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Lignin-based hydrogels for application in agriculture: A review

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ABSTRACT

Agriculture is an important sector for maintaining environmental sustainability and ensuring global food security. However, the sector faces significant challenges caused by soil degradation, water scarcity, and resource limitations. To overcome the challenges, several studies have shown that innovative materials, including hydrogels, have the ability to improve agricultural practices. Lignin, the sole polyaromatic biopolymer, and the second most abundant biopolymer, has been extensively explored for a wide range of applications. For example, lignin valorization represents a significant issue for lignocellulosic biorefineries as well as the pulp and paper industry. This has led to an increase in interest over the past decade in its utilization to create innovative, advanced smart materials. Therefore, this study aims to discuss the applications, advantages, and possibilities of lignin-based hydrogels in addressing the primary difficulties of contemporary agriculture to increase sustainability. The initial section of the study discussed the introduction of lignin and its isolation methods, followed by an in-depth examination of polymeric hydrogels, encompassing their composition and applications in agriculture. The third section focused on lignin-based hydrogels, detailing preparation procedures for their primary application in agriculture. This study also analyzed the progress in lignin-based hydrogels over the past decade and provided a relevant assessment of the promising material.

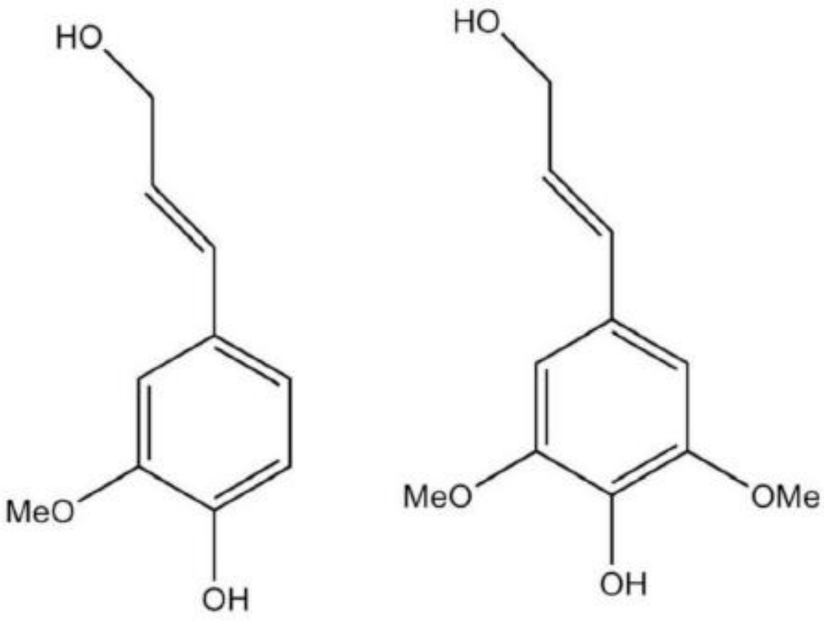
Keywords: Lignin, polymeric hydrogels, smart materiál, growth stimulator, agricultural applications

1. Introduction to lignin, chemical structures, properties and advantages

Lignin is the second most prevalent plant polymer on Earth and one of the 3 principal constituents of the cell walls in lignocellulosic plants. In addition, [**129**] reported that it is the only scalable renewable feedstock with aromatic components, accounting for approximately 30 % of the organic carbon in the biosphere. This material also accounts for approximately 30 % of the mass of softwood and 20 to 25 % of the total mass of hardwood [**1**]. Although lignin is abundant in nature and serves as an important byproduct of the production of pulp and paper, it is often subjected to burning to recover energy and replace fossil fuels [**2**]. However, lignin has gained increasing attention in recent years due to its properties, including biocompatibility, environmental friendliness, low toxicity, and susceptibility to enzymatic biodegradation [**3**].

According to previous studies, lignin consists of phenylpropane components that are connected by 3 aromatic alcohol ancestors, including sinapyl, coniferyl, and p-coumaryl alcohols (**Figs. 1 and 2**). P-hydroxyphenyl (H, from coumaryl alcohol), guaiacyl (G, from coniferyl alcohol), and syringyl (S, from sinapyl alcohol) moieties have been reported to be phenolic compounds that originate from these monolignols. The components of monolignols are connected by radical link processes to create a complex 3-dimensional ($3D$) molecular structure that includes a wide range of bonds, especially ether linkages [**4**]. Several studies have shown that various species and the environment affect the composition and content of lignin. Softwood lignin primarily consists of G units with trace amounts of H units, while those from hardwood are composed of G and S units [**5**].

The Lignin content of a given material typically depends on the type of wood as well as the cultivation and extraction methods [**6**]. Compared to other constituents of the cell wall, it is hydrophobic and prevents the penetration of water. In recent years, there has been increasing focus on the use of lignin to produce biocomposite materials, such as hydrogen for various applications, especially agriculture [**7**]. However, the complex nature of the lignin structure, which depends on several variables, such as the source and extraction techniques, limits some applications [**8**]. Due to its profusion of phenolic and aliphatic hydroxyl groups, lignin is an excellent candidate for chemical reactions and alterations aimed at generating novel biomaterials. There has also been a growing focus on its chemical alteration to customize some features [**9,10**]. Modifications to the hydroxyl groups significantly reinforce the performance of biocomposite materials.



p-coumaryl alcohol (H) Coniferyl alcohol (G) Sinapyl alcohol (S)

Fig. 1. Precursors and basic units in lignin molecules [**11**].

