RESEARCH PAPER

HARNESSING PLANT-BASED BIOPOLYMERS FOR ECO-EFFICIENT AND RESILIENT AGRICULTURAL PRACTICES

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Abstract:
The increased uptake and usage of green products in agrochemicals and agricultural products need more projects with respect to studying product types such as plant-based biopolymers. The plant-derived biopolymers, although as such may not be referred to, are categorised as polysaccharides comprising cellulose, starches, pectin, type of natural gum described as mucilage obtained through amusingly derived natural processes comprising guar, and other natural gums, proteins representative of soybean proteins and zein, hence, lignin; this creates interest based on the aspect of decomposable, biodegradable, and use-friendly. In this study, therefore, the different types of plant-derived biopolymers are categorized and researched on the different applicability in agriculture under headings such as in management of soil health, treatment of seeds, increase of crop production, and provision of agriculture inputs. The review will also focus on the physiochemical properties of the different plant-derived biopolymers in predicting their suitability of use in agriculture considering aspects like soil conditioning, retention of water, creation of biodegradable films and coating and use of the products as carrier substances for fertilizers, pesticides, and biostimulants. Furthermore, the emergence of innovation of biopolymer-based hydro gels will create sustainability of the plant-derived biopolymers.

Keywords: Plant biopolymers, Soil conditioners, Water retention agents, Organic farming inputs, Crop yield improvement.

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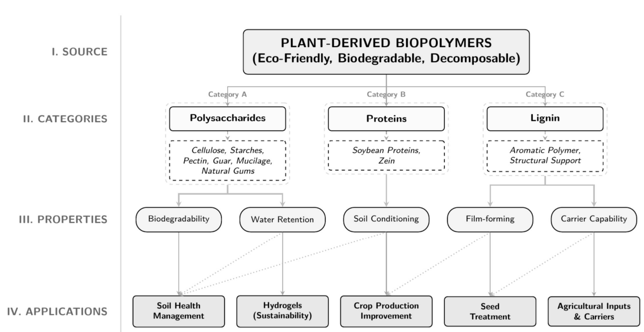
GRAPHICAL ABSTRACT



1.Introduction

The use of traditional petroleum-based polymers has been instrumental in the evolution of the whole plastics industry for many years. They have been employed in the production of many industries including the automobile, packaging, consumer, healthcare, and construction industries. The various polymers have been derived from crude oil, and some of the examples of such polymers being applied today include polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Despite the fact that these polymers have played a vital role in the advancement of technology in plastics as well as other industrial developments, their excessive usage is causing problems in terms of the environment, economy, and health.

Among the striking features of petroleum-based polymers is their versatility. These polymers can be designed and produced in various forms to satisfy specific requirements; for instance, the polymers can be made rigid or flexible, depending on the use of particular materials for certain applications. The fact that it is possible to modify various properties of the polymers such as flexibility, toughness, and strength has resulted in innovations that benefit people in everyday life. For instance, polyethylene is lightweight and moisture-resistant making it suitable for packaging needs whereas rigid PVC is known for its strength thus making it popular in construction works.

It should also be noted that conventional petroleum-based polymers, no matter how useful they are, have been attracting more and more criticism for their negative effect on the environment, as both production and disposal of these materials lead to environmental pollution and even further greenhouse gas emission and worsen the situation with plastic waste.Numerous plastics that are based on petroleum are not biodegradable and may remain in the environment for up to hundreds of years. Plastic waste accumulation causes serious threats to human beings, animals, and ecology in general.

However, petroleum-derived polymers present not only adverse effects on the environment but also serious human health implications. Certain polymers together with their stearates like BPA in polycarbonate plastics have negative influence on the hormonal system and other human health aspects. As the danger becomes clear to human beings, they become more attentive to the substances contained in food contact materials [2].

In order to cope with the problems brought about by petroleum-based polymers, various industries are making efforts to switch to sustainable alternative materials. Biodegradable plastics, biopolymers, and advanced recycling technologies are being implemented in a bid to decrease the negative influence of plastic on the environment. Nevertheless, there remain challenges in terms of performance, cost-effectiveness, implementation, and public acceptance with respect to these alternatives [3].

Nevertheless, the emergence of traditional petroleum-based polymers has completely transformed modern way of living. However, it is necessary to reconsider their usage taking into account environmental concerns and different human health aspects. One should choose the perfect mix of sustainable materials as well as manage existing petroleum-based plastics appropriately. Such an approach is to be applied over existing practices because it helps to allow for new development in sustainable material production [4].

