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Exploring the influence of polymers on soil ecosystems: prospective from agricultural contexts

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The utilization of advanced polymeric materials has indeed emerged as a significant trend in sustainable agriculture, offering a range of innovative applications aimed at enhancing productivity, minimizing environmental impact, and promoting resource efficiency. Smart polymeric materials enable the controlled release of pesticides, herbicides, and fertilizers, thereby enhancing their efficacy while reducing the quantities needed. Superabsorbent polymeric materials act as soil conditioners, assisting in alleviating the negative impacts of drought by retaining moisture and enhancing soil structure. This fosters improved plant growth and resilience in water-scarce environments. Polycationic polymers play a role in plant bioengineering, facilitating genetic transformation processes aimed at enhancing crop productivity and disease resistance. Advanced polymeric systems contribute to the arsenal of precision agriculture tools by enabling precise delivery and targeted application of agricultural inputs. This approach enhances resource efficiency, reduces waste, and minimizes environmental impact while optimizing crop yields. In reviewing recent developments in the design and application of advanced polymeric systems for precision agriculture, several key considerations emerge.

KEYWORDS

biodegradable polymers, biopolymers, polymeric nanoparticles, polymers, soil ecosystem

1 Introduction

Agriculture is vitalin promoting health, addressing environmental challenges, ensuring nutrition, and fostering economic development (Sikder et al., 2021). Initially, the primary aim of agricultural advancement globally was to increase productivity per unit of land allocated for crop cultivation. This goal led to extensive fertilizer and pesticide use, as well as the exploitation of natural resources such as soil and water over time. These practices aimed to enhance soil fertility, combat pests, and optimize water usage to meet the rising demand for food as populations expanded. However, while these methods have significantly boosted agricultural output, concerns about their long-term sustainability have emerged. Issues such as soil degradation, water pollution, biodiversity loss, and health risks associated with pesticide use have prompted a shift towards more sustainable agricultural practices that balance productivity with environmental and social considerations (Damalas and Eleftherohorinos, 2011). As a reaction to the growing ecological effects, there's been a heightened global emphasis on embracing more sustainable agricultural methods for a brighter future (Mishra et al., 2017). Presently, the pressing issues confronting global agriculture encompass the immediate need to regulate the utilization of agrochemicals and tackle concerns such as soil degradation, water pollution, climate change, and the continual emergence of plant pathogens and diseases (Prasad et al., 2017). With scientific advancements, innovative polymeric materials are emerging as potent solutions to address various challenges.

A polymer is a large molecule formed by combining multiple smaller units called monomers. The term originates from the Greek words meaning 'many parts', highlighting their ubiquitous presence in nature. Found in various living organisms, polymers such as proteins, cellulose, and nucleic acids play crucial roles. Additionally, they are fundamental components of both natural substances like diamond, quartz, and feldspar, and synthetic materials such as concrete, glass, paper, plastics, and rubbers. Polymers can be categorized as either natural or synthetic based on their source, and carbon chain or hetero chain based on their main chain as illustrated in Figure 1. Polymers offer unique properties and diverse applications that hold significant promise in mitigating issues related to soil degradation, water pollution, climate change, combating plant pathogens and diseases (Patterson et al., 2014). Moreover, they can absorb and retain water, as seen in superabsorbent polymers and hydrogels. This ability helps maintain soil moisture levels. Additionally, polymeric delivery systems enable the controlled release of agrochemicals and nutrients, which facilitates precise administration (Cherwoo et al., 2024). They constitute a versatile category of materials extensively used in agriculture due to their adaptable properties. There is a need to modify the polymers to enhance their efficiency and easy degradation. Recent studies have explored customized and stimuli-responsive smart polymeric systems and, the application of advanced functional polymeric materials, synthetic polymers, and biopolymers, which has facilitated improvements in the controlled delivery of agrochemicals, soil conditioners, nutrients, water management, genetic engineering, and various other agricultural practices (Pascoli et al., 2018; Abobatta, 2018).

Functional polymers constitute a class of polymers distinguished by the presence of functional groups that differ in chemical composition from the polymer backbone chain. These functional groups impart specific properties to the polymer, which can be modified by altering the groups along the backbone. Functional polymers have several advantages in agriculture like control release of agrochemicals, super absorbent, soil conditioner, biogenesis, and augmented photosynthesis (Figure 2). Furthermore, "smart" polymers belong to a subset of functional polymers equipped

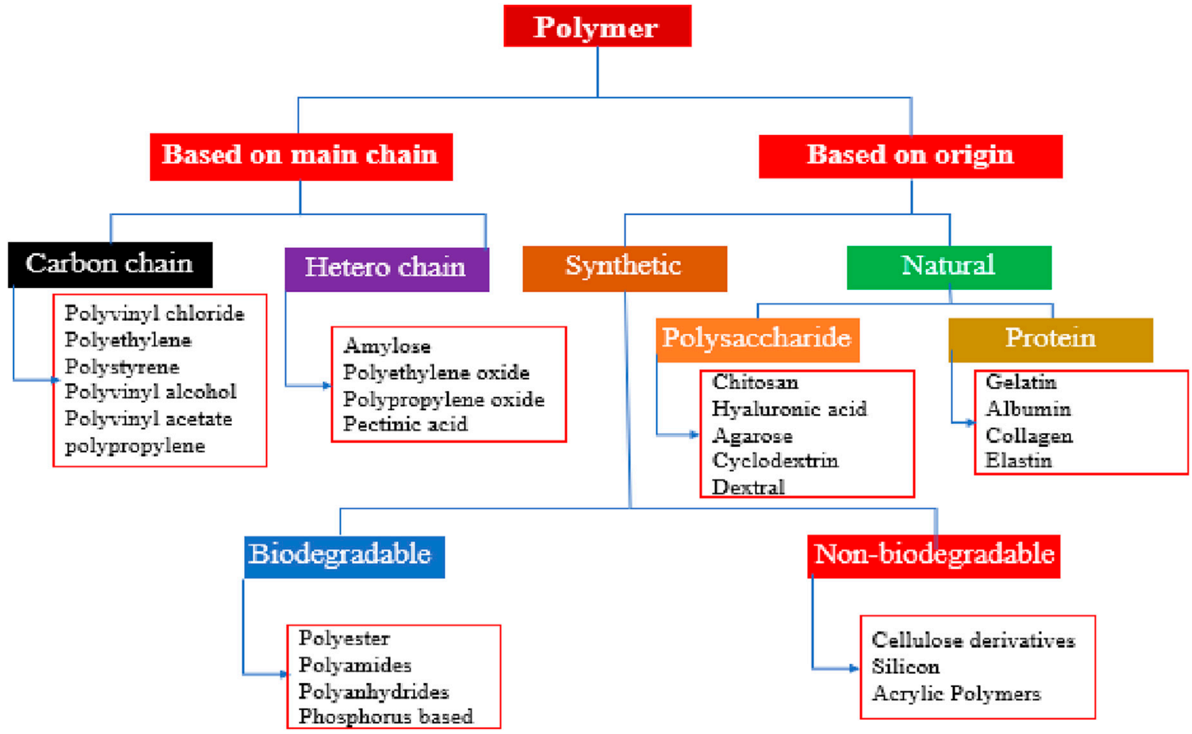

FIGURE 1
Classification of polymers.