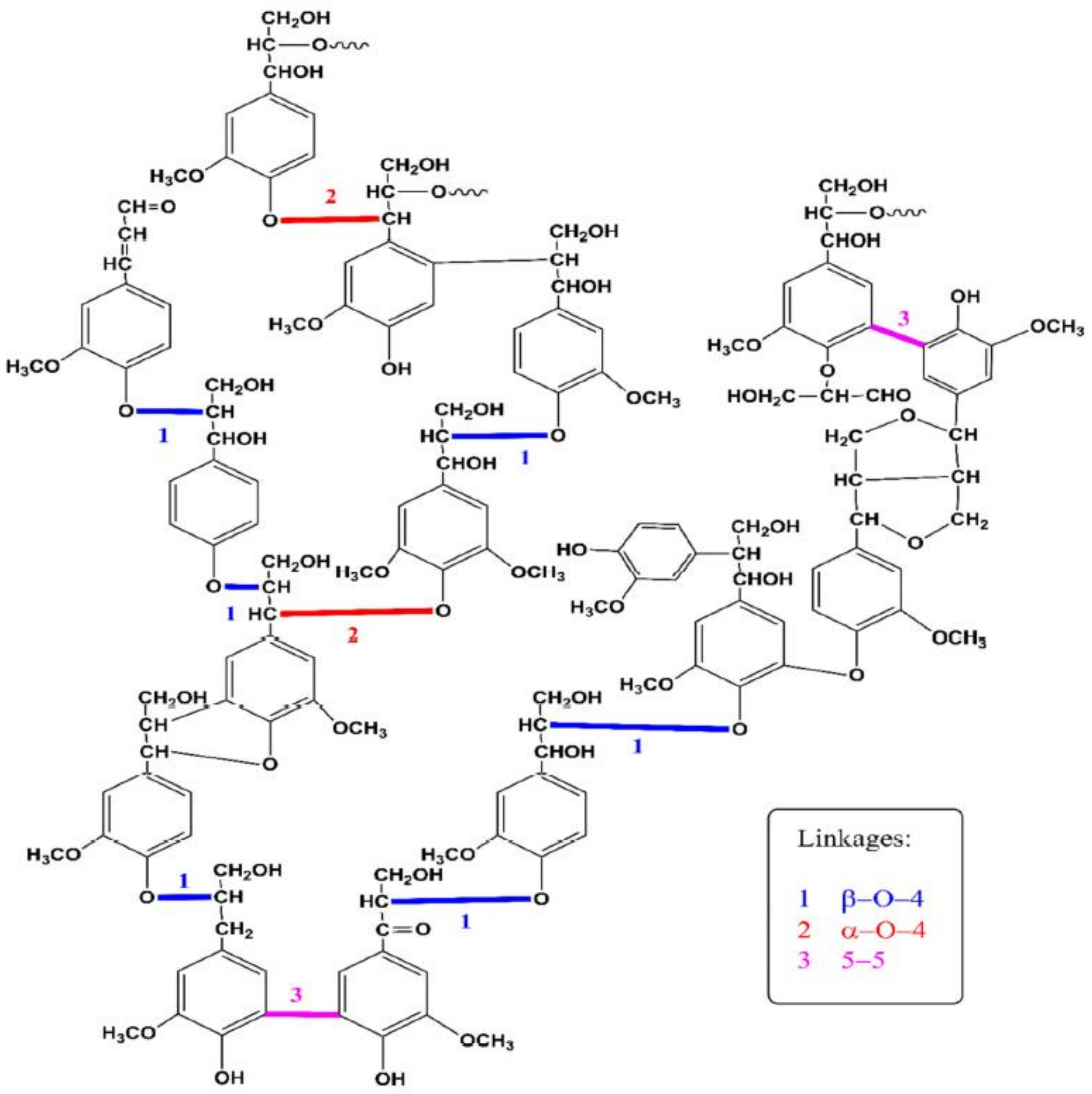


Fig. 2. Illustration of lignin structure. Reconstructed from Figueiredo et al. [**12**].

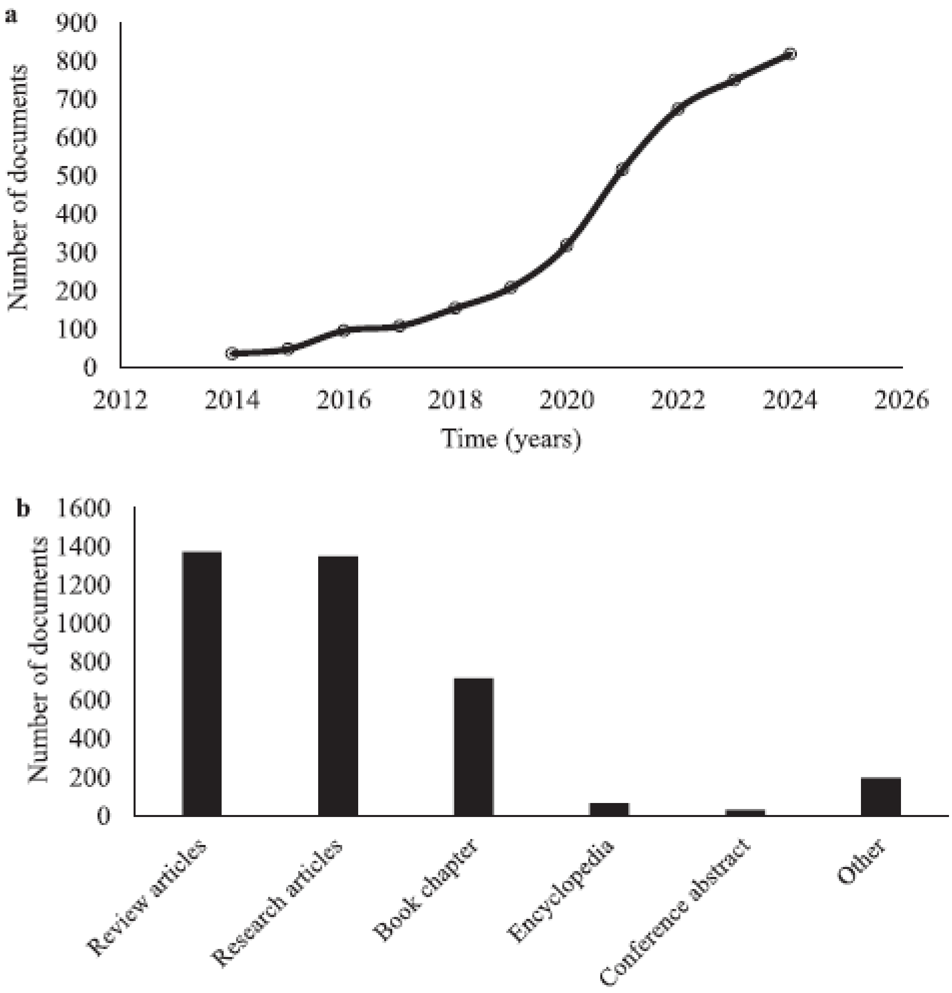


Fig. 3. a) Trend of publications and b) types of documents related to lignin-based hydrogels for application in agriculture from 2014 to 2024. Source indirectly dated 12.08.2024.

