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REVIEW ARTICLE

Polymer-mediated delivery of agrochemicals

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Abstract

A major challenge in modern agriculture is the inefficient delivery and utilization of agrochemicals, which often leads to their overuse, causing environmental pollution and harming beneficial organisms such as earthworms and bees. This challenge can potentially be addressed by using advanced and efficient methods such as polymer-mediated delivery systems. Polymers offer the potential to enhance the efficiency of agrochemicals used in agriculture. Incorporating polymers into agrochemical delivery systems can overcome the limitations associated with conventional methods. This article aims to analyse the potential role of polymers in agrochemical delivery system. Polymer can enable the precise delivery of active ingredients, nutrients, pesticides and herbicides into plants, making the process more resilient to agrochemical loss associated with conventional delivery methods. Enhancing our understanding of polymers and their properties may improve the efficiency and efficacy of agrochemicals by influencing their interaction with plants, carrier capabilities and release mechanisms.

Keywords: agrochemicals; agrochemical delivery; polymer; sustainable agriculture

Introduction

The continuous rise in global population and the impacts of climate change have led to the excessive use of agrochemicals such as pesticides, herbicides, fertilizers and growth regulators. Currently, more than three billion tons of crops are produced annually, requiring around 187 million tons of fertilizers and four million tons of pesticides (1). However, the persistent use of pesticides has resulted in resistance among targeted organisms, prompting increased application rates. Much of these agrochemicals fail to reach their intended targets, leading to environmental contamination and adverse effects on non-target organisms (2). Agrochemicals are indispensable in modern agriculture, with global spending reaching USD 234.2 billion in 2019 and expected to exceed USD 300 billion by 2025 (3). Residues of agrochemicals have been widely reported in soil, water and air (4). The excessive use of nitrogen fertilizers has led to nitrate leaching, causing eutrophication that harms aquatic ecosystems (5). Similarly, phosphate bound to soil particles contributes to the acidification of soils and water bodies through erosion (6).

Nanotechnology-based encapsulation has emerged as a promising approach for developing advanced formulations that enable controlled release of agrochemicals (7). Specifically, polymer-based encapsulation slows the dissolution rate of agrochemicals, facilitates controlled release, enhances plant uptake, reduces plant stress and minimizes the required dosage (8). It also protects agrochemicals from degradation due to light and oxidation (9). While the Green Revolution increased crop yields, it also led to significant environmental consequences, including soil degradation, groundwater depletion, chemical pollution and salinization (10).

This review highlights the application of polymer-based delivery of agrochemicals and its targeted release mechanism of different polymers and its potential to reduce the negative effect on the environment. The delivery of agrochemicals using the biopolymeric nanocarriers is one of the best alternatives for agrochemical delivery and it gives the solution to the degradation of the environment by agrochemicals (7). Although the use of agrochemicals is indispensable in meeting the growing global food demand, polymer-mediated delivery can significantly reduce their negative environmental impacts. This also increases the use efficiency of agrochemicals. The controlled release technique, which was produced by merging agrochemicals with the polymers, has produced the mechanism to deliver agrochemicals for a longer period of time with a sustainable quantity. This method of delivering agrochemicals protects from the environmental factors and prevents degradation, evaporation and leaching of agrochemicals and using polymer along with agrochemicals reduces the toxicity produced by agrochemicals. The polymer-mediated delivery system of agrochemicals should have the properties of delivering the agrochemicals effectively with a low quantity, preventing degradation of agrochemicals from pH and light and the toxicity of the agrochemicals should be lower than the conventional method and the agrochemicals delivered by polymer through nanotechnology should last long to prevent frequent application of agrochemicals like pesticides, herbicides, fertilizers and growth regulators (11). Furthermore, the multifunctional nature of polymers allows their use in fabricating agrochemicals that can respond to external stimuli, offering controlled and site-specific release (12).

Overview of agrochemicals and their importance in agriculture

Agrochemicals are important materials for increasing crop production; although they are costly, their optimum use at the correct time and dosage yields better results (13). Usage of agrochemicals, including chemical fertilizer, pesticide, herbicide and growth regulator, resulted in increased agricultural production, but it also caused adverse effects like environmental problems, such as water eutrophication, air pollution, soil acidification and degradation, biodiversity loss and global warming (14). Protecting crops from pests using pesticides is unavoidable; using it protects and enhances the quality of crops (15). Agrochemicals are used to provide the necessary nutrients, such as nitrogen, phosphorus, potassium, zinc, iron, magnesium, calcium, etc. and protection to the plant (16).

