; Faltin, E.; Becker, R.; Görlich, A.S.; Rillig, M.C. Microplastics Can Change Soil Properties and Affect Plant Performance. *Environ. Sci. Technol.* **2019**, *53*, 6044–6052. [\[CrossRef\]](#)
548. Jiménez-Rosado, M.; Perez-Puyana, V.; Guerrero, A.; Romero, A. Micronutrient-Controlled-Release Protein-Based Systems for Horticulture: Micro vs. Nanoparticles. *Ind. Crop. Prod.* **2022**, *185*, 115128. [\[CrossRef\]](#)
549. Lincmaierová, K.; Botyanszká, L.; Lichner, L.; Toková, L.; Zafeiriou, I.; Bondarev, D.; Horák, J.; Šurda, P. Assessing Microplastic-Induced Changes in Sandy Soil Properties and Crop Growth. *AgriEngineering* **2023**, *5*, 1555–1567. [\[CrossRef\]](#)
550. Yu, Y.; Flury, M. Current Understanding of Subsurface Transport of Micro- and Nanoplastics in Soil. *Vadose Zone J.* **2021**, *20*, e20108. [\[CrossRef\]](#)
551. Rillig, M.C.; Ingrassia, R.; de Souza Machado, A.A. Microplastic Incorporation into Soil in Agroecosystems. *Front. Plant Sci.* **2017**, *8*, 1805. [\[CrossRef\]](#)
552. Molecules | Free Full-Text | Influence of Different Microplastic Forms on pH and Mobility of Cu<sup>2+</sup> and Pb<sup>2+</sup> in Soil. Available online: <https://www.mdpi.com/1420-3049/27/5/1744> (accessed on 15 April 2024).
553. Accumulation of Microplastics in Agroecosystems and Its Effects on Terrestrial Plants: A Short Review | Current Applied Science and Technology. Available online: <https://li01.tci-thaijo.org/index.php/cast/article/view/256076> (accessed on 15 April 2024).
554. Qiang, L.; Hu, H.; Li, G.; Xu, J.; Cheng, J.; Wang, J.; Zhang, R. Plastic Mulching, and Occurrence, Incorporation, Degradation, and Impacts of Polyethylene Microplastics in Agroecosystems. *Ecotoxicol. Environ. Saf.* **2023**, *263*, 115274. [\[CrossRef\]](#) [\[PubMed\]](#)
555. Chandran, R.R.; Thomson, B.I.; Natishah, A.J.; Mary, J.; Nachiyar, V. Nanotechnology in Plastic Degradation. *Biosci. Biotechnol. Res. Asia* **2023**, *20*, 53–68. [\[CrossRef\]](#)
556. Barragán, D.H.; Pelacho, A.M.; Martín-Closas, L. Degradation of Agricultural Biodegradable Plastics in the Soil under Laboratory Conditions. *Soil Res.* **2016**, *54*, 216–224. [\[CrossRef\]](#)
557. Abda, E.M.; Muleta, A.; Tafesse, M.; Prabhu, S.V.; Aemro, A. Recent Endeavors in Microbial Remediation of Micro- and Nanoplastics. *Phys. Sci. Rev.* **2023**, *8*, 2853–2877. [\[CrossRef\]](#)
558. Chang, X.; Xue, Y.; Li, J.; Zou, L.; Tang, M. Potential Health Impact of Environmental Micro- and Nanoplastics Pollution. *J. Appl. Toxicol.* **2020**, *40*, 4–15. [\[CrossRef\]](#)

559. Yee, M.S.-L.; Hii, L.-W.; Looi, C.K.; Lim, W.-M.; Wong, S.-F.; Kok, Y.-Y.; Tan, B.-K.; Wong, C.-Y.; Leong, C.-O. Impact of Microplastics and Nanoplastics on Human Health. *Nanomaterials* **2021**, *11*, 496. [CrossRef]
560. Verma, K.K.; Song, X.-P.; Xu, L.; Huang, H.-R.; Liang, Q.; Seth, C.S.; Li, Y.-R. Nano-Microplastic and Agro-Ecosystems: A Mini-Review. *Front. Plant Sci.* **2023**, *14*, 1283852. [CrossRef]
561. Kumari, R.; Suman, K.; Karmakar, S.; Mishra, V.; Lakra, S.G.; Saurav, G.K.; Mahto, B.K. Regulation and Safety Measures for Nanotechnology-Based Agri-Products. *Front. Genome Ed.* **2023**, *5*, 1200987. [CrossRef]
562. The Circular Economy for Plastics—A European Analysis 2024. Available online: <https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-analysis-2024/> (accessed on 29 August 2024).
563. Bioplastics Global Production Capacity 2022–2028, by Type, Statista Research Department. 2024. Available online: <https://www.statista.com/statistics/678684/global-production-capacity-of-bioplastics-by-type/> (accessed on 29 August 2024).
564. Global Bioplastics Industry—Statistics & Facts, Statista Research Department. 2024. Available online: <https://www.statista.com/topics/8744/bioplastics-industry-worldwide/> (accessed on 29 August 2024).
565. Global Market Value of Bioplastics 2023–2033, Statista Research Department. 2024. Available online: <https://www.statista.com/statistics/981762/market-value-bioplastics-worldwide/> (accessed on 29 August 2024).
566. Bergmann, M.; Almroth, B.; Brander, S.; Dey, T.; Green, D.; Gündoğdu, S.; Krieger, A.; Wagner, M.; Walker, T. A Global Plastic Treaty Must Cap Production. *Science* **2022**, *376*, 469–470. [CrossRef]
567. Thompson, R.C.; Pahl, S.; Sembiring, E. Plastics Treaty—Research Must Inform Action. *Nature* **2022**, *608*, 472. [CrossRef]
568. UNEP Environment Assembly (5th) 2021: End Plastic Pollution: Towards an International Legally Binding Instrument: Resolution/: Adopted by the United Nations Environment Assembly, Nairobi. 2022. Available online: <https://digitallibrary.un.org/record/3999257?v=pdf> (accessed on 29 August 2024).

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.