Within this framework, the use of biopolymers represents a special class of materials in the field of materials sciences. Due to their positive characteristics as eco-friendly materials which are biodegradable and recyclable biopolymers deserve high attention from scholars as sustainable alternatives to traditional petroleum-based polymers and principles since they match the trends of ecological sustainability and eco-innovation [5].

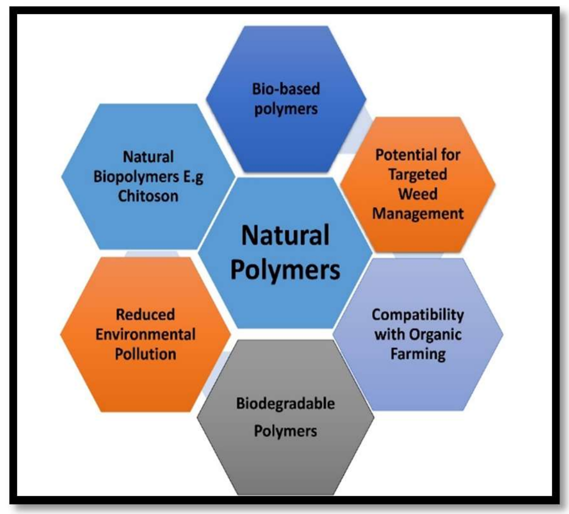


Figure No: 1 Natural polymers with their catergories

1.1. Natural biopolymers: (like cellulose, chitin, and starch) which are inherent in biological systems.

1. 2. Biodegradable polymers: (such as polylactic acid and polyhydroxyalkanoates) that are synthetically produced but derived from renewable sources.

1.3. Bio-based polymers: that may not necessarily be biodegradable but are synthesized from biomass.

1.4. Environmental beneath**:** Because of their lower impact on the environment, biopolymers offer several benefits that are among the most significant. Traditional plastics contribute to severe pollution, including persistent microplastics that taint ecosystems and human health. In contrast, biopolymers can degrade more efficiently and often leave behind non-toxic residues. Furthermore, in comparison to their equivalents that are based on fossil fuels, the manufacture of biopolymers typically results in a lower energy consumption and is associated with a lower emission of greenhouse gases.

1.5. Versatility and applications**:** Biopolymers exhibit remarkable versatility, finding applications in various fields, including packaging, textiles, agriculture, and biomedical devices. For instance, starch-based biopolymers are used for biodegradable packaging materials that can reduce plastic waste in landfills. In a similar vein, developments in biopolymer technology are making it easier to create drug delivery systems which can improve treatment efficacy while simultaneously reducing the risk of adverse effects.Categories with there suitable examples as shown in table no 1.

Table No-1 Classification, Environmental Benefits, and Applications of Biopolymers.

Category	E.g	Source / Origin	Biodegradability	Environmental Benefits	Major Applications	Ref
Natural Biopolymers	Cellulose, Chitin, Starch	Plants, animals, microorganisms	Highly biodegradable	Renewable, non-toxic, low environmental burden	Packaging, textiles, wound dressings, pharmaceutical excipients	(5,6)
Biodegradable Polymer	Polylactic acid (PLA), Polyhydroxyalkanoates (PHA)	Corn starch, sugarcane, microbial fermentation	Completely biodegradable	Reduced plastic accumulation, lower carbon footprint	Packaging films, agricultural mulch, biomedical implants, sutures	(7,8)
Bio-based Polymer	Bio-polyethylene, Bio-PET	Sugarcane, vegetable oils, biomass feedstock	May or may not be biodegradable	Reduced fossil-fuel dependency, lower greenhouse gas emissions	Bottles, automotive components, consumer goods	(9,10)
Environmental Benefits	—	Renewable raw materials	Generally high	Reduced microplastic pollution, lower energy use, reduced GHG emissions	Sustainable materials, eco-friendly packaging	(12,15)
Versatility & Applications	Starch blends, cellulose derivatives, PLA systems	Plant and microbial sources	Formulation-dependent	Safe degradation, design flexibility, eco-compatibility	Packaging, agriculture, drug delivery, biomedical devices	(13,14)

2.Applications of Plant-Based Biopolymers for Field of Agricultural technology:

The significance of plant-based biopolymers such as starch, cellulose, hemicellulose, pectin, alginate, guar gum, and lignin in the field of agriculture has been increasing owing to their benefits. Their sustainability, biodegradability, and functionality, have made them favorable materials for a range of applications in agriculture. Plant materials are primarily used in soil moisture management via hydrogels where they help retain moisture, improve structure, and reduce water consumption especially where drought conditions prevail. Nutrient management is an area of concern where plant products are also useful in coating and encapsulation of fertilizers and agrochemicals thereby optimizing the use of the nutrients and minimizing losses through leaching and volatilization. They are used to make biodegradable mulch films that regulate soil temperatures, suppress weeds, conserve moisture, etc. Under seed technology, plant biopolymers are used in seed coating to guard against diseases, enhance germination and improve nutrient delivery to the root zone. Plant materials can also serve as carriers for biofertilizers and bio-control agents.

Table No-2 Show that various recent applications of natural accuring plant based Biopolymers for field of agricultural technology.

Application	Description	Benefits	Ref
1. Soil Moisture Retention & Soil Conditioning	**Biopolymer-based hydrogels** (e.g., starch, chitosan, guar gum, alginate) are used to enhance soil water retention and structure. They can absorb and slowly release water, improving soil moisture, reducing irrigation frequency, and enhancing root growth.	• Increases water availability for plants (especially under drought) • Reduces soil erosion and compaction • Improves aeration and soil fertility	16
2. Controlled Release of Fertilizers & Agrochemicals	Plant-derived biopolymers can encapsulate fertilizers or pesticides and release them gradually, increasing nutrient use efficiency and reducing environmental leaching.	• Reduced application frequency • Enhanced nutrient uptake • Lower environmental pollution	17
3. Biodegradable Mulch Films	Mulches made from plant-based biopolymers (e.g., PLA, starch blends) act as **biodegradable soil covers** that suppress weeds, regulate soil temperature, and retain moisture.	• Decomposes into non-toxic products • Reduces plastic waste in fields • Improves crop microclimate	18
4. Seed Coatings & Crop Protection	Biopolymer coatings (e.g., alginate, chitosan) applied on seeds protect them from pathogens, support germination, and can deliver nutrients or beneficial microbes.	• Enhanced seedling vigor • Pathogen protection • Targeted nutrient/pesticide delivery	19
5. Biopolymer Capsules for Microbial Delivery	Encapsulation of beneficial microbes (e.g., *Bacillus*, *Trichoderma*) within plant-derived biopolymers enhances microbial survival and stress resistance in soils.	• Promotes plant health • Biocontrol of pathogens • Supports sustainable farming	20
6. Soil Amendment & Erosion Control	Certain biopolymer particles improve soil structure, bind soil particles, and help reduce water and wind erosion while improving organic content.	• Improves soil health • Enhances crop yield • Reduces erosion	21,22

3. Biopolymers: Applications, Benefits, and Future Prospects :

Biopolymers are regarded as naturally happening large molecules which are made by living beings and have gained popularity due to their many advantages regarding sustainability and multifunctionality. Biopolymers are made from renewable biological resources, and thus their production is seen as a sustainable alternative to conventional oil-based polymers which harm the environment. The significant advantage of biopolymers is that they are biodegradable, biocompatible, and have a broad range of applications in various industries. This paper provides details on the new uses of biopolymers in different industries.

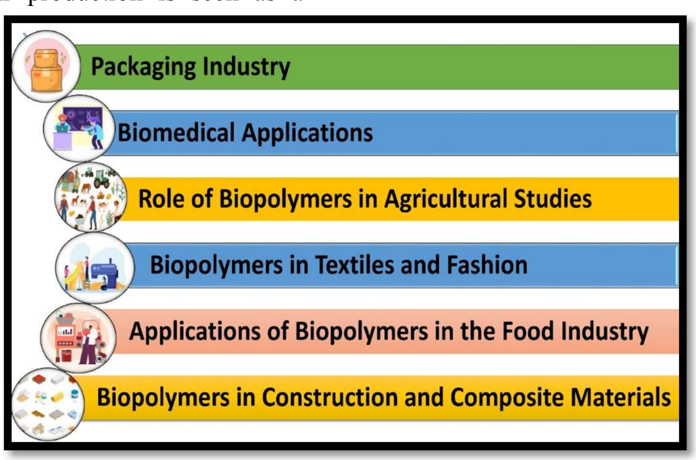


Figure No-2 Different Applications, Benefits, and Future Prospects

3.1. Applications of Biopolymers in the Packaging Industry

The packaging industry represents one of the most prominent areas for biopolymer utilization.