Fertilizers are manufactured in industries or occurred naturally used to increase soil fertility by providing essential nutrient to the crop development (7). The nutrient required for plants divided into macronutrient and micronutrient, macronutrient is required in bulk quantity, they are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). Micronutrients are required for plants in trace quantity. They are boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn) (17). Over time, these substances reduce the soil's fertility. They may cause acidification or alkalization of the soil by altering its pH. Because nitrogenous fertilizers lower the pH of the soil from 5.8 to 4.7, they can lead to acidification (18).

Insects, fungi, bacteria, viruses, nematodes, weeds, rodents, animals and birds affect crop production, which generally denoted by the term pest (19). Pesticide is used to control the damage caused by pests, which are synthetic or natural chemicals, biotic agents, or microorganisms (20). Due to incorrect pesticide application, a number of insect, weed, disease and rodent species have become resistant to chemical pesticides (21). The improper application of fungicide affects human health, contaminates the soil, pollutes the environment and presence of the fungicide residue in the food chain (22).

Factors influencing stability and degradation of agrochemicals

The degradation of agrochemicals is influenced by both biotic and abiotic factors. Biotic degradation occurs through the metabolic activity of microorganisms and plants, whereas abiotic degradation is driven by chemical and physical processes (23). In some instances, degradation products may exhibit greater toxicity than the parent compound, depending on their chemical structure (24). Agrochemicals with high water solubility are more susceptible to leaching from plant surfaces and soil (25). Volatilization represents another degradation pathway and is affected by various environmental and chemical factors, including temperature, humidity, air movement, soil characteristics (such as texture, organic matter content and moisture), pesticide properties (e.g., vapor pressure, heat of vaporization, solubility) and the mode of application (26).

Elevated temperatures generally enhance both the degradation rate and the physical loss of agrochemicals from plant and soil surfaces (27). Photodegradation, induced by sunlight, is influenced by factors such as light intensity, wavelength, exposure duration and the chemical nature of the agrochemical (28). Environmental conditions also play a significant role in agrochemical degradation. Factors such as rainfall, relative humidity and wind can accelerate degradation. For instance, evaporation is affected by humidity levels, while drift and leaching are promoted by wind and rain, leading to the movement of agrochemicals away from target areas (29).

Impact of agrochemicals on environment

Agrochemicals including fertilizers, pesticides, herbicides and fungicides are widely used in modern agriculture to enhance crop yields, prevent pest infestations and control plant diseases. While they have significantly contributed to agricultural productivity, their intensive use since the Green Revolution has led to rising levels of chemical residues in soil, water, air and agricultural products across the globe (30). This persistent contamination has become a growing environmental concern.

One of the primary issues involves the improper use of nitrogen-based fertilizers, which can result in nitrate leaching into water bodies. This process contributes to eutrophication, leading to oxygen depletion, disruption of aquatic ecosystems and a decline in water quality (31). Similarly, the overuse of insecticides and herbicides has accelerated the development of resistance in targeted pest and weed species, rendering these chemicals less effective over time (32).

Agrochemicals also have detrimental effects on soil ecosystems. They interfere with soil enzyme activities and microbial metabolism, both of which are critical for maintaining soil fertility and supporting agrochemical degradation (33). Prolonged and intensive use of these chemicals alters the functional diversity and metabolic functions of non-target soil microorganisms (34). Moreover, weather and climatic factors influence agrochemical degradation and distribution. Elevated temperatures can cause soil cracking, which increases leaching into ground and surface water. This leaching is exacerbated by the decline in soil organic matter, a condition linked to the formation of soil cracks and reduced water retention capacity (35, 36).

Polymer

The term polymer was introduced by Swedish chemist J J Berzelius (37). Polymers are increasingly used in the formulation of pesticides and herbicides to develop controlled-release systems that minimize the harmful effects of active ingredients and ensure targeted delivery (38). The following polymers play a significant role in the efficient and sustainable delivery of agrochemicals which shown in Table 1, 2 respectively.