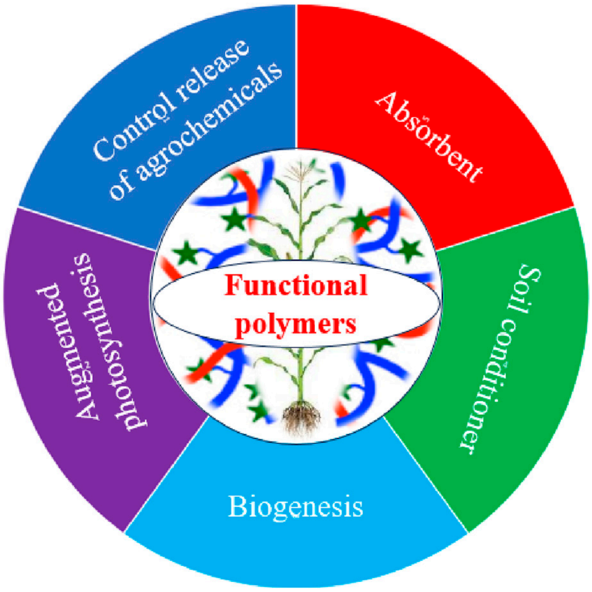

FIGURE 2
Different functions of functional polymers in agriculture.

with functional groups that respond to external stimuli like pH variations, exposure to light, or temperature changes. These stimuli trigger changes in the polymer's properties, making them highly adaptable and responsive materials for various applications. The three dimensional (3D) cross-linked hydrophilic polymer hydrogels, also known as smart polymers, possess the ability to absorb and retain larger amounts of water. This absorption capability is primarily determined by factors such as their chemical composition, the increase in entropy during absorption, the hydrophilic nature of functional groups, the affinity between the hydrogel and water, and the osmotic pressure generated by mobile counter ions (Bajpai and Giri, 2002). Consequently, these hydrogels find application as matrices in agriculture, particularly for controlled release purposes (Yu and Hui-min, 2006).

Synthetic polymers are human-engineered compounds mainly derived from petroleum sources, categorized into thermoplastics, elastomers, and synthetic fibers. The effectiveness of soil treatment with a polymer relies on its ability to efficiently coat soil particles and its inherent physical attributes (Tingle et al., 2007). Polymer stabilizers offer a promising solution to mitigate issues like greenhouse gas emissions and groundwater pollution linked with conventional methods (Almajed et al., 2022). Generally, synthetic polymers are used in geotechnical engineering as soil stabilizers, and are used in liquid, powder, and fiber forms. Enhancing soil properties like strength, stiffness, permeability, erosion resistance, water stability, and volume changes is crucial in geotechnical applications. Among the commonly utilized synthetic polymers for this purpose are polyacrylamide (PAM), polyethylene (PE), polypropylene (PP), polyurethane (PU), polystyrene (PS) and styrene copolymer, polyvinyl acetate (PVA), polyvinyl alcohol (PVAO), and polyvinyl chloride (PVC).

Biopolymers are polymers derived from biological organisms like plants, animals, bacteria, fungi, and algae (Figure 3). As far as our knowledge extends, comprehensive reviews encompassing the spectrum of research "hotspots" in advanced polymers for agriculture have not been published to date. Within this context, we have assembled an extensive review concentrating on the influence of synthetic polymers on agriculture. Application of biopolymers could be able to control diseases and pest control, plant growth enhancers, and soil conditioners (Raj et al., 2011). Our analysis delves into the structural and design components of these materials, emphasizing pivotal findings on impact assessment in soil ecosystems, environmental impacts, and agricultural perspectives, from the literature in a comprehensive manner. Briefly introduce the significance of soil health in environmental and agricultural sustainability. Highlight the increasing use of polymers in various applications and their potential impact on soil ecosystems. Geopolymers, which are typically ceramic alumino-silicates, form long-range, covalently bonded, non-crystalline (amorphous) networks. Some geopolymer blends include obsidian (volcanic glass) fragments as a component. The raw materials utilized in the synthesis of silicon-based polymers primarily consist of rock-forming minerals of geological origin, thus leading to the term "geopolymer." It can be categorized into two primary groups: pure inorganic geopolymers and organic-containing geopolymers, which are synthetic analogs of naturally occurring macromolecules. Geopolymer is essentially a mineral chemical compound or mixture of compounds consisting of repeating units, for example, silico-oxide (-Si-O-Si-O-), silico-aluminate (-Si-O-Al-O-), ferro-silico-aluminate (-Fe-O-Si-O-Al-O-) or alumino-phosphate (-Al-O-P-O-), created through a process of geopolymerization. Geopolymers have found diverse applications, primarily in construction and cementitious materials. However, researchers have discovered new uses for these materials, including fire protection, immobilization of waste and toxic materials, encapsulation of radioactive waste, and pH indicator.

2 Polymer interactions with soil

2.1 Mechanisms of polymer interactions with soil

Unlike organic polymers, geopolymers have distinct ways of interacting with soil minerals because of their inorganic Si-Al backbone frameworks. Geopolymer is known as alkali-activated cement, geo-cement, alkali-bonded ceramic, inorganic polymer concrete, and hydroceramic, it is an inorganic polymeric material synthesized like thermosetting organic polymers (Abdullah et al., 2015). Geopolymerization includes three stages (i) dissolution of source Al and Si, (ii) gelation, and (iii) reorientation of Si- and Al-complexes, and polycondensation are the primary mechanisms of geo-polymer stabilization (Huang et al., 2021) (Figure 4). The soil's structure and mineralogy are changed by the cementitious elements produced by this process, which bind soil particles together. After dissolution, aluminosilicate minerals create aluminosilicate oligomers, which finally form an aluminosilicate gel (Huang et al., 2021). At ambient temperature, the geopolymer solidifies and takes on an amorphous to semi-crystalline form. The more complex (N, C)-A-S-H (sodium/calcium aluminum hydrated) gel model is presented in the context of calcium-based geopolymer systems. This type, which is less well-known than the N-A-S-H gel, is divided into two phases: the C-S-H gel and the N-A-S-H gel. Calcium may come from a variety of sources, including calcium

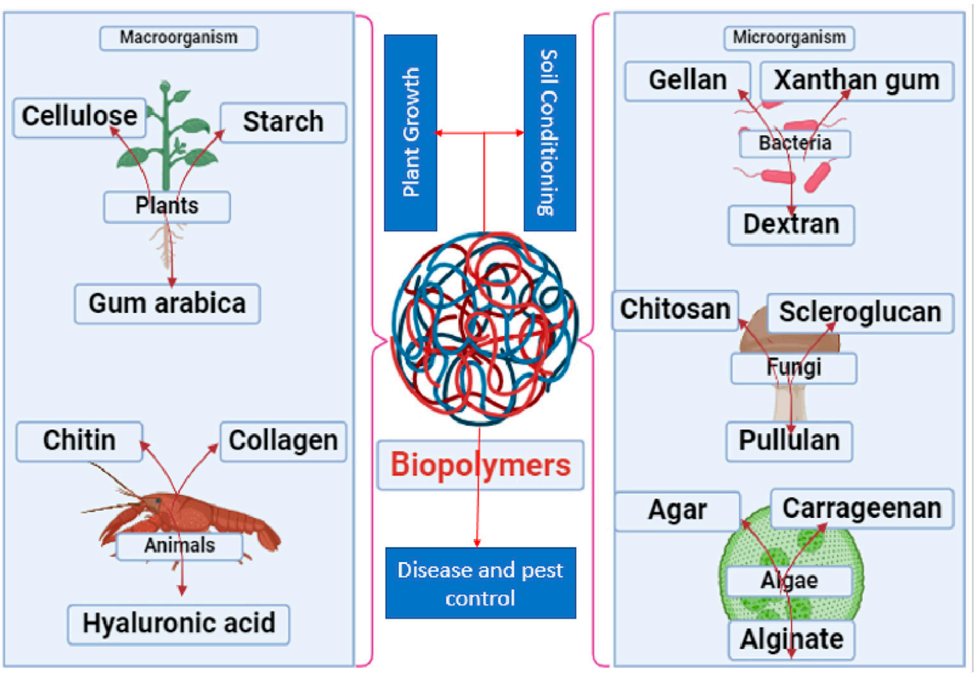

FIGURE 3
Biopolymers produced from different biological organisms and its functions.