Recent studies have focused on the use of lignin to create novel biocomposite materials in the form of hydrogels for diverse uses, including agriculture [**7**]. In this study, the utilization and potential application of lignin in the development of hydrogels to mitigate certain challenges associated with sustainable agriculture are discussed, referencing some of the scientific work published from 2014 to 2024. The initial section of the review emphasizes a summary of the chemical, physical, and biological approaches for lignin extraction, along with an overview of strategies for its valorization. This emphasized the importance of the material, which has proven to be a useful precursor for the production of various high-value products. The following section provides a general overview of hydrogels and their applications in agriculture. Hydrogels are well-recognized, but their utilization in agriculture remains scarce compared to that in healthcare. Interest in the creation of new hydrogel formulations, particularly those based on biopolymers, has increased tremendously. Studies, alongside interest in biopolymer utilization, have also concentrated on discovering novel methods to valorize components found in biomasses. Lignin serves as an example, as the final section of the review presents lignin-based hydrogels and examines its influence on several critical aspects of hydrogels, including their mechanical properties, water retention capacity, biodegradability, and morphology. The utilization of lignin-based hydrogels in agriculture is examined, with a focus on 3 primary uses, namely new methods for the controlled release of fertilizers, for enhancing water efficiency, and as seed coating materials. Limitations associated with utilization and pertinent concerns that require resolution are also presented.

2. Methodologies

Several sources were used to search for literature on the development and application of lignin-based hydrogels in agriculture, namely Scien-ceDirect, Web of Science, PubMed, and Google Scholar. The period between 2014 and 2024 was selected as the search time frame.

2.1. Search equation

The search query was developed with keywords related to the synthesis of hydrogels in general and lignin-based hydrogels as well as their application in agriculture. The following keywords in combination with Boolean operators were used: (TITLE -KEY (lignin*) AND TITLE-ABS-KEY (hydrogel*) AND TITLE-ABS-KEY (synthesis* characterization*) AND TITLE-ABS-KEY (agriculture*) AND TITLE-ABS-KEY (biocomposite*).

2.2. Filtering of information

All selected papers focused on English-language publications regarding lignin-based hydrogels for agriculture applications. The medium of doing this preselection was reading the data in the abstract. At this point, academic articles and reviews addressing the application of lignin in the development of hydrogels for agricultural uses were considered. Those that did not discuss hydrogels with lignin as a component that and used in applications unrelated to agriculture were discarded.

2.3. Trend of publications, including scientific articles and review articles

An overview of the scientific publications, including reviews, study papers, and book chapters, was produced from 2014 to 2024 through PubMed, Science Direct, Web of Science, and Google Scholar databases. This used the following search queries: i) Lignin [Title/Abstract] AND ii) hydrogels [Title/Abstract] AND iii) agriculture as represented in Figs. 3 and B. A total of 3733 articles, 1371 review articles, and 1351 study articles were included. The number of publications growing exponentially from 2014 to 2024 confirmed the increasing scientific interest in the use of lignin as a component of the hydrogels used in agriculture. Most of the publications addressed composite materials in which lignin was found in combination with other biomolecules and not only individually.

3. Lignin extraction strategies

High-purity and high-yield lignin could be obtained through different lignin extraction processes. Lignin extraction strategies were essential for using lignin, and some common extraction strategies included chemical, biological, and physical methods as well as the use of ionic liquids and supercritical fluids.

3.1. Chemical methods

Among the chemical methods, the Kraft process was the most widely used method for lignin extraction in the pulp and paper industry. This included treating wood chips with a mixture of sodium hydroxide and sodium sulfide, breaking down lignin, as well as separating it from cellulose and hemicellulose [**13**]. The soda process was similar to the Kraft method but used sodium hydroxide alone, and it could preserve more cellulose due to the milder conditions. Meanwhile, the organosolv process was another approach in which organic solvents (such as ethanol or methanol) along with acids or bases were used to dissolve lignin. In such an approach, high-yield and high-purity lignin was obtained in a more eco-friendly way. Another chemical approach was acid hydrolysis, in which strong were used to break down lignin into smaller fragments, then separated from other components.

3.2. Biological methods

Among the various biological methods, enzymatic extraction and microbial fermentation were the most common [**14**]. Both bacteria and fungi were capable of biologically breaking down or decomposing lignin [**15-17**]. Compared with fungi, bacteria were less effective at breaking down lignin, and their delignification process was slower and more restricted [**18**].

The metabolism of lignin by bacteria has not been thoroughly investigated as that of fungi. However, bacteria benefited from their remarkable environmental adaptability, varied biochemistry, and ability to produce enzymes. The soil contained a variety of bacteria that could break down lignin. Streptomyces viridosporus T7A, Sphingomonas paucimobilis SYK-6, Comamonas, Nocardia, Rhodococcus, and sulfate-reducing bacteria were examples of Actinomycetes bacteria that breakdown lignin [**18**]. Furthermore, bacterial systems were more effective than fungal systems at modifying lignin and releasing smaller aromatic molecules that could enter cells and be broken down by aromatic catabolism [**19**]. A potential method for breaking down lignin in cold areas and reintroducing agricultural waste to the soil was the use of psychrotrophic bacteria [**20**].