Mechanisms of polymer-mediated agrochemical delivery

The primary mechanisms employed in polymer-mediated agrochemical delivery are diffusion, degradation and swelling processes as shown in Fig. 1 (39).

Diffusion-controlled release

Diffusion-controlled release entails the gradual release of agrochemical molecules from the polymer matrix or membrane, driven by concentration gradients. Agrochemicals dissolve within the polymer matrix or surrounding medium and diffuse across the polymer network or membrane (40). Various factors govern the release rate, including polymer permeability, agrochemical solubility and diffusivity within the polymer, thickness of the polymer barrier and concentration gradient. Polymers with dense or highly crystalline structures may exhibit slower diffusion rates, while those with more open or amorphous structures facilitate faster diffusion and release. This mechanism is commonly observed in reservoir-type devices, where agrochemicals are encapsulated within a polymer shell or coating and release occurs through diffusion across the polymer barrier (41).

Degradation-controlled release

Degradation-controlled release involves the gradual breakdown or erosion of the polymer matrix, leading to the release of encapsulated agrochemicals. This mechanism encompasses two types: bulk erosion and surface erosion. Bulk erosion occurs throughout the polymer matrix, facilitated by the penetration of water or other degradation agents, leading to the gradual release of agrochemicals (42). Surface erosion, on the other hand, primarily occurs at the polymer matrix's surface, resulting in a gradual erosion of the outer layers and subsequent release of agrochemicals. The rate of degradation-controlled release is influenced by factors such as polymer composition, presence of degradation agents, environmental conditions and matrix size and geometry (43).

Swelling-controlled release

Swelling-controlled release is observed in hydrogel-based delivery systems, where the polymer network swells and expands upon exposure to water or specific environmental conditions. As the hydrogel swells, agrochemicals are released through diffusion or erosion processes. The release kinetics are governed by the degree of swelling, influenced by factors such as polymer composition, cross-linking density and the presence of hydrophilic or ionic functional groups. Swelling-controlled release systems can be designed to respond to environmental triggers, allowing for targeted release of agrochemicals in response to specific conditions or plant growth stages (44).

Table 1. Natural polymers and its role in delivery of agro chemicals

Natural polymer	Delivery method	Role	Reference
Chitosan	Nanoparticles, hydrogels, films	Controlled release of pesticides, herbicides and fertilizers. Biodegradable and biocompatible carrier for agrochemicals.	(98, 99)
Alginate	Microspheres, hydrogels, nanoparticles	Controlled release of pesticides, herbicides and plant growth regulators.	(100)
Cellulose	Nanofibers, microspheres, hydrogels	Controlled release of pesticides and fertilizers.	(101)
Starch	Microspheres, nanoparticles, films	Controlled release of pesticides and herbicides. Biodegradable carrier for agrochemicals.	(102)
Gelatin	Microspheres, nanoparticles	Controlled release of pesticides and plant growth regulators.	(103)
Gum Arabic	Nanoparticles, microspheres	Controlled release of pesticides and fertilizers.	(104)
Xanthan Gum	Hydrogels, microspheres	Controlled release of pesticides and plant growth regulators.	(105)
Pullulan	Nanoparticles, microspheres	Controlled release of pesticides and insecticides.	(106)
Guar Gum	Hydrogels, microspheres	Controlled release of pesticides and fertilizers.	(107)
Pectin	Microspheres, nanoparticles	Controlled release of pesticides and herbicides.	(108)
Dextran	Nanoparticles, microspheres	Controlled release of pesticides and plant growth regulators.	(109)
Cyclodextrin	Inclusion complexes, nanoparticles	Controlled release of pesticides and herbicides.	(110)
Hyaluronic Acid	Nanoparticles, hydrogels	Controlled release of pesticides and plant growth regulators.	(111)
Carrageenan	Hydrogels, microspheres	Controlled release of pesticides and fertilizers.	(112)
Konjac Glucomannan	Nanoparticles, microspheres	Controlled release of pesticides and insecticides.	(113)
Gum Ghatti	Microspheres, nanoparticles	Controlled release of pesticides and herbicides.	(114)
Gum Karaya	Hydrogels, microspheres	Controlled release of pesticides and plant growth regulators.	(115)
Agar	Nanoparticles, microspheres	Controlled release of pesticides and fertilizers.	(116)
Gum Tragacanth	Microspheres, hydrogels	Controlled release of pesticides and herbicides.	(117)