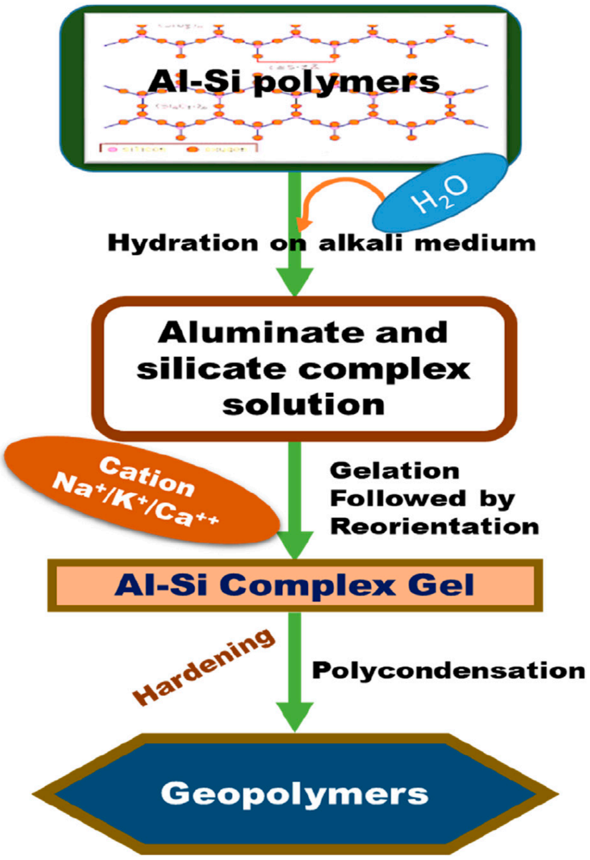

FIGURE 4
Mechanism of Geopolymerisation of inorganic polymers on soil.

silicate activators, slag, Class C fly ash, and additions like Portland cement. The coexistence of N-A-S-H and C-S-H gels contributes to the development of strength in geopolymers. Research indicates that higher curing temperatures (60°C–80°C) may lead to greater early strength but inferior long-term strength compared to lower curing temperatures (10°C–40°C). Furthermore, it has been observed that geopolymerization can take place at temperatures below 100°C (Huang et al., 2021). Applying geopolymers to stabilize soil has shown potential for strengthening soil via the production of cementitious geopolymerization products (Pourakbar et al., 2016). Complexity arises when applying geopolymers to soil because of variables that affect the process of geopolymerization, such as moisture level, alkaline concentration, and sources of silica and alumina. In the geopolymer-soil system, quality monitoring becomes difficult, especially when the geopolymer fraction is low. Changes in soil characteristics, such as cation exchange, may result from the interaction of soil and geopolymers, particularly when calcium-rich precursors or a KOH activator are used (Huang et al., 2021). This increases the complexity since the same geopolymer may have various effects on soils with different mineralogies. Even though this part of geopolymer stabilization has received little research attention, addressing these problems is essential to a thorough comprehension of the underlying processes.

Similarly, chemical reaction, enwrapping, and pore filling are all components of the reinforcing technique used for an organic polymer in clayey soil, as elucidated in several studies (Almajed et al., 2022). However, compared to interactions with sand, the chemical reaction between polymer and clay particles shows some significant differences. Soltani et al. (2018) described how adding a polymer to clay causes changes in the microstructural fabrics that result in the creation of nanocomposites. The adsorption process of

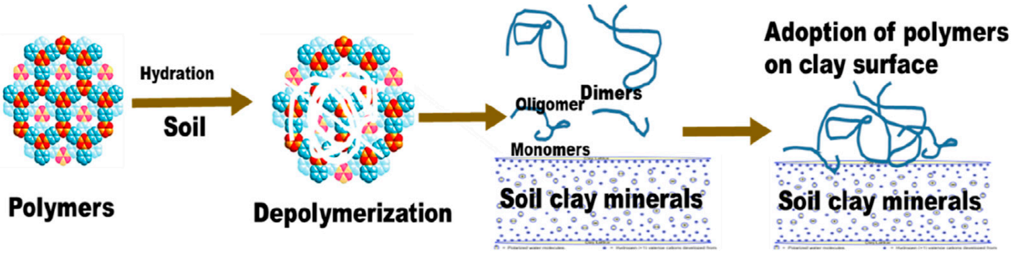

FIGURE 5
Schematic diagram represents the polymers adsorption on soil.

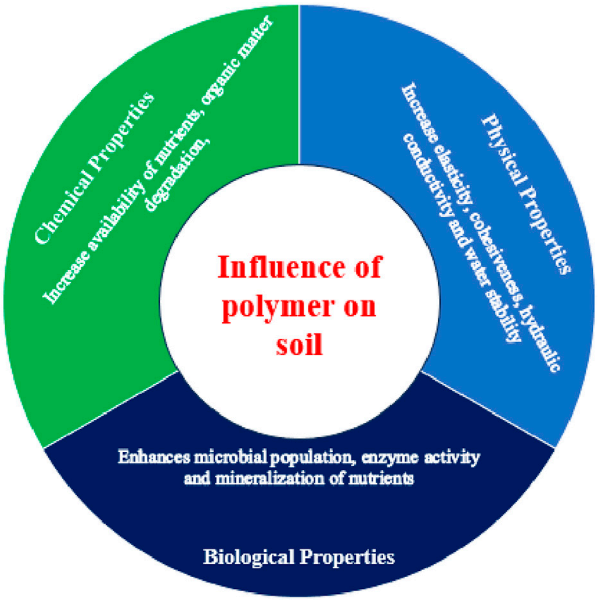

FIGURE 6
Influence of polymers on soil properties.

polymer in soil has been illustrated in Figure 5. Specifically, electrostatic forces draw cationic polymers, also referred to as polycations, towards the negatively charged clay surface. On the other hand, because of the initial charge repulsion between the polymer and the negatively charged clay surface, anionic polymers, also known as polyanions, undergo less adsorption. However, the adsorption of polyanions can be improved by the presence of polyvalent cations. Furthermore, electrostatic attraction to the positively charged edges of clay surfaces may be the dominant mechanism governing the interaction between anionic polymers and clay (Ghasemzadeh et al., 2021). According to the literature currently under publication (Soltani et al., 2018), non-ionic polymers cling to clay particles via hydrogen bonding or van der Waals (dispersion) forces. Physicochemical bonds, including ionic, electrostatic, cation bridge, ion-dipole, hydrogen bonding, or Van der Waals bonds, are formed as a result of this contact (Soltani-Jigheh et al., 2019). For example, Kang and Bate (2016) observed that kaolinite soil treated with polyethylene oxide (PEO) led to significant face-to-face aggregations. Deng et al. (2006) identified ion-dipole interactions between exchangeable cations and carbonyl (C=O) oxygens of amide groups ($CONH_2$) as a predominant mechanism for smectite about clay-polymer interactions with particular clay minerals, especially in the context of transition-metal cation exchanged smectite. It was also shown that in the hydration shells of exchangeable cations, amide groups, and water molecules form hydrogen bonds. Additionally, it was shown that montmorillonite significantly and irreversibly adsorbed partly acetylated polyvinyl acetate (PVAC), mostly due to hydrogen interactions formed between the polymer's hydroxyl groups and the oxygen on the clay surface (Greenland, 1963).