3.3. Physical methods

The physical method used was a steam explosion, which included the treatment of biomass with high-pressure steam, followed by rapid decompression. This disrupted lignin structure, facilitating its extraction and mechanical milling. Finally, physical grinding helped break down lignin structure, making it more accessible for subsequent extraction processes [**21**]. In addition to traditional methods, innovative approaches for lignin extraction included the use of ionic liquids that dissolved lignin effectively, allowing extraction without the need for harsh chemicals. This method was gaining attention for its potential to be more sustainable. Lignin could also be extracted by the use of supercritical fluids, such as CO_2, which selectively extracted lignin while minimizing the degradation of the polymer [**22**]. Solvent fractionation was another approach that required the use of different solvents to selectively dissolve and separate lignin from other components due to differences in solubility. Every process had benefits and drawbacks, as it was based on factors such as lignin source, purity, environmental impact, and financial viability. The intended application of lignin usually influenced the extraction technique selected. Lignin extraction remained a complex activity due to the potential for lignin sources to change the structural properties and molecular weights of derivatives.

Furthermore, any simplification of laboratory-scale tests did not consider their behavior in real processing situations.

4. Valorization of lignin

Lignin was considered a waste product in the paper and pulp industry, as it was often burned for energy or discarded as a byproduct. Recent studies, however, demonstrated the considerable utility of lignin as a biobased, sustainable, and renewable feedstock for a range of high-value goods [**23**]. One of the primary challenges in the valorization of lignin was its complex chemical structure, which made it difficult to break down and convert lignin into useful products. However, previous studies have developed innovative methods to depolymerize lignin into smaller, more valuable molecules. These molecules were then used to produce a wide range of products, such as biofuels, chemicals, and materials. For instance, lignin-derived phenols could be used as antioxidants in food and pharmaceuticals, while lignin-based polymers were used to create biodegradable plastics [**24**].

According to Bilal et al. [25], valuing lignin reduced the negative environmental impacts of the paper and pulp sector while simultaneously offering new opportunities for biobased enterprises. Several studies contributed to the development of a more circular and sustainable economy by transforming lignin into valuable products. This could also lessen the dependency on fossil fuels and contribute to the development of a biobased and sustainable economy. When all factors were considered, lignin value-adding process was a potentially successful way to add value to a frequently ignored and underutilized resource.

4.1. Hydrogels

The capacity to absorb vast amounts of water, often more than their mass, was a special property of hydrogels, which were $3D$ networks of hydrophilic polymers that expanded in water without disintegration. These consisted of hydrophilic polymer chains that were cross-linked through covalent or physical interactions. Furthermore, these networks were obtained from bio-sourced, neutral, zwitterionic, or synthetic polymers. Hydrogels were hydrophilic, suggesting their expansion in volume when encountering water. In this study, hydrogels could be broadly divided into 2 groups, namely chemical and physical. Chemical hydrogels were $3D$ cross-linked networks created by polymerizing hydrophilic monomers in the presence of cross-linkers. Meanwhile, physical hydrogels formed when polymer chains were linked through noncovalent interactions such as hydrogen bonds, ionic bonds, and van der Waals interactions [**26**]. Additional classification criteria included the source (natural/synthetic gels), stiffness (soft/hard gels), and pores (micro/microgels). Hydrogels were also divided into 2 groups based on their swell, namely simple hydrogels, which had swelling ratios that were independent of their external environment, and smart hydrogels, whose swelling changes in response to exogenous stimulation.

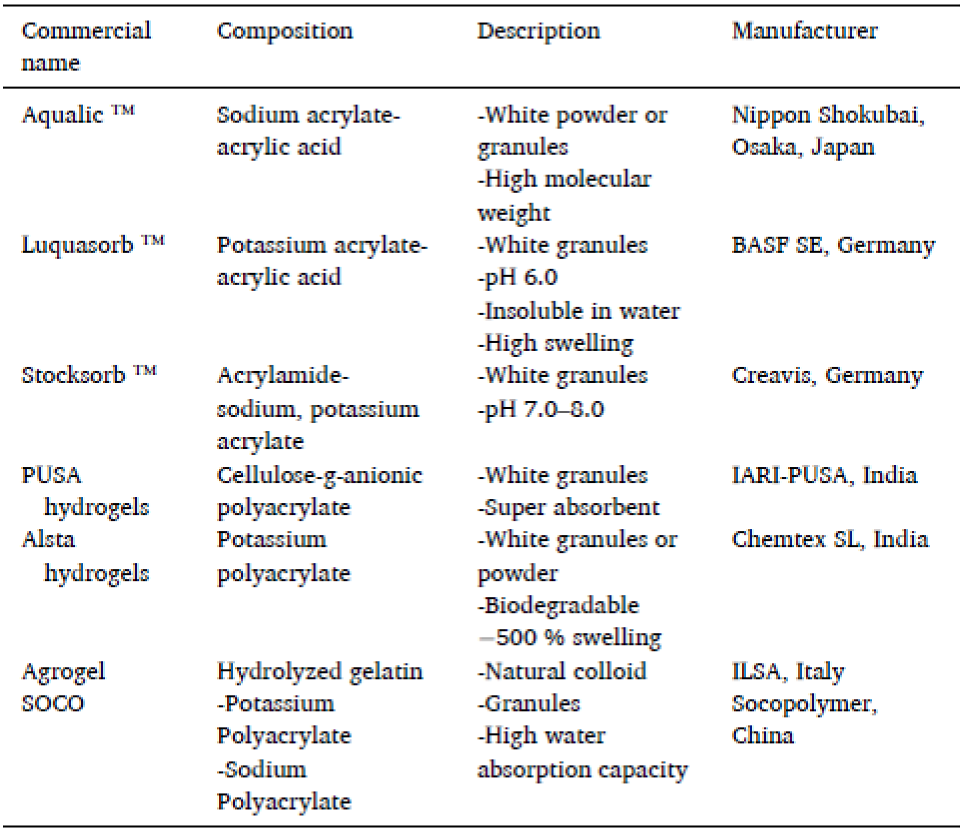
The commonly used polymeric materials in the manufacturing of hydrogels included polyethylene glycol (PEG), poly(N, N-dimethyl acrylamide), and poly(vinyl alcohol) when interest in the use of natural polymers to replace synthetic polymers was increasing [**27**]. Due to their wide range of innate properties, such as good biocompatibility, large surface area, tunable pore structure, and countless functionalizations, hydrogels were receiving increasing amounts of attention from previous authors and the public.