Table 2. Synthetic polymers and its role in delivery of agro chemicals

Synthetic polymer	Delivery method	Role	Reference
Polyethylene Glycol (PEG)	Matrix systems, microspheres, hydrogels	Controlled release of pesticides, herbicides and plant growth regulators.	(118)
Polylactic Acid (PLA)	Microspheres, nanoparticles, films	Controlled release of pesticides, herbicides and fertilizers. Biodegradable carrier for agrochemicals.	(119)
Polyhydroxyalkanoates (PHA)	Microspheres, nanoparticles	Controlled release of pesticides, herbicides and fertilizers. Biodegradable carrier for agrochemicals.	(120)
Polyvinyl Alcohol (PVA)	Hydrogels, nanofibers	Controlled release of pesticides, herbicides and fertilizers.	(121)
Polyurethane (PU)	Microspheres, nanoparticles	Controlled release of pesticides, herbicides and fertilizers.	(122)
Polyvinylpyrrolidone (PVP)	Nanoparticles, microspheres	Controlled release of pesticides and insecticides.	(123)
Polyacrylic Acid (PAA)	Hydrogels, microspheres	Controlled release of pesticides and plant growth regulators.	(124)
Polyvinyl Acetate (PVAc)	Microspheres, nanoparticles	Controlled release of pesticides and fertilizers.	(125)
Polyethylene Oxide (PEO)	Hydrogels, microspheres	Controlled release of herbicides and plant growth regulators.	(126)
Polyethylene Terephthalate (PET)	Nanofibers, microspheres	Controlled release of pesticides and herbicides.	(127)
Polyvinyl Chloride (PVC)	Microspheres, nanoparticles	Controlled release of insecticides and fungicides.	(128)
Polycaprolactone (PCL)	Nanofibers, microspheres	Controlled release of pesticides and herbicides.	(129)
Polydimethylsiloxane (PDMS)	Microspheres, nanoparticles	Controlled release of insecticides and fungicides.	(130)
Polyethylene-co-Vinyl Acetate (EVA)	Microspheres, films	Controlled release of pesticides and plant growth regulators.	(131)
Poly (N-vinylpyrrolidone-co-vinyl acetate) (PVP-VA)	Nanoparticles, microspheres	Controlled release of pesticides and insecticides.	(132)
Poly (glycolic acid) (PGA)	Microspheres, nanoparticles	Controlled release of pesticides and plant growth regulators.	(18)
Poly (methyl methacrylate) (PMMA)	Microspheres, nanoparticles	Controlled release of herbicides and insecticides.	(39)