2.2 Biodegradation of polymers in the soil environment

Biodegradation is a process in which microbes are involved in breaking down complex material into simpler forms. The biodegradation process is influenced by environmental factors, microorganisms and their enzymes, and the properties of the polymer itself. The biodegradation process is influenced by environmental factors, microorganisms and their enzymes, and the properties of the polymer itself. Microbial degradation in this process occurs through enzymatic action. Microorganisms, such as bacteria and fungi, play an active role in biodegradation (Bher et al., 2022). These microorganisms have specific optimal growth conditions, making biotic degradation a complex process influenced by various factors related to the polymer, microorganisms, and the environment (Devi et al., 2016). The biodegradation characteristics of bio-polymers can vary depending on the soil environment, which is the least studied. Because biodegradation in soil happens slowly under natural conditions, it allows for a detailed investigation of the initial stage, known as biodeterioration. Research into soil biodegradation is particularly important for farmers, as it can encourage the transition from traditional polyethylene (PE) mulch films to bio-based plastics (Hayes et al., 2017; Slezak et al., 2023).

2.3 Polymers and soil properties

The most intriguing application of polymers is to modify the surface properties of soil particles (Figure 6). The effective,

TABLE 1 Influences of polymers on soil physical properties.

Sl. No.	Physical properties of soil	Inference	References
1	Atterberg Limit	Atterberg limits are primarily influenced by the size and proportion of clay minerals	Dolinar and Škrabl (2013)
		Atterberg limit is one of the standards used to define and describe expansion of clay polymer in soil	Sridharan and Prakash (2000)
		decrease in liquid limit (LL) for high plastic clay treated with PVC is due to the agglomeration of soil particles	Bekkouche and Boukhatem (2016)
		Inclusion of PP polymer creates nanocomposite materials inside the clay matrix, leading to a dramatic reduction in LL and PL by forming a hydrophobic composite material	Azzam (2014)
		hydrophilicity of acrylic polymer increases the PL and decreases the LL of expanding clay by creating a hydrophobic composite material that improves resistance to water	Mushtaq and Bhalla (2020)
		Molar mass of PAM significantly impacts the liquid limit	Lieske et al. (2019)
2	Compaction	Increase in the maximum dry density of clayey soil treated with various concentrations of PVC polymer	Bekkouche and Boukhatem (2016)
		Clayey soil with high plasticity was treated with vinyl copolymer	Kolay et al. (2016)
		Dry density and optimal moisture content for a sand-bentonite soil combination treated with acrylamide copolymer (AC) did not differ considerably	Ozhan (2019)
		Addition of PAM to expansive clayey soil increase in the maximum dry density and capillary tension	Soltani et al. (2018)
3	Soil strength	Cationic polymer molecules with the clay particles is a process that enhances soil stability	Yunus et al. (2014)
		PE materials used for enhancing physical properties of sandy soil	Al-Saray et al. (2021)
		10% VA to fine-grained soil, increased cohesiveness significantly about 6.5 times	Song et al. (2019)
		Acetic Ethylene Ester (AEE) lower increase in cohesiveness, around 1.4 times	Liu et al. (2011)
		PE and PVC polymer treated with clay soil	Souhila et al. (2018)
		10% of PU1 and PU2 were added to sand, cohesiveness rose by 9 and 5 times, respectively	Almajed et al. (2022)
		Addition of PVC and HDPE to clay decreased in soil void volume	Bekkouche and Boukhatem (2016)
4	Permeability and Hydraulic Conductivity	PAM 2a-c polymers to three fine-grained soils resulted in a significant reduction in hydraulic conductivity, ranging from approximately 63%–99%	Almajed et al. (2022)
		Clay modified with 5% VC enhanced hydraulic conductivity by around 2.5 times	Taher et al. (2020)
		0.5% acrylic-based polymers (VA, SA, and AP), which significantly reduced hydraulic conductivity by 2, 2, and 5 times	Al-khanbashi and Abdalla (2006)
		decrease in saturated hydraulic conductivity in sandy soil that had been changed with varying quantities of a tripolymer of acrylamide, acrylic acid, and potassium, and a hydrophilic isopropylacrylamide polymer	Andry et al. (2009) Dehkordi (2018)
5	Water Stability Index	PAM and CMC crosslinked polymer, and ADNB inceases improvements in water stability	Almajed et al. (2022)
		Improvements in water stability have been noted in response to increases in the concentrations of AEE	Liu et al. (2011)
		Water stability index rose and specimen disintegration decreased as the PU polymer content rose	Qi et al. (2020a)
		PU-treated sand specimens in water on shear strength parameters	Liu et al. (2018)
6	Erosion resistance	Sand treated with PU polymer showed a much-reduced erosion ratio	Liu et al. (2019)
		PAM significantly decreased the amount of soil mass loss in sandy soil	Georgees et al. (2017)
		Decrease in the rate of erosion of clayey soil is associated with an increase in the concentration of AEE and VAE polymers	Liu et al. (2011) Song et al. (2019)
		Addition of anionic, high-quality PAM to irrigation water reduces silt in runoff water by over 90%, thereby enhancing water erosion resistance	Orts et al. (2007)

individual component of the soil, known as the particle, might take the form of a sheet, crystal, or aggregate. Very strong primary valence bonds keep atoms together in sheets; strong or weak secondary valence bonds hold sheets together in crystals, as in the cases of kaolinite and montmorillonite; and weak secondary valence bonds hold crystals together in aggregates. It is only the intra-aggregate forces that can be disrupted by chemical additions or pressures provided by engineering, or the intra crystal forces in the case of expanding clays. Chemicals can change the direction and even the amount of intra-aggregate forces. The methods by which additives might generate repulsive forces between particles and subsequently scatter the soil or attract forces between particles and aggregate the soil have been explained by Michaels (1952). It has been observed that the addition of polymers in specific quantities can change the characteristics of soil.

2.3.1 Physical properties

The influence of polymers on soil physical properties has been described in this section. The different findings are tabulated in Table 1. The Atterberg limits test is utilized to determine the critical moisture content at which fine-grained soils transition between different consistency states. These limits, crucial for construction and tillage operations, delineate the physicomechanical behavior of soils. According to Dolinar and Škrabl (2013), in non-expansive soils, the Atterberg limits are primarily influenced by the size and proportion of clay minerals. Conversely, in expansive soils, the amount of interlayer water is chiefly determined by factors such as the type of clay minerals present, exchangeable cations, and the chemical composition of the pore water. The Atterberg limit is one of the standards used to define and describe expansive soils (Sridharan and Prakash, 2000).