Hydrogels had been explored for a long time, and new applications and improved versions of existing hydrogels were being proposed. However, several challenges were yet to be overcome, making the development and commercialization of hydrogels slow processes. To ensure that companies remained competitive and keep up with ever-changing technologies, increasing awareness regarding hydrogels for the development of new formulations and products was essential.

4.2. Hydrogels in agriculture

Interest in utilizing hydrogels in agriculture has been steadily growing, particularly regarding the substitution of synthetic polymers with natural polymers due to their environmental safety. As water reservoirs in soil, hydrogels had shown the greatest potential in agriculture. These could also be used as seed-coating agents to promote germination and seedling establishment and to immobilize nutrients, plant growth regulators, or protectants for controlled release [**28**]. Furthermore, hydrogels were used to prevent the drainage or evaporation of rainfall or irrigation water through interactions between hydrophilic polymer groups and water molecules.

Table 1 Typical hydrogel formulations available on the market.



Commercial name	Composition	Description	Manufacturer
Aqualic ™	Sodium acrylate-acrylic acid	-White powder or granules -High molecular weight	Nippon Shokubai, Osaka, Japan
Luquasorb ™	Potassium acrylate-acrylic acid	-White granules -pH 6.0 -Insoluble in water -High swelling	BASF SE, Germany
Stocksorb ™	Acrylamide-sodium, potassium acrylate	-White granules -pH 7.0–8.0	Creavis, Germany
PUSA hydrogels	Cellulose-g-anionic polyacrylate	-White granules -Super absorbent	IARI-PUSA, India
Alsta hydrogels	Potassium polyacrylate	-White granules or powder -Biodegradable –500 % swelling	Chemtex SL, India
Agrogel SOCO	Hydrolyzed gelatin -Potassium Polyacrylate -Sodium Polyacrylate	-Natural colloid -Granules -High water absorption capacity	ILSA, Italy Socopolymer, China

One of the most significant advantages of using hydrogels in agriculture was its potential to reduce irrigation frequency, which in turn decreased the amount of water used and associated costs [**29**]. The soil around the roots was dry, and the water from the hydrogel was slowly released and available for plant uptake through a simple diffusion process. This process, which was based on absorption or desorption, was the basis for the sustainable use of water resources. Furthermore, the addition of hydrogels to the soil improved nutrient absorption inhibited nutrient dissolution, and allowed nutrient particles to be maintained for slow controlled release [**29**]. Hydrogels also enhanced soil characteristics, including porosity, texture, and permeability, facilitating the interchange and transport of gases, oxygen, ions, and nutrients through plant roots, all of which were essential for plant growth [**30**]. Specifically, the swellable nature of hydrogels caused the soil to become less compact.

The agricultural sector's genuine adoption of hydrogels was motivated by the multifunctional advantages offered to producers. Hydrogels had 4 main applications in agriculture, namely i) improving crop resilience to drought; ii) serving as nutrient transporters; iii) coating seeds; and iv) acting as transplanting aids. A list of commercially available hydrogen-based agricultural products is shown in **Table 1**.

Despite the increasing interest in this field and the encouraging results, there was still a multitude of issues and challenges that must be addressed to enhance and increase the efficacy of hydrogels in agriculture. This study showed that the first had to do with their ability to absorb water. Some hydrogels, referred to as "smart hydrogels," could soak up to 1000 g of water per g of dry mass. However, most commercial hydrogels held only 10 to 100 g of liquid per g of dry mass [**31**]. Most of these findings were based on the study performed with distilled water and under settings far different from those found in practical applications. Despite this potential, hydrogels in soil had a much lower water absorption capacity because, under pressure, the polymers could not expand and absorb water. For instance, acrylamide and potassium acrylate copolymer hydrogels placed 30 cm deep in soil presented a water absorption capacity of 5 g/g in comparison with 200 g/g water absorption in the absence of external pressure [**31**]. Similarly, Kaur et al. [**32**] examined the absorption capacity of a cross-linked copolymer of acrylamide and potassium acrylate hydrogels in soil. These results indicated an inverse relationship between pressure and water absorption. As the depth of the soil samples increased, the degree of swelling decreased. For example, under 5.89 kPa pressure (corresponding to a top-soil layer thickness of 40 cm), the water absorption values for sandy loam and coarse sand were 18 % (52.70 g/g) and 24 % (71.40 g/g), respectively, compared with the water absorption without soil or pressure.

The soil structure, salinity, moisture content, temperature, pH, and presence of microbes affected the hydrogel's ability to absorb water [**28**]. According to a previous study, the creation of novel crosslinks with soil-resident ions such as Ca^{2+} and Al^{3+} reduced the amount of water that the soil could absorb [**33**]. The ability of a polymer to retain water was greatly diminished when mineral components were dissolved in it [**34**].

The internal network elasticity of the hydrogel and the external pressure must be counterbalanced by osmotic pressure, which was responsible for the enlargement of the hydrogel [**35**]. Furthermore, the increase in the number of crosslinking sites and density, together with the presence of external pressure from the soil, reduced the swelling capacity of the hydrogel [**36**]. The utilization of hydrogels with higher osmotic pressure (e.g., hydrophilic polymers and charged polymer backbones), those with higher porosity and lower rigidity, and a reduction in the characteristic size of hydrogels were advantageous for swelling [**35**].

Mechanical strength proved to be another challenge that must be addressed. Hydrogels lose much of their mechanical strength during swell. The swelling process had a substantial effect on the ability of a hydrogel sample to endure tension and strain. This restriction was addressed by adding certain crosslinkers and inorganic nanoparticles when hydrogels were being synthesized [**37**] or by using other chemical modifications, such as graft polymerization. By self-crosslinking or combining with other polymers, such as starch [**38**], hydroxyethyl cellulose [**39**], and chitosan [**40**], the mechanical characteristics of hydrogel films based on carboxymethyl cellulose were enhanced. Several recent studies have focused on improving mechanical strength through methods that included modifying the composition of hydrogels and designing various microstructures, such as supramolecular hydrogels, nanocomposite hydrogels, double-network hydrogels, and macromolecular microsphere composite hydrogels [**41**].