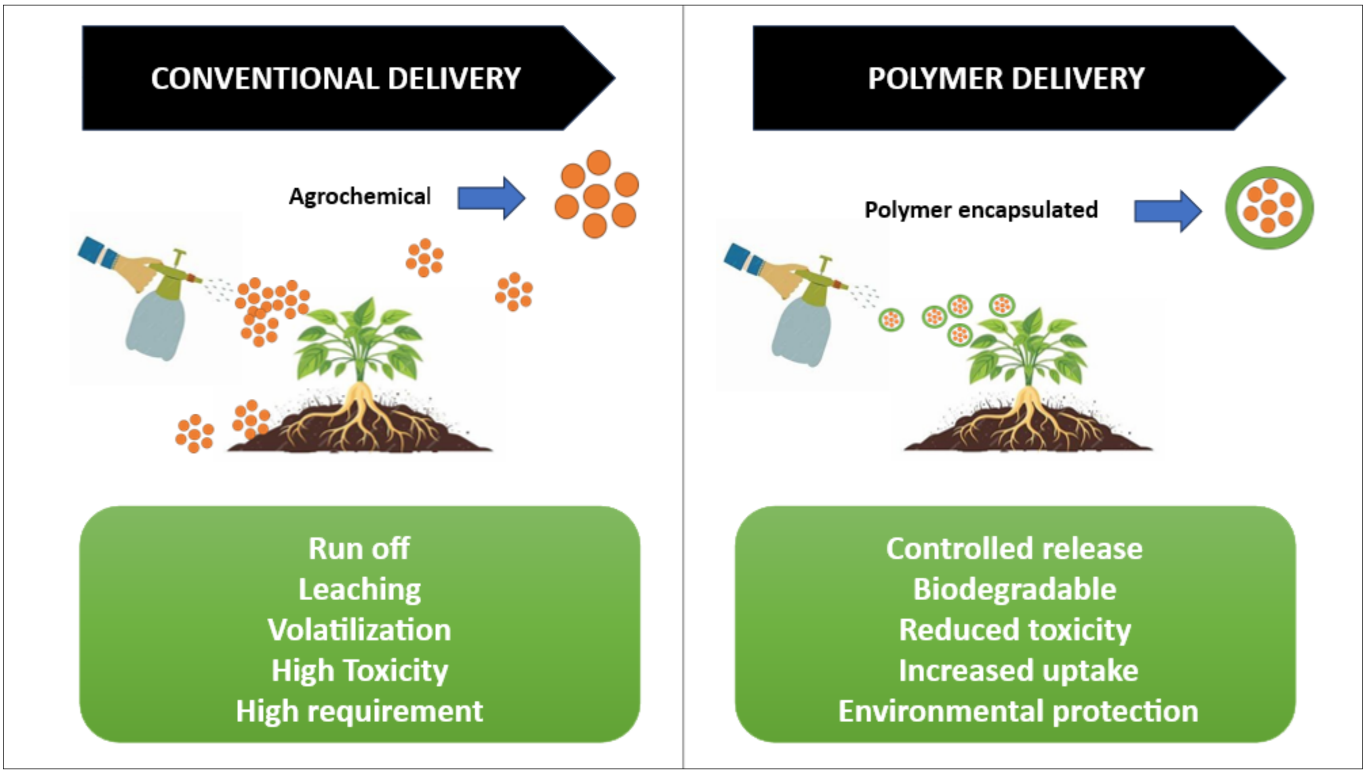

Fig. 1. Mechanisms of polymer mediated agrochemical delivery.

These mechanisms, individually or in combination, allow polymer-based delivery systems to offer enhanced control over agrochemical release, minimizing environmental contamination and improving overall efficacy and bioavailability. Fine-tuning of release kinetics can be achieved through adjustments in polymer composition, agrochemical properties and environmental conditions, ensuring tailored release profiles for specific agricultural applications (45).

Poly lactic-co-glycolic acid (PLGA)

PLGA is a copolymer formed by the combination of poly lactic acid (PLA) and poly glycolic acid (PGA). Due to its tunable properties and biocompatibility, PLGA is considered one of the best biomaterials for drug delivery systems (46). PLGA can be molded into any shape and size and can encapsulate any particle of any shape and size. Chlorinated solvents, tetrahydrofuran, acetone, or ethyl acetate are the common solvent in which PLGA is soluble (47). Ester linkage of PLGA is biodegraded by hydrolysis in water. PLA is more hydrophobic than PGA is due to the presence of methyl side groups in PLA. The low hydrophilic nature of the copolymer PLGA is degraded slowly in the water. The biodegradation of the copolymer PLGA influences the release of the encapsulated drug in the copolymer PLGA (48). The degradation of polymer encapsulated drugs and the mechanism of active ingredient release and rate of active ingredient release is vary depending on the type of drug (49). For instance, thifluzamide encapsulated in PLGA showed enhanced fungicidal activity against *Rhizoctonia solani* and significantly reduced phytotoxicity in cucumber seedlings (50).