Depending on the types and quantities of polymers used, the Atterberg limits of soil treated with polymers often exhibit distinct behaviors. As the polymer content increases, changes in the liquid limit (LL) and plasticity limit (PL) of fine-grained soil may vary—decreasing, increasing, or remaining relatively unchanged. Azzam (2014) noted that the inclusion of PP polymer creates nanocomposite materials inside the clay matrix, leading to a dramatic reduction in LL and PL by forming a hydrophobic composite material that enhances the net electrical attraction between clay particles, thereby increasing water resistance. Conversely, PAM polymer molecules, being hydrophilic, provide more adsorption sites for water molecules, thus increasing LL and PL. Mushtaq and Bhalla (2020) suggested that the hydrophilicity of acrylic polymer increases the PL and decreases the LL of expanding clay by creating a hydrophobic composite material that improves resistance to water. Additionally, the molar mass of PAM significantly impacts the liquid limit (Lieske et al., 2019).

The compaction behavior of the soil-polymer mixture showed variations. Specifically, there was a slight increase in the maximum dry density of clayey soil treated with various concentrations of PVC polymer was observed by Bekkouche and Boukhatem (2016). The optimal moisture content was affected by the ionic exchange mechanism, leading to moisture dissipation and absorption during the chemical reaction. The modifications observed in both cases were attributed to the formation of hydrophobic nanocomposite materials within the soil particles, which acted as nano-fillers. However when 3% of the PVC polymer was added, the optimal moisture content was seen to rise significantly, and when the concentration was increased to 6%, the optimal moisture content climbed gradually.

Unconfined Compressive Strength (UCS) in clayey soil was often not considerably increased by the addition of polymer, whereas in silty soil, UCS increased with polymer concentration. Nevertheless, in several cases, exceeding the ideal polymer concentration resulted in a decrease in strength. It was proposed that the increase in UCS was caused by an electrostatic link that improved the connection between the soil particles in the laterite soil by Joining the cationic polymer molecules with the clay particles is a process that enhances soil stability and modifies its properties (Yunus et al., 2014). Moreover, when the concentration increased from 0% to 3%, the cohesiveness of clayey soil treated with PE and PVC polymer (Souhila et al., 2018) showed a notable rise of around 10% and 60%, respectively. However, for PVC polymer, increasing the polymer concentration led to an 18% decrease in cohesiveness (Bekkouche and Boukhatem, 2016), but high-density PE (Souhila et al., 2018) showed an additional increase of almost 29%. There was no discernible variation in the friction angle of the fine-grained soil treated with VA (Song et al., 2019) and AEE (Liu et al., 2011) polymers, which ranged from 29° to 31° to 56°–62°, respectively. When the polymer content increased from 0% to 9%, Canlite (Marto et al., 2013) caused the friction angle to rise by 18%. Comparably, at a concentration of 3%, PVC and high-density PE (Souhila et al., 2018) increased the friction angle by 15%; however, upon doubling the concentration, the friction angle decreased by around 37% and 17%, respectively. Significant cohesion increase was seen with polymer concentration in cohesionless soil. When 10% of PU1 and PU2 were added to sand, cohesiveness rose by 9 and 5 times, respectively (Almajed et al., 2022). Overall, the findings of the direct shear test show that the type and concentration of the polymer have an impact on the various impacts of polymer inclusion on soil shear strength. To improve the CBR of high-plasticity clay, Mousavi et al. (2021) used CBR Plus and RPP. They found that CBR values increased as polymer concentrations increased. Hasan and Shafiqu (2017) and Ahmed and Radhia (2019) observed comparable patterns upon adding different amounts of HDPE and UFR polymer to high-plasticity clay and sand, respectively. The creation of a more compact structure as polymer concentration rises is responsible for the improvement in CBR. The reason behind the increase in CBR, when PVC and HDPE polymers are added to highly plastic clay, is explained by the decrease in soil void volume and the efficient dispersion of soil particles with polymer particles, as reported by Bekkouche and Boukhatem (2016).

Hydraulic conductivity is the term used to describe the coefficient of permeability when the fluid is water. Several investigations have documented a significant and prompt decrease in the permeability of soils treated with polymers. A few instances, meanwhile, showed an increase in hydraulic conductivity. For instance, the addition of 1% of anionic PAM 2a-c polymers to three fine-grained soils resulted in a significant reduction in hydraulic conductivity, ranging from approximately 63%–99% (Almajed et al., 2022). Conversely, Taher et al. (2020) found that expanding clay modified with 5% VC enhanced hydraulic conductivity by around 2.5 times. Al-khanbashi and Abdalla (2006) modified sand using 0.5% acrylic-based polymers (VA, SA, and AP), which significantly reduced hydraulic conductivity by 2, 2, and 5 times, respectively. Additional decreases were the consequence of increasing the polymer concentration. It has been discovered that sand combined with PAM had 1.3 times less hydraulic conductivity than untreated sand. Both Andry et al. (2009) and Dehkordi (2018) observed a significant decrease in saturated hydraulic conductivity in sandy soil that had been changed with varying quantities of a tripolymer of acrylamide, acrylic acid, and potassium, and a hydrophilic isopropyl acrylamide polymer.

The water stability and soaking experiments have been carried out with different polymer kinds and concentrations to obtain a deeper knowledge of the interaction between polymer-soil admixtures and water molecules. The purpose of these tests is to assess a polymer-soil admixture's resistance to degradation in the presence of water. The treated specimen's resistance to collapse over time is measured by the water stability index, or "k." For example, the coefficient is five if the soil collapses within the first minute of immersion; it is 15 if the collapse happens between the first and second minute of immersion; and 100 if the collapse does not happen over the full 10-minute immersion (Almajed et al., 2022). Qi et al. (2020) examined the water stability of PU-sand admixtures by analyzing the shear strength and disintegration area. The water stability index rose and specimen disintegration decreased as the PU polymer content rose. Research has also looked at how water affects the strength of admixtures of polymer and soil. The impact of submerging PU-treated sand specimens in water on shear strength parameters was investigated by Liu et al. (2018). It was proposed that the PU polymer's membrane would become softer when immersed, which could change how the admixture behaves.

The physical process of water erosion, which is caused by flowing water, is impacted by the soil's response to hydrodynamic stress. According to Liu et al. (2019), when running water was applied, natural sand began to erode right away, while sand treated with PU polymer showed a much-reduced erosion ratio that was almost nil in the early stages of erosion. This implies that the polymer treatment causes a delay in erosional behaviour. Moreover, the maximum erosion ratio per minute decreased by 1.5% when 5% PU polymer was added to sand, and the erosion incidence time lengthened as the PU concentration increased. Similarly, to this, Georgees et al. (2017) found that treating three sandy soils with water-soluble anionic PAM significantly decreased the amount of soil mass loss. Liu et al. (2011) and Song et al. (2019) have reported in their investigations that a decrease in the rate of erosion of clayey soil is associated with an increase in the concentration of AEE and VAE polymers, respectively. Orts et al. (2007) observed that the addition of anionic, high-quality PAM to irrigation water reduces silt in runoff water by over 90%, thereby enhancing water erosion resistance. Additionally, during intense simulated rains, the use of PAM polymer at road cuttings and construction sites significantly reduced sediment flow, by 60%–85%. Similar findings were made by Sojka et al. (1998) about PAM's ability to dramatically lower silt flow in water. In comparison to water-treated soil, PVA polymer-treated soil showed a reduction in erosion rates of more than 90%, according to Bakhshi et al. (2021) and Movahedan et al. (2012). When PVA polymer was incorporated into sandy and loamy sandy soil, soil mass loss was significantly reduced. Following drying, the surface layer of polymeric samples of sandy soil exhibited uniformity and firmness. Applying cationic PAM significantly decreased sand weight loss, according to Ding et al. (2020).