The leaching of components presented another challenge. In this study, there were no instances of hydrogel polymers entering the food chain or bioaccumulating and no absorption of plants. However, components from hydrogels leaked out and adversely affected the pH and microbiology of the soil. In the case of nanocomposite hydrogels, for example, the leaching of nanoparticles was observed, particularly when the crosslinking density was low [**42**]. According to Karchoubi et al. [**43**], this effect was typically observed in nanocomposite hydrogels, which were created by gelating a hydrogel to create a monomer solution while material nanoparticles were present. Although the controlled release was reportedly made easier by cellulose in its nanostructured form, cross-linking provided some hydrophobicity to the carrier molecule [**44**]. Meanwhile, leaching hydrogel components were recently used to release nutrients for soil conditioning [**32**].

The use of a hydrogel as a seed coating agent carried a significant risk as well. According to a previous theory, there could be too much water close to the seed, impeding air diffusion and slowing the rate at which the embryo emerged. Gorim and Asch [**45**] reported that, in comparison with uncoated grains, cereal grains coated with Stockosorb, accounting for more than 75 % of the total mass, presented lower levels of oxygen saturation in the embryos. According to the authors, air diffusion to the seed embryo was effectively handled by using macroporous hydrogels for seed coating [**45**]. However, the increased water imbibition of the hydrogel network due to the existence of these macropores increased the possibility of mold and fungus growth, which could ultimately kill the seed, so-called damping off. Additional study into the impact of macroporous hydrogels on seed coatings could be advantageous. The polymer coating physically prevented certain inhibitors from being released from the seed coat [**46**].

Coated seeds had a significant effect on the efficiency with which specific reserve metabolites, such as starch and sucrose, were mobilized from stored tissues during the germination phase. This had an impact on the metabolism of seeds, which was necessary to meet the energy requirements for germination, resulting in a decrease in the rate of germination [**47**]. To achieve favorable outcomes, it was therefore necessary to carefully optimize the hydrogel type, dose, and seed coating technique (pelleting, film coating, slurry coating, and seed dressing). Fertilizer burns, also known as the “salt effect,” occurred when fertilizer was added to a hydrogel network. This condition was dominant when fertilizer was placed next to or alongside a germination seed, causing harm to or death of the seedling [**32**].

Damage occurred when the osmotic pressure in the soil was greater than that in the seeds because the salt concentration in the fertilizer was greater than that in the plant cells. Care must be taken to adjust the fertilizer concentration in the hydrogel network properly. Moreover, hydrogel-coated seeds needed to be packed, stored, and transferred properly in addition to addressing these seed-related issues. The disadvantages and advantages of lignin-based hydrogels for agriculture are reported in **Fig. 4**.

Fig. 4. Disadvantages and advantages of biopolymeric hydrogels in agriculture. Reconstructed from Tariq et al. [**48**]. $WHC =$ water holding capacity.

Fig. 5. Schematic representation of the strategies for the synthesis of lignin-based hydrogels.

4.3. Lignin-based hydrogels and their preparation

Natural polymers and their modified forms replaced synthetic polymers in the production of hydrogels because of their low toxicity, biocompatibility, biodegradability, eco-friendliness, and sensitivity to enzymatic degradation [**30,48**]. As a result, renewable polymer-based hydrogels had emerged as sustainable and environmentally friendly substitutes for hydrogels containing harmful substances. Due to its unique properties, lignin was an appropriate biomaterial for the development of hydrogels [**49**]. Lignin was a cross-linked polymer with many active and functional hydrophilic groups, including hydroxyls, carbonyls, and methoxyl. Therefore, the use of various approaches for the production of biodegradable hydrogels was promising.

Lignin had been used in the last 10 years to generate several hydrogel types, making their preparation simpler and improving their properties [**50-53**]. The synthesis of extremely valuable lignin derivatives through chemical modification of lignin made it possible to produce a variety of lignin-based hydrogels, which were acknowledged as more environmentally friendly and sustainable substitutes for synthetic hydrogels.

Lignin-derived hydrogels were made through several approaches, including copolymerization with other polymers, such as esterification reactions, acrylic acid, ultrasonication, wet spinning, hydrothermal processes, and other cross-linking methods (**Fig. 5**). The most frequently used method was the physical or chemical crosslinking of lignin with other polymers, such as synthetic polymers, chitosan, or cellulose [**52**]. For example, lignin combined with polysaccharides such as pectin, gum arabic, and calcium ions produced very stiff and stretchable hydrogels [**6**]. However, as a consequence of its complex structure, which varied according to the source and extraction methods, and rigid properties, few studies were reported on lignin hydrogels compared with other biopolymers, such as cellulose [**52**].