Chitosan

Deacetylation of chitin produces chitosan; during this process, moieties of N-acetylglucosamine are converted into glucosamine units (51). Protonation of around fifty percent of all amino groups makes the chitosan become soluble (52). The molecular weight of the polymer determines the viscosity of the chitosan. Stability of the polymer is determined by the viscosity of the polymer; the reduction in viscosity is due to the degradation of the polymer (53). Antimicrobial property exhibited by chitosan against bacteria, filamentous fungi and yeast (54). Polymer size influences the antimicrobial property of chitosan and the antimicrobial property of oligosaccharides is low (55). The lower molecular weight sample exhibits the property of antioxidant rather than the higher molecular weight sample because the fewer intramolecular hydrogen bonds have shorter chains that form and the accessibility of the reactive group is high and causes radial scavenging activity (56). Highly controlled release behavior is exhibited by the chitosan-based agrochemicals. The triggered chitosan polymer matrix releases agrochemicals by stimuli caused by biotic stress and abiotic stress (57). The chitosan contains 9 to 10 percent nitrogen, which acts as a macronutrient for plant development (58). Chitosan nano-formulations, such as those loaded with polyacrylic acid, have been effective in managing common pests like cotton aphids and beetles in soybean crops (59). Moreover, chitosan can induce defense-related enzymes such as phenylalanine ammonia-lyase (PAL), polyphenol oxidase, catalase and peroxidase, enhancing plant immunity (60).

Polylactic acid (PLA)

PLA is an aliphatic polyester composed of repeating ester units derived from renewable resources (61). It exhibits a helical chain structure and is fully biodegradable (62). PLA can be broken down through hydrolysis under suitable conditions or by microbial action during composting (63, 64). It was first synthesized by Carothers in 1932 by heating lactic acid under vacuum (65). Biodegradable lactic acid is obtained from PLA through hydrolytic processes (66) and under favourable end-of-life conditions, PLA products can be either composted or recycled (67). Recycling involves hydrolysing PLA with water at temperatures ranging from 100 to 250 °C to yield lactic acid (68), which can then be repolymerized to form new PLA (69).

PLA is increasingly used in active compound delivery systems due to its enhanced bioavailability, high encapsulation efficiency, controlled release capability and lower toxicity compared to conventional methods (70). Its relatively slow degradation rate makes it ideal for long-term release applications (71). The ability to encapsulate active ingredients allows PLA-based systems to deliver compounds directly to target sites, reduce systemic toxicity and enhance therapeutic effects (72). However, its hydrophobic nature can limit its effectiveness in delivering hydrophilic molecules such as proteins, which is a challenge in fields like tissue engineering (73). Interestingly, in textile applications, PLA is considered more hydrophilic than other synthetic fibres (73).

Alginate

Alginate is a naturally occurring polysaccharide composed of linear sequences of (1→4)-linked α-L-guluronate (G) and β-D-mannuronate (M) monomers (74). It is a non-toxic, biocompatible polymer widely used in biomedical and pharmaceutical applications (75, 76). In various pharmaceutical formulations, alginate is used as a stabilizing agent excipient in drug-delivery systems and it is one of the most common applications of alginate (77). The alginate is readily soluble in neutral and alkaline condition due to carboxyl groups which are charged at pH values higher than 3-4 and it promote widespread use of alginate (78). Protonation take place in carboxyl group of alginates in acidic environment cause limiting of drug release (79).

Alginate hydrogels are extensively used in wound dressings and tissue regeneration therapies due to their high-water retention and gel-forming abilities (80, 81). Dendrimers, nanocrystals, emulsions, liposomes, solid lipid nanoparticles, micelles and polymeric nanoparticles are the form of alginate used in nanomedicines for its high advantage over conventional medicine including efficacy, safety, physicochemical properties and pharmacokinetic/pharmacodynamic profiles (82). In industry, alginate is used to stabilize the viscosity, increase the viscosity of gels, storage and transfer of various drugs and biomolecules and water retention (83).

Carboxymethyl cellulose (CMC)

CMC is a water-soluble, anionic derivative of cellulose, which is a linear polysaccharide composed of repeating anhydro-glucose units linked by β-1,4-glycosidic bonds. It was first synthesized in 1918 and commercial production began in Germany in the early 1920s (84). Studies on the structure of CMC reveal complex flow behaviours when subjected to stress-strain, which directly influence the suitability of CMC for various applications, including food packaging, film production and material coating

(85).