2.3.2 Soil biological properties

The preservation of soil quality is significantly influenced by the composition and diversity of microbial communities in soils (Rong et al., 2017; Qian et al., 2018). The diverse community's makeup and activity serve as the main biological markers of changes in the soil environment because they play an essential role in the soil's ability to cycle carbon, nitrogen, phosphorous, and potassium (Bergkemper et al., 2016; Delgado-Baquerizo et al., 2016). The plastic film contains approximately 20%–60% phthalate esters (PEs), which are widely known to pollute the environment, impact microbial ecosystems, and interfere with soil enzymatic activity. The comparison of bacterial composition between soil exposed to plastic film and control soil done by Qian et al. (2018) revealed that the presence of plastic film can modify the soil microbiome, resulting in higher levels of *Proteobacteria, Bacteroidetes*, *Gemmatimonadetes,* and *Nitrospirae* compared to the control soil. *Nitrospirae* are widely distributed nitrite-oxidizing bacteria found in terrestrial habitats which significant contributions to the process of biological nitrogen cycling and soil nitrification in agricultural ecosystems (Xia et al., 2011). Qian et al. (2018) also concluded that the proportions of some bacterial phyla in soils coated with plastic film were significantly different from those in the control soil, indicating a gradual adjustment to the presence of plastic film contamination.

A study conducted by Tian et al. (2020) found that the use of polymer materials did not have any negative impact on the soil microbial ecosystem. These studies have shown that the presence or absence of plants in the soil is a significant factor influencing the diversity of soil microorganisms (Li et al., 2014; Zhang et al., 2015). According to Liu et al. (2022), combined application of polyethylene (PE)/phenanthrene (PHE) significantly enhanced microbial diversity and enzyme activity. Qian et al. (2018) in their study on the effect of residual plastic films (RPF) on microbial community stated that Gemmatimonadetes has strong adaptability to both arid and oligotrophic environments which suggests that RPF has altered soil fertility and led to the emergence of resilient microbes in an unfavourable environment, which was also demonstrated by Hanada and Sekiguchi (2014). Studies consistently show that soil Proteobacteria is the most prevalent bacterial phylum, exhibiting significant genetic and metabolic diversity (Janssen, 2006). Betaproteobacteria, a class of Proteobacteria, forms a symbiotic association with plants, including nitrogen-fixing bacteria (Dedysh et al., 2004). The presence of a large number of Alphaproteobacteria and Betaproteobacteria can significantly improve the process of soil nitrogen fixation. The application of humic acid and modified polymer increased the proportion of Betaproteobacteria compared to the control group (Tian et al., 2020). The addition of humic acid primarily increased to the proportions of Planctomycetes, Acidobacteria, Chloroflexi, Firmicutes, and Latescibacteria. Sphingomonas strains are commonly isolated from polluted soils due to their ability to degrade polycyclic aromatic hydrocarbons (PAHs). They can be regarded as significant biocatalysts for the process of soil bioremediation (Leys et al., 2004). The utilization of noxious compounds will undoubtedly lead to the proliferation of specific bacterial species (Cai et al., 2015). The bacteria *Sphingomonas* and *Pseudomonas* can facilitate the process of nitrate reduction, resulting in the production of nitrogen (Chen et al., 2017; Tao et al., 2018). *Pseudomonas* is a type of microorganism that acts as a surfactant, facilitating the process of denitrification in the nitrogen cycle (Chen et al., 2017; Wang et al., 2017). The plastic film contains about 20%–60% phthalate esters (PEs), which ubiquitously contaminate the environment and affect microbial communities and soil enzymatic activities (Qian et al., 2018; Jambeck et al., 2015).

Judy et al. (2019) found that the presence of high-density polyethylene (HDPE), polyethylene terephthalate (PET), or polyvinyl chloride (PVC) microplastics (MPs) at levels up to 1% (w/w) did not cause any noticeable alteration in the bacterial populations present in the soil. Fei et al. (2020) discovered notable alterations in the makeup of the bacterial population when 1% (w/w) of PVC and 1% (w/w) of PE were introduced. They also discovered that the introduction of PVC or PE increased the capacity for nitrification and denitrification in the soil. The addition of polyethylene (PE) and polypropylene (PP) microplastics (MPs) microplastics likely enhances biological nitrogen fixation and subsequently impacts nitrogen cycling in the soil (Kim et al., 2023).

2.3.2.1 Microbial activity and functionality

Microplastics that are brought into the soil from outside sources can be inhabited by microorganisms, which is a common occurrence in water and sediment environments (Harrison et al., 2014; Kettner et al., 2017; McCormick et al., 2014; Phuong et al., 2016). The breakdown of colonized particles may lead to a decrease in the size of microplastic particles and their eventual extinction. The bacteria found in the digestive systems of earthworms resulted in a significant 60% decrease in the overall mass of microplastics in sterilized soil within a short period of 4 weeks (Helmberger et al., 2020). Nevertheless, it is possible that bacteria might not always establish colonies and break down plastics in natural soils where alternative sources of nourishment are present (Ng et al., 2018). Microorganisms may have a preference for carbon sources that require less energy, and the simultaneous breakdown of plastic alongside other compounds is unlikely to happen significantly in natural soil environments (Ng et al., 2018). However, Liu et al. (2017) documented an augmentation in microbial enzyme activity, suggesting that certain soil bacteria are capable of reacting to the existence of microplastics. Macroplastic detritus, such as agricultural film or garbage, can also be colonized by microbes, which could potentially lead to the creation of autochthonous microplastics. Certain bacteria have been demonstrated to induce a substantial reduction in weight from the agricultural film, however, other investigations indicate minimal or no deterioration (Wei and Zimmermann, 2017). Microorganisms can physically weaken plastic, as demonstrated by Lucas et al. (2008). Furthermore, Kyrikou and Briassoulis (2007) highlight that weight loss reported in any study may suggest not just breakdown and mineralization or assimilation by microorganisms, but also the physical fragmentation of plastic. According to a study conducted by Meng et al. (2022), one possible reason for the decrease in permanganate oxidizable carbon (POXC) concentration could be the impact of LDPE-MPs and Bio-MPs on soil biological processes, leading to alterations in these processes. In another study, Qi et al. (2020) discovered that starch-based biodegradable microplastics (MPs) caused a significant increase in decanal levels in the rhizosphere. It is well-established that decanal has detrimental effects on fungal growth. A study conducted by Cluzard et al. (2015) found that PE contains antibacterial compounds, which can control the types of microorganisms present in soil and impact the amount of microorganisms in the soil.

In microplastic polluted soil, bacteria, fungi, and algae are attached to the surface of MP (De Tender et al., 2017) and different types of MP can stimulate the proliferation of bacteria and fungi (Omidoyin and Jho, 2023). Whereas, nematodes and Rotifera, are very sensitive to MP and show alterations in the gut microbiome, reproduction rate, motility, and life span, showing stress reactions, and malfunctioning metabolism in response to different types of MP (Büks et al., 2020). Arbuscular mycorrhizal fungi (AMF) reduced root colonization and infectivity (Leifheit et al., 2021).