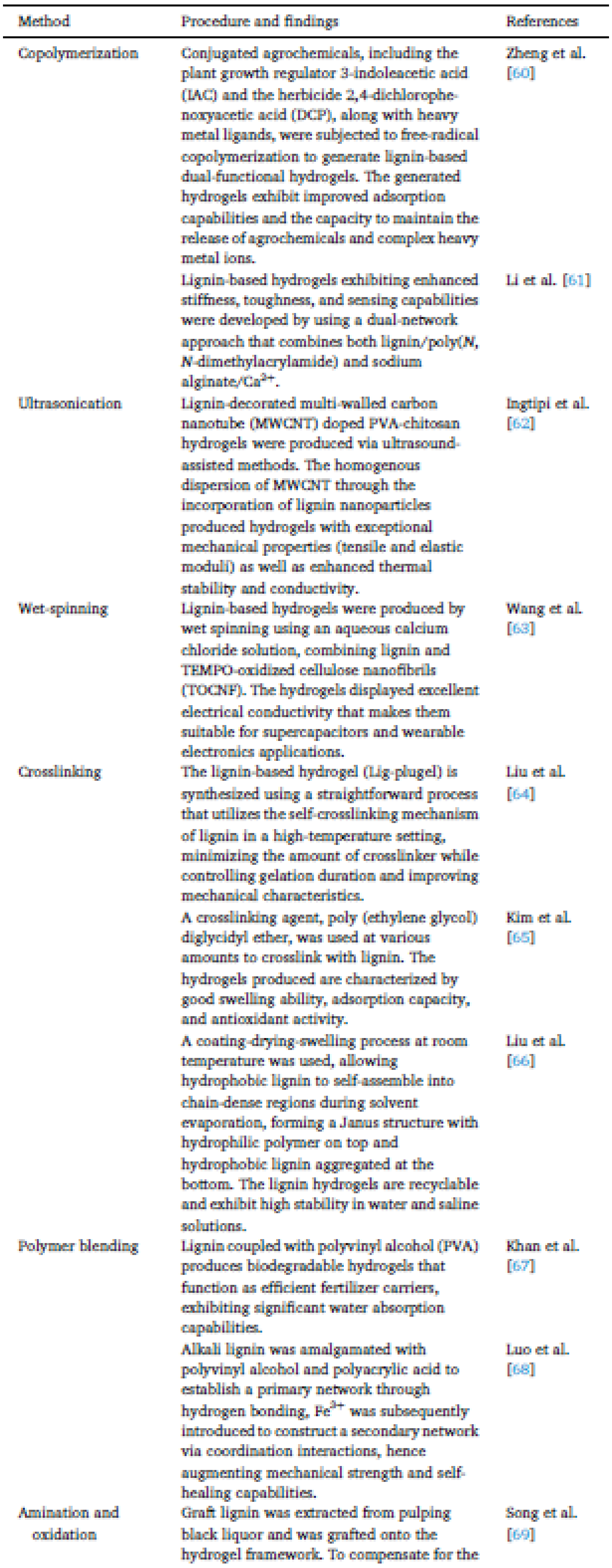
4.3.1. Cross-linking

Various crosslinking strategies have been explored to improve the mechanical, chemical, and biological properties of lignin-based hydrogels. Chemical crosslinking methods, such as the use of glutaraldehyde, epoxy compounds, or carbodiimide-mediated reactions, could introduce covalent bonds between lignin and other polymeric components, leading to increased stability and improved mechanical performance [**52**]. Furthermore, physical crosslinking approaches, such as the exploitation of ionic interactions or hydrogen bonding, were used to create hydrogels without the use of potentially cytotoxic chemical crosslinkers. The choice of crosslinking method and the selection of appropriate polymers and crosslinking agents were crucial in determining the final properties of lignin-based hydrogels.

4.3.2. $ATRP$ and $RAFT$ methods

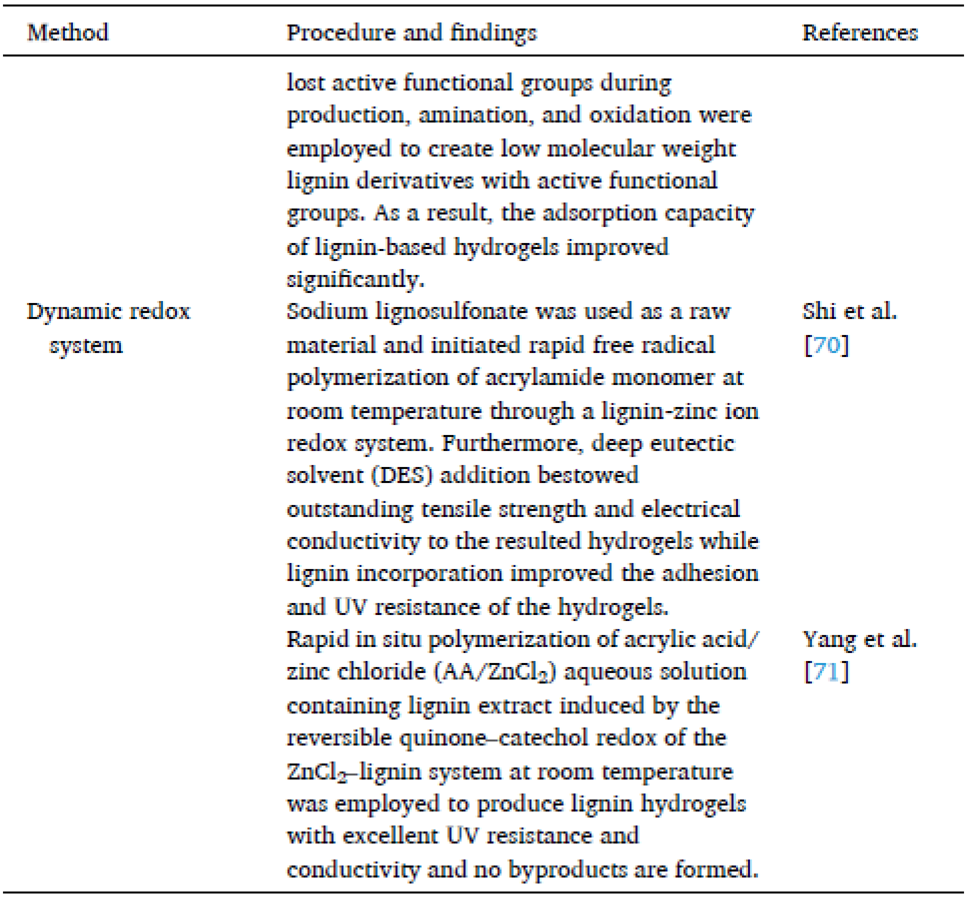
Lignin-derived hydrogels with regulated architectures were produced through reversible addition-fragmentation chain transfer ($RAFT$) and atom transfer radical polymerization ($ATRP$) techniques [**54**]. Hydrogels could be produced in aqueous or ionic liquid media by the “graft from” and “graft onto” techniques of $ATRP$ and $RAFT$ polymerization, respectively.Active sites on the backbone of lignin polymers were created through $ATRP$ and $RAFT$. For example, azobisisobutyr-onitrile ($AIBN$) acted as an initiator for the polymerization of lignin core by a radical reaction in the $RAFT$ technique, where lignin acted as a core [**54**].