At low concentrations, CMC behaves like a Newtonian fluid, while its viscoelastic properties become more pronounced at higher concentrations, as demonstrated by increased creep compliance and flexible recovery index and the CMC is readily deformed by applying stress at higher creep compliance (86, 87). To enhance their current properties or introduce new ones, the production of CMC from cotton fibers, which are composed of approximately 95 % cellulose, has been undertaken (88). CMC derivatives are also being used in textile products due to their antimicrobial activity (89). CMC and CMC-based hybrid materials are also utilized in the biosensors to detect the presence of various biogenic compounds in the human body or other living organisms (90). Anionic linear and long-chain compounds of CMC that contain glucopyranosyl units with a high molecular weight it is the reason for strength and structural integrity in edible coatings (91).

Pectins

Pectin is a plant-derived polysaccharide primarily composed of pectinic acid, which is water-soluble and capable of forming gels under suitable conditions (92). It contains about 65 % galacturonic acid units and its major sources include citrus peels, apple pomace and sugar beet (93, 94). The low degree of methylation in the pectin form gel in the presence of multivalent ions and the higher degree of methylation in the pectin form gel in the presence of different sugar in acid medium such as sucrose and glucose (95). In food industry pectin are widely used as gelling agent for the production of food products like jam, jelly, fruit juice and bakery fillings (96). Beads made up of pectin and calcium chloride has higher surface cross linking which provide higher encapsulation efficiency and slow releasing (97).

Future perspective of polymer mediated agrochemical delivery

Polymer-mediated agrochemical delivery presents a forward-looking strategy to transform modern agriculture into a more sustainable and environmentally responsible practice. As the demand for food increases alongside growing concerns over environmental degradation, the integration of smart and biodegradable polymers into agrochemical formulations holds immense potential.

Future developments will likely focus on multifunctional polymer systems capable of delivering a combination of agrochemicals-fertilizers, pesticides, herbicides and growth regulators-from a single, optimized platform. These systems will respond to environmental stimuli such as temperature, pH, moisture, or biotic stress to release active ingredients only when needed, thereby reducing waste and improving resource efficiency.

Nanotechnology will continue to play a critical role in enhancing the encapsulation, targeted delivery and controlled release of agrochemicals. By tuning polymer properties such as biodegradability, hydrophobicity and molecular weight, it will be possible to design carriers that offer extended-release durations and minimize premature degradation.

Moreover, field-scale application and regulatory validation will be essential to transition these technologies from research laboratories to agricultural practice. Future studies should focus on long-term environmental impacts, cost-effectiveness, biodegradation behaviour and residual safety to ensure compliance with international agricultural standards.

The development of eco-friendly, cost-efficient and farmer-adaptable polymeric delivery systems will be vital in achieving the dual goals of enhancing crop productivity and minimizing environmental harm. With continued interdisciplinary research and collaboration between scientists, industry stakeholders and policymakers, polymer-mediated agrochemical delivery systems can pave the way for a more sustainable and resilient agricultural future.

Conclusion

The escalating environmental concerns and inefficiencies associated with conventional agrochemical application methods necessitate the adoption of more sustainable and precise alternatives. Polymer-mediated delivery systems offer a transformative approach to agrochemical application by enhancing stability, enabling targeted and controlled release and reducing ecological risks. Biodegradable polymers such as PLGA, chitosan, PLA, alginate, CMC and pectin exhibit significant potential in minimizing agrochemical loss through leaching, volatilization and photodegradation, while also reducing toxicity to non-target organisms.

These polymer systems not only prolong the effectiveness of fertilizers, pesticides and herbicides but also allow for stimuli-responsive release based on environmental cues such as pH, moisture and temperature. Furthermore, they can significantly improve the uptake efficiency and bioavailability of active ingredients, contributing to increased crop yield and reduced chemical input.

Despite their promise, challenges such as production scalability, cost and regulatory compliance must be addressed to facilitate widespread adoption. Future research should focus on optimizing polymer formulations for diverse agroecosystems, developing multifunctional carriers capable of co-delivering various agrochemicals and conducting extensive field trials to validate laboratory findings. Polymer-mediated agrochemical delivery represents a pivotal step toward sustainable agriculture by harmonizing productivity with environmental stewardship, offering a viable path to reducing chemical dependency while maintaining global food security.

Authors' contributions

RE involved in collection of articles and writing the original draft of the manuscript, CSR involved in assessing the manuscript, KR involved in the data analysis in the manuscript, GA involved in designing of the manuscript format, TS involved in conceptualization and validation of the manuscript, MR involved in data analysis and validation of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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