Traditional plastic packaging has been widely criticized for its persistence in the environment and contribution to plastic pollution. Biopolymers such as **polylactic acid (PLA)** and **polyhydroxyalkanoates (PHA)** have emerged as viable alternatives due to their biodegradability and ability to decompose into non-toxic products. These materials are increasingly adopted for food and consumer-goods packaging, helping to reduce plastic waste while simultaneously enhancing brand value by meeting the growing demand for eco-friendly packaging solutions [23].

3.2. Biomedical Applications of Biopolymers

Biopolymers have gained substantial importance in biomedical applications, particularly in **drug delivery systems, tissue engineering, and wound management**. Natural polymers such as **chitosan, alginate, and collagen** exhibit excellent biocompatibility and can be chemically tailored to meet specific medical requirements. For instance, chitosan is widely used in wound dressings due to its antimicrobial activity, whereas alginate-based scaffolds support cell growth and tissue regeneration. The incorporation of biopolymers in biomedical technologies not only improves therapeutic outcomes but also encourages the adoption of sustainable materials within healthcare systems [24].

3.3. Role of Biopolymers in Agricultural Studies

In agriculture, biopolymers are employed to improve soil quality, reduce erosion, and enhance nutrient availability. **Starch-based biodegradable mulches** effectively suppress weed growth while decomposing naturally and enriching soil organic matter. Additionally, biopolymers are used as matrices for **slow-release fertilizers**, enabling controlled nutrient delivery and minimizing the environmental risks associated with conventional chemical fertilizers. These applications contribute to improved crop productivity while supporting environmentally responsible agricultural practices [25].

3.4. Biopolymers in Textiles and Fashion

The textile and fashion industries are progressively shifting toward sustainable materials, with biopolymers playing a central role in this transition. Fibers derived from biopolymers such as **PLA and soy protein** are increasingly used to produce biodegradable and bio-based textiles. These materials significantly reduce the carbon footprint associated with garment production while offering consumers environmentally conscious alternatives. The adoption of biopolymer-based fibers supports the growing demand for sustainable fashion and circular economy models [26].

3.5. Applications of Biopolymers in the Food Industry

Biopolymers are widely utilized in the food industry due to their functional and safety attributes. Naturally derived polymers such as **pectin, agar, and carrageenan** serve as gelling agents, thickeners, and stabilizers, enhancing food texture and extending shelf life without synthetic additives. Moreover, **biopolymer-based edible coatings** are being developed to preserve freshness, inhibit microbial growth, and reduce food spoilage. These innovations align closely with global efforts to improve food sustainability and minimize waste [27].

3.6. Biopolymers in Construction and Composite Materials

The construction sector is increasingly exploring biopolymers for use in composite materials to improve mechanical performance while reducing environmental impact. **Biocomposites composed of natural fibers and bio-resins** offer lightweight, durable, and eco-friendly alternatives to conventional construction materials. These materials contribute to energy efficiency and support the adoption of green building practices, thereby promoting sustainable infrastructure development [28].**Figure 3** shows that plant based biopolymers in various plant management system.

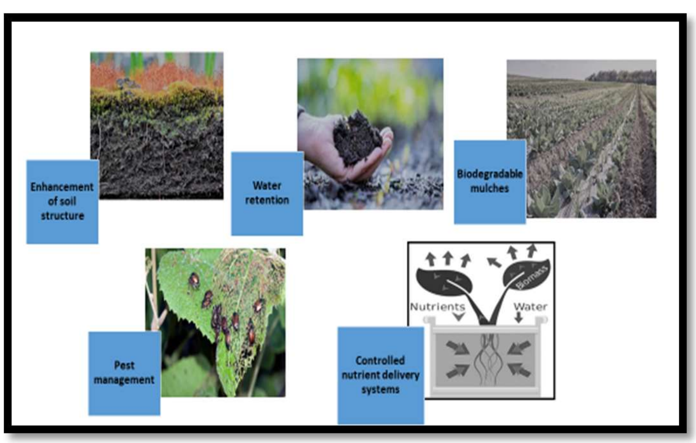


Figure 3 Plant based biopolymers in various crop management system.