The production of soil enzymes by microorganisms and plants is strongly linked to the flow of energy and cycling of nutrients in the soil. These enzymes are highly responsive to changes in the soil and may adapt quickly (Cui et al., 2018). The addition of polypropylene particles smaller than 180 μm to Chinese Loess soils led to an increase in the activity of fluorescein diacetate hydrolase (FDAse), which serves as an indicator of total microbial metabolic activity (Liu et al., 2017). Recent research has indicated that the effects of microplastics (MPs) on soil FDAse activity may vary depending on the types of MPs (de Souza Machado et al., 2018; de Souza Machado et al., 2019). Meanwhile, various soil enzymes may have diverse reactions to the same microplastics (MPs). In the study conducted by Liu et al. (2017), the researchers also examined the activity of phenol oxidase (PO) and observed that it was significantly reduced in the soils exposed to microplastics (MPs) compared to the control soils during the initial 7-day period.

Wang et al. (2016) found that Phthalate esters (PEs) can either decrease fluorescein diacetate hydrolysis and dehydrogenase activity or improve phosphatase activity. These effects may be due to variations in ambient or experimental settings used to control RPF contamination (Qian et al., 2018). The study found that the presence of both PVC and PE microplastics (MPs) in the soil had an impact on the activities of urease, acid phosphatase, and FDAse. Prior research has examined the impact of microplastics on soil enzymatic activity, specifically focusing on FDAse and phenol oxidase (PO) as the key enzymes in the analysis (de Souza Machado et al., 2019). The adverse impacts of microplastics (MPs) on the fluorescein diacetate hydrolase (FDAse) in the current investigation differed from prior research conducted in Chinese Loess soil (Liu et al., 2017) and another alkaline soil in Berlin (de Souza Machado et al., 2018). The variation could be attributed to the characteristics of the soil and the types of microplastics (MPs) (Fei et al., 2020).

Soil with high levels of SOC and N in an acidic environment can lead to variations in microbial communities across various soils. Simultaneously, the bacterial community experienced a loss in both richness and diversity due to the introduction of MPs, which aligns with the observed decline in FDAse activity within the soil (Fei et al., 2020). In addition, the types of MP used in the experiments varied between the current study and previous investigations. Furthermore, the significant decrease in FDAse activity was primarily attributed to the high concentration (5% w/w) of PVC in this investigation. The activity of FDAse was not uniformly impacted by the various microplastics (MPs) examined in the studies conducted by de Souza Machado et al. (2018) and de Souza Machado et al. (2019). Unlike the inhibitory effect of FDAse activity induced by PVC or PE, the presence of microplastics (MPs) in the soil resulted in the stimulation of both urease and acid phosphatase activities. Soil moisture has a significant impact on the activities of urease and acid phosphatase. Research has demonstrated that a decrease in soil moisture by 21% resulted in a decrease of 10%–67% and 31%–40% in urease and acid phosphatase, respectively (Sardans and Peñuelas, 2005). According to de Souza Machado et al. (2018), microplastics like polyacrylic fibers, polyamide beads, polyester fibers, and polyethylene fragments have the ability to enhance the soil's water retention capacity. Consequently, soil contaminated with microplastics may retain moisture for an extended period of time. Fei et al. (2020), also proposed that the rise in the number of diazotrophs had a significant impact on enhancing the urease activity of the soil treated with MPs. Furthermore, it is likely that the acid phosphatase activity was associated with the amount of diazotrophs. So, Microplastics' effects on terrestrial ecosystems have been extensively studied, but little is known about how they affect the dynamics of microbial diversity and functionality.

2.4 Impact on water management

SAPs (super absorbents polymers) otherwise known as "miniature water reservoirs" are made up of lightly cross-linked networks of hydrophilic polymer chains and are capable of swelling in water, absorbing, storing, and releasing water upon root demand based on the principle of osmotic pressure (Huettermann et al., 2009). Thus, SAPs reduce evaporation and percolation loss of water and ultimately improve the water holding capacity of the soils (Malik et al., 2022). Such polymers hold practical relevance for growing crops, especially in sandy and drought-prone soils.

Polymer/clay superabsorbent composites are also great water absorbers and are more cost-efficient. On the other hand, gel-forming polymers made up of three-dimensional cross-linked polymeric networks can absorb water up to 1,000 times their weight, form gels, and absorb large amounts of water along with soil nutrients in a similar fashion to sponges (Jnanesha et al., 2021). Overall, these polymers prevent water loss, store water efficiently and release it as per crop demand, thereby largely reducing the irrigation frequency (Kujur et al., 2022). Thus, SAPs and hydrogels are promising technologies for effectively dealing with agricultural drought, especially in rainfed areas (Feng et al., 2020).

While synthetic polymers are more efficient in storing water than natural polymers, the latter ones are more biocompatible, biodegradable, and cost-effective (Krasnopeeva et al., 2022). However, the effectiveness of hydrogels reduces with increased salinity and ions such as Mg^{2+}, Ca^{2+}, and Fe^{2+} as they can break the polymeric structures and release the stored water molecules (Reddy et al., 2015). Nevertheless, the effectiveness of the SAPs would also depend on the initial soil status i.e., soil pH, clay content, soil organic matter status, bulk density, total nitrogen status, nitrogen fertilization, and water supply (El-Asmar et al., 2017). Agri polymers are supposed to work better at a higher initial pH than at a lower initial pH (Zheng et al., 2023). SAP polymers are reported to be more effective under water deficit and rainfed conditions rather than in well-irrigated situations (Zheng et al., 2023). Moreover, SAP application under irrigated conditions may even reduce crop yields (Wang et al., 2012).

2.5 Impact on nutrient availability

These cross-linked polymers also help in reduced nutrient loss, their greater absorption, and subsequent slow release to crop root zones meeting timely crop demand for nutrients. Polymers can reduce nitrogen leaching by 45% (Mikkelsen, 1994). Mazloom et al. (2020) reported higher phosphorus uptake in maize by application of lignin hydrogel. Chen et al. (2016) noted that polymers containing both acrylamide and acrylate side chains exhibited a greater capacity to retain Ca^{2+} ions, thereby promoting the flocculation state of the soils. Eneji et al. (2013) documented reduced nitrate leaching and improved nitrogen uptake by maize crops when superabsorbent polymers (SAP) were applied under deficit irrigation conditions. Yang et al. (2022) reported that SAP application enhanced soil organic carbon status, enzymatic activity, and microbial biomass carbon in a long-term experiment in wheat crops. Recently, Al-Amiri and Al-Baraka (2023) observed that the application of agricultural polymers resulted in increased availability of nitrogen, phosphorus, and potassium in wheat crops. Enhanced availability of nutrients by application of agricultural polymers can be attributed to (i) improved soil physicochemical properties ensuring conservation of soil nutrients, (ii) improved soil moisture status, (iii) nutrient retention in the soluble state for enhanced periods, (iv) preserving of nutrients in soluble form, (v) minimizing nutrient loss for soil ecosystems, and (vi) improved cation exchange capacities (Al-Amiri and Al-Baraka, 2023). Zheng et al. (2023) observed that SAPs act best in soils with low fertility, low total nitrogen, low fertilizer inputs, and low soil organic carbon status.