4.Significance of Biopolymers in Sustainable Agriculture

Growing concerns about environmental sustainability, resource conservation, and the efficiency of modern farming systems have accelerated interest in biopolymers within the agricultural sector. Biopolymers are naturally derived macromolecules obtained from renewable biological sources and have gained recognition for their multifunctional role in agriculture. Owing to their biodegradability, biocompatibility, and functional versatility, biopolymers offer promising alternatives to conventional synthetic materials. This section reviews the key agricultural applications of biopolymers, highlighting their benefits, limitations, and future prospects [29].

4.1. Enhancement of Soil Quality and Structural Stability

One of the most important agricultural applications of biopolymers is soil improvement. Natural biopolymers such as polysaccharides, proteins, and biodegradable polyesters contribute to improved soil aggregation by enhancing particle binding and porosity. Materials such as guar gum and xanthan gum have demonstrated the ability to strengthen soil structure, thereby improving aeration, root development, and water infiltration. Improved soil structure also supports beneficial microbial activity, which plays a vital role in nutrient cycling and overall soil fertility [30].

4.2. Moisture Conservation and Improved Irrigation Management

Biopolymers play a significant role in agricultural water management, particularly in regions facing water scarcity. Superabsorbent biopolymer materials can retain substantial amounts of water and gradually release it into the surrounding soil, ensuring continuous moisture availability to crops. This controlled water release reduces irrigation frequency, minimizes water loss, and supports crop growth during drought conditions, making biopolymers valuable tools in climate-resilient agriculture [31].

4.3. Biodegradable Mulching Materials for Weed Suppression

Biopolymer-based biodegradable mulches, including those derived from polylactic acid (PLA) and starch, offer an environmentally friendly alternative to conventional plastic films. These mulches help regulate soil temperature, reduce moisture evaporation, and suppress weed growth, thereby improving crop productivity. Their ability to degrade naturally in the soil eliminates the need for post-harvest removal and reduces long-term plastic contamination in agricultural ecosystems [32].

4.4. Natural Pest Management and Crop Protection

Certain biopolymers possess inherent antimicrobial and pest-repellent properties, making them suitable for sustainable crop protection strategies. Chitosan, obtained from crustacean shells, has been widely studied for its ability to stimulate plant defense responses and suppress fungal pathogens. By enhancing plant resistance and reducing disease incidence, biopolymers can decrease dependence on synthetic pesticides and support environmentally responsible pest management practices [33].

4.5. Controlled Nutrient Delivery and Fertilizer Efficiency

Biopolymers also offer innovative solutions for nutrient management through the development of controlled-release fertilizer systems. Nutrients encapsulated within biopolymer matrices are released gradually, ensuring sustained nutrient availability over extended periods. This approach reduces nutrient leaching, improves fertilizer-use efficiency, and enhances plant nutrient uptake, ultimately contributing to improved crop yields and reduced environmental impact [34].

5.Challenges and Future Perspectives

Despite their considerable advantages, the widespread application of biopolymers in agriculture faces several challenges. High production costs, variability in material performance, and the need for extensive field validation under diverse agro-climatic conditions can limit adoption. Additionally, greater awareness and acceptance among farmers and agricultural stakeholders are essential for successful implementation [35]. Continued research, technological innovation, and interdisciplinary collaboration among scientists, agronomists, and farmers are crucial to developing cost-effective, region-specific biopolymer solutions that support sustainable agricultural development [37,38].

6.The Role of Biopolymers in Agriculture

Growing concern over environmental degradation and the urgent need for sustainable farming systems have accelerated interest in biopolymers as innovative materials in modern agriculture. Biopolymers are naturally derived macromolecules produced by living organisms and renewable biological sources. Owing to their biodegradability, biocompatibility, and functional versatility, they have gained considerable attention as eco-friendly alternatives to conventional synthetic polymers. This review highlights the multifaceted roles of biopolymers in agriculture, focusing on their applications, benefits, and associated limitations [30].

6.1. Soil conditioning and enhancement of soil structure

One of the most significant agricultural applications of biopolymers is soil improvement. Natural polymers such as polysaccharides, proteins, and polyesters contribute to better soil aggregation by binding soil particles together. Biopolymers like guar gum and xanthan gum improve soil porosity, enhance water-holding capacity, and facilitate better aeration. Improved soil structure supports deeper root development and stimulates beneficial microbial activity, which plays a vital role in nutrient transformation and availability [31].

6.2. Water retention and improved irrigation efficiency

Effective water management is essential, particularly in water-limited regions. Superabsorbent biopolymers possess the ability to absorb and retain substantial amounts of water, gradually releasing moisture to plant roots over time. This controlled release reduces irrigation frequency, minimizes water loss, and improves drought tolerance in crops. Such properties make biopolymers valuable components of water-efficient and climate-resilient agricultural systems [32].

6.3. Biodegradable mulches for weed management

Biopolymer-based biodegradable mulches, including those derived from polylactic acid (PLA) and starch, offer a sustainable alternative to conventional plastic mulches. These materials suppress weed growth, regulate soil temperature, and reduce surface evaporation. Unlike petroleum-based plastics, biodegradable mulches decompose naturally in the soil, eliminating disposal issues and reducing long-term environmental pollution, thereby supporting sustainable crop production practices [33].

6.4. Pest management and plant health promotion

Certain biopolymers possess inherent bioactive properties that enhance plant defense responses. Chitosan, obtained from crustacean shells, has demonstrated effectiveness in reducing fungal infections and stimulating plant immunity. Its use in integrated pest management (IPM) systems can lower dependence on chemical pesticides, contributing to safer, environmentally responsible agricultural practices and improved crop resilience [34].

6.5. Controlled nutrient delivery systems

The importance of biopolymers in controlled-release fertilizers is significant in the sense that, through biopolymer matrices, it is possible to encapsulate fertilizers which will be subsequently released to the plants in compliance with their needs over a period of time. This will prevent leaching and loss of fertilizers through evaporation, which will result in full utilization of fertilizers thus resulting to high production of crops [31].

However, it is noteworthy to mention that the use of biopolymers in agriculture, though beneficial, is faced by some challenges. Among the challenges being experienced in biopolymers application in agriculture include high cost of production of biopolymers, availability of various types of materials with different properties, and the need for extensive examinations in the field [32].

More research studies in the fields of technology are needed in order for biopolymers to be rolled out for long-term use. This includes research done by scientists and agronomists, working together with farmers in coming up with new methods and new biopolymers that will be fitted with the needs of the farming communities [33].

7.Challenges and Future Directions:

Challenges

Regardless of the growing demand for agricultural plant based biopolymers, there are a lot of constraints that restrict their adoption. The parameters of the crop are very important because plant materials differ from one batch to another due to the factors such as type of the plant species and cultivation conditions. Another serious problem in this case is the fact that these natural materials do not have a high durability and strength in comparison with the artificial ones. Some materials can decompose and spoil according to changing conditions like humidity or temperature.

Other limitations that can prevent the use of agricultural biopolymers include the cost of production and processing.

8.Future Directions

It is suggested that the focus should put on improving the physicochemical parameters of biomaterials by means of physical blending, chemical modifications, and nanocomposite production. As a result, biomaterials will become more solid, moisture-resistant, and able to provide steady delivery of active substances, which will widen the broader scope of their use in agriculture.

Biopolymers based on plants can also provide unification with innovative technologies in precision agriculture. First of all, the important idea is to apply smart delivery mechanisms for fertilizers, pesticides, and growth regulators that use biodegradable systems in order to increase efficiency and reduce damage to nature.

It is necessary to develop eco-friendly extraction technologies and inexpensive methods for production because of the economic side of the issue. It is very important to take into account agricultural wastes and by-products when producing polymers because this is a good way to follow the principles of sustainability and circular economy.

From the regulatory point of view, it is essential to create certification and testing techniques to make it easier to commercialize the application of plant-based biopolymers and help farmers with the products they buy.

9.Conclusion

Plant-based biopolymers, being an eco-friendly and sustainable alternative to synthetic polymers and traditional agrochemicals, create opportunities in agriculture. Biopolymers are biodegradable, renewable, and eco-friendly and can effectively address soil health problems, increase nutrient use efficiency, and minimize negative impact on nature. Despite challenges related to cost, stability, and usage of biopolymers on large scale, continuous innovations and advancements in processing methods, modification of materials, and precision agriculture solve these challenges.

Declarations

Ethical Approval and Consent to Participate

Not applicable. This study did not involve human participants or animals.

Consent for Publication

Not applicable.

Availability of Data and Materials

All data generated or analyzed during this study are included in this published article. Additional data may be obtained from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Authors' Contributions

All authors contributed equally to the conception, design, experimental work, data analysis, and manuscript preparation. All authors have read and approved the final manuscript.

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