2.6 Controlled delivery of agricultural inputs

Crosslinked polymers are utilized as carriers for various biocides, including herbicides, molluscicides, fungicides, insecticides, algicides, and bactericides. Polymers are reported to be beneficial for the controlled delivery of formulations/biologically active agents (Milani et al., 2017). Major benefits of applying these agricultural inputs by polymers include (i) the need for less quantity of biocide, (ii) slow and precise release of active ingredient over a long period, (iii) reduced mobility of biocides ensuring targeted application, (iv) protecting the non-persistent biocides from environmental degradation, (v) increase the use efficiency of pesticides and herbicides, (vi) minimizing the need for repeated application, and (vii) health benefits for farm workers. However, the requirement of a large amount of inert material as carriers and disposal of the herbicide residuals are the major limitations of polymers as carrier materials (Ekebafe et al., 2011). Seed

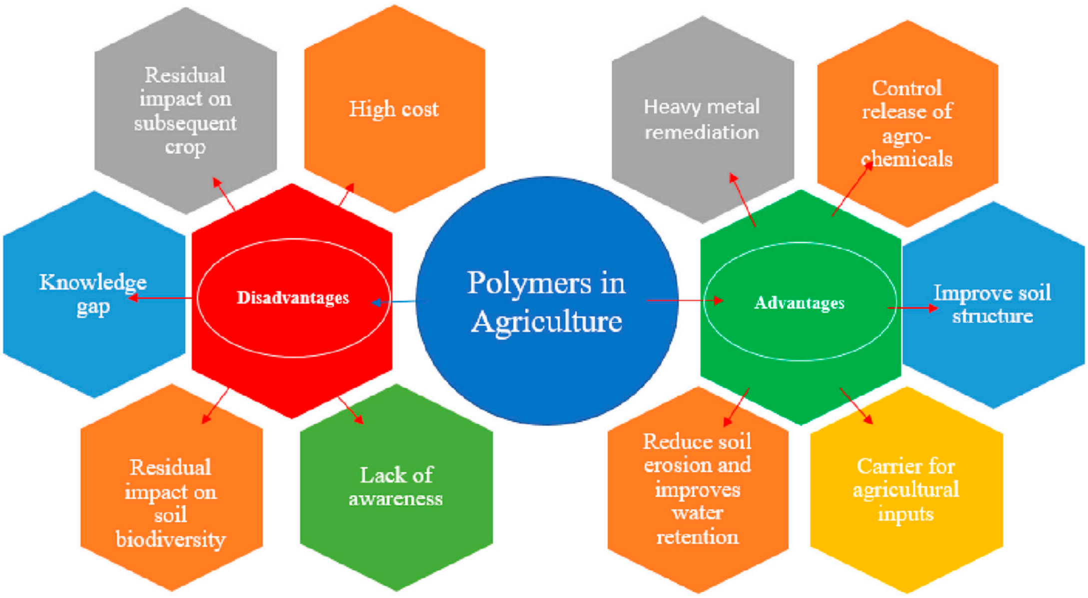

FIGURE 7
Schematic diagram of advantages and disadvantages of polymers uses in agriculture.

additives and some growth regulators can also be applied through SAPs (Krasnopeeva et al., 2022).

2.7 Impact on crop yield

Improved crop yield by application of polymers has been reported for many crops e.g., corn (Al-Amiri and Al-Baraka, 2023), peanut (Islam et al., 2011), senna (Jnanesha et al., 2021), potato (Hou et al., 2018). In a study conducted by Reddy et al. (2015), the impact of a cross-linked polymer composed of polyacrylamide and potassium acrylate (PAM) on the yield and water productivity of tomato crops cultivated in sandy loam soil was examined. The research indicated that applying the aforementioned polymer at a rate of 25 kg per hectare, coupled with irrigation on alternate weeks, led to increased yield, improved water retention, and reduced irrigation needs. The enhancement in crop yield due to the utilization of SAPs can largely be credited to the improvement in soil physicochemical properties, increased soil nutrient availability, enhanced water retention, and augmented microbial activity. Furthermore, the application of SAPs can also elevate soil temperature, leaf area temperature, and photosynthetic rate, ultimately leading to higher yields (Yang et al., 2018).

A recent comprehensive review by Zheng et al. (2023) summarizing the results of 310 studies across the world has reported that by application of SAPs, there is an average improvement in yield and water productivity by 13% and 17%, respectively. Tuber crops and vegetables have been reported to be best benefited by the application of SAPs in terms of yield and economics, respectively Zheng et al. (2023). Thus, considering the ever-declining water availability for irrigation, the use of polymers is a potential option for managing water stress and safeguarding food security.

2.8 Limitations and way forward

Major limitations of the use of polymers in agriculture include high costs, especially for synthetic ones (Figure 7). Moreover, there exists a knowledge gap regarding the time required for complete biodegradation of different types of polymeric compounds in different environmental conditions. The environmental impacts of the residues and the impact of the residues on subsequent crops/cropping systems are still not fully explored. Thus, identification and mitigation of any potential environmental threat of the agricultural polymers is required. Future research also needs to be conducted considering the impact of different tillage practices on the effectiveness of agricultural polymers. Standardizations also need to be established concerning effective and suitable doses and methods of application of agricultural polymers in different crops. Despite that controlled release of agrochemicals may fail to supply an adequate amount of desired chemicals/nutrients during high crop demand also causes unwanted residue in the soil, which affects soil acidity. Non-biodegradable polymers cause soil pollution destroy soil biodiversity and enter into the human food chain.

To minimize the lingering impacts of herbicide carriers, there have been advancements in dual-application products designed for both herbicide and fertilizer use. In this system, the residual products resulting from polymer degradation serve as beneficial agents for plant growth and soil enrichment, acting as fertilizers (Bourzac, 2020). Such products need to be adopted more. The use of more and more natural polymers/bio-based materials, e.g., polysaccharides and polypeptides/natural-based SAPs should be encouraged to reduce cost and environmental impacts. In the future, there is an opportunity to explore the potential of semi-synthetic, hybrid polymeric materials, and polymeric nanocarrier systems (Sikder et al., 2021). More field trials across a wide range of crop species and with different water management approaches are the need of the hour to establish concrete facts regarding the practical applicability of polymeric substances at a larger scale.

3 Conclusion

The potential applications of polymers in agriculture are indeed vast, but their full-scale adoption faces significant challenges, primarily related to cost and regulatory hurdles. Advanced polymeric materials offer promising capabilities for smart agriculture, yet their production costs tend to be higher due to increased complexity. This cost factor can limit widespread implementation, especially in field applications where large quantities of materials are required. Complex regulatory frameworks often necessitate extensive testing and validation before new materials can be approved for use in agricultural settings. Increased investment in field trials and real-world testing is crucial to demonstrate the efficacy and safety of functional polymers in diverse agricultural environments. Gathering empirical data from field applications can inform further refinements and validate the practical utility of these materials. By addressing these challenges and fostering interdisciplinary collaboration, the potential of functional polymers in revolutionizing agriculture can be realized, paving the way for sustainable and innovative farming practices.

Author contributions

DS: Conceptualization, Software, Visualization, Writing–original draft, Writing–review and editing. SM: Data curation, Methodology, Writing–original draft. KM: Conceptualization, Formal Analysis, Methodology, Resources, Visualization, Writing–original draft. PD: Conceptualization, Formal Analysis, Methodology, Software, Visualization, Writing–original draft. SS: Data curation, Investigation, Software, Supervision, Validation, Writing–original draft. KP: Conceptualization, Methodology, Resources, Software, Validation, Writing–original draft. KK: Conceptualization, Methodology, Software, Supervision, Writing–review and editing. RM: Data curation, Software, Validation, Writing–review and editing. NP: Data curation, Investigation, Methodology, Resources, Visualization, Writing–review and editing. SP: Investigation, Methodology, Project administration, Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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