Table 2 Preparation methods for lignin-based hydrogels and their enhanced properties.



Method	Procedure and findings	References
Copolymerization	Conjugated agrochemicals, including the plant growth regulator 3-indoleacetic acid (IAC) and the herbicide 2,4-dichlorophenoxyacetic acid (DCP), along with heavy metal ligands, were subjected to free-radical copolymerization to generate lignin-based dual-functional hydrogels. The generated hydrogels exhibit improved adsorption capabilities and the capacity to maintain the release of agrochemicals and complex heavy metal ions.	Zheng et al. [60]
	Lignin-based hydrogels exhibiting enhanced stiffness, toughness, and sensing capabilities were developed by using a dual-network approach that combines both lignin/poly(*N*, *N*-dimethylacrylamide) and sodium alginate/Ca^{2+}.	Li et al. [61]
Ultrasonication	Lignin-decorated multi-walled carbon nanotube (MWCNT) doped PVA-chitosan hydrogels were produced via ultrasound-assisted methods. The homogenous dispersion of MWCNT through the incorporation of lignin nanoparticles produced hydrogels with exceptional mechanical properties (tensile and elastic moduli) as well as enhanced thermal stability and conductivity.	Ingtipi et al. [62]
Wet-spinning	Lignin-based hydrogels were produced by wet spinning using an aqueous calcium chloride solution, combining lignin and TEMPO-oxidized cellulose nanofibrils (TOCNF). The hydrogels displayed excellent electrical conductivity that makes them suitable for supercapacitors and wearable electronics applications.	Wang et al. [63]
Crosslinking	The lignin-based hydrogel (Lig-plugel) is synthesized using a straightforward process that utilizes the self-crosslinking mechanism of lignin in a high-temperature setting, minimizing the amount of crosslinker while controlling gelation duration and improving mechanical characteristics.	Liu et al. [64]
	A crosslinking agent, poly (ethylene glycol) diglycidyl ether, was used at various amounts to crosslink with lignin. The hydrogels produced are characterized by good swelling ability, adsorption capacity, and antioxidant activity.	Kim et al. [65]
	A coating-drying-swelling process at room temperature was used, allowing hydrophobic lignin to self-assemble into chain-dense regions during solvent evaporation, forming a Janus structure with hydrophilic polymer on top and hydrophobic lignin aggregated at the bottom. The lignin hydrogels are recyclable and exhibit high stability in water and saline solutions.	Liu et al. [66]
Polymer blending	Lignin coupled with polyvinyl alcohol (PVA) produces biodegradable hydrogels that function as efficient fertilizer carriers, exhibiting significant water absorption capabilities.	Khan et al. [67]
	Alkali lignin was amalgamated with polyvinyl alcohol and polyacrylic acid to establish a primary network through hydrogen bonding, Fe^{3+} was subsequently introduced to construct a secondary network via coordination interactions, hence augmenting mechanical strength and self-healing capabilities.	Luo et al. [68]
Amination and oxidation	Graft lignin was extracted from pulping black liquor and was grafted onto the hydrogel framework. To compensate for the	Song et al. [69]

Table 2 (continued)



Method	Procedure and findings	References
	lost active functional groups during production, amination, and oxidation were employed to create low molecular weight lignin derivatives with active functional groups. As a result, the adsorption capacity of lignin-based hydrogels improved significantly.	
Dynamic redox system	Sodium lignosulfonate was used as a raw material and initiated rapid free radical polymerization of acrylamide monomer at room temperature through a lignin-zinc ion redox system. Furthermore, deep eutectic solvent (DES) addition bestowed outstanding tensile strength and electrical conductivity to the resulted hydrogels while lignin incorporation improved the adhesion and UV resistance of the hydrogels.	Shi et al. [70]
	Rapid in situ polymerization of acrylic acid/ zinc chloride (AA/$ZnCl_2$) aqueous solution containing lignin extract induced by the reversible quinone–catechol redox of the $ZnCl_2$–lignin system at room temperature was employed to produce lignin hydrogels with excellent UV resistance and conductivity and no byproducts are formed.	Yang et al. [71]

4.3.3. Copolymerization method

Lignin was copolymerized with other polymers by using crosslinkers, enzyme-based initiators, or graft copolymerization to create lignin-derived hydrogels. In the presence of laccase/$t - BHP$ as an initiator and N, N-methylene-bis-acrylamide (MBA) as a cross-linker, polymers, such as acrylic acid, could be copolymerized with lignosulfonates to produce lignosulfonate g-acrylic acid (LS-g-AA) hydrogels [**55**]. A previous study used the graft copolymerization process alongside alkaline or kraft lignin, poly(vinyl alcohol), and an acrylamide monomer to facilitate the green synthesis of lignin-based hydrogels, which subsequently blended with the monomer [**56**].

4.3.4. Ultrasonication methods

Hydrogel synthesis through ultrasonication was based on the premise of a cavitation-induced polymerization process. Following ultra-sonication, a rarefaction cycle and a compression cycle of ultrasonic waves were produced [**57**]. Therefore, the many cavitation bubbles that were produced when ultrasonic waves passed through the reaction medium promoted the synthesis of hydrogels. Wang et al. [**58**] described the synthesis of sodium lignosulfonate hydrogels from pulping waste liquid through ultrasonic-assisted polymerization at 40 kHz for 3 h. Maleic anhydride was used as a substitute for acrylamide to mitigate the toxicity of hydrogels, while lignin was incorporated to decrease the cost of hydrogels.

4.3.5. Wet spinning method

The environmentally friendly method of wet spinning was effectively used to produce microfiber hydrogels [**59**]. This approach used an aqueous calcium chloride solution for hydrogel synthesis, which caused the hydrogel precursor, consisting of TEMPO-oxidized cellulose nanofibrils ($TNFs$) and lignin produced from wood, to aggregate quickly. Wang and colleagues successfully synthesized carbon microfibers by wet-spinning bicomponent precursors, including lignin and cellulose nanofibrils. Subsequently, 1-step carbonization at 900 °C was performed [**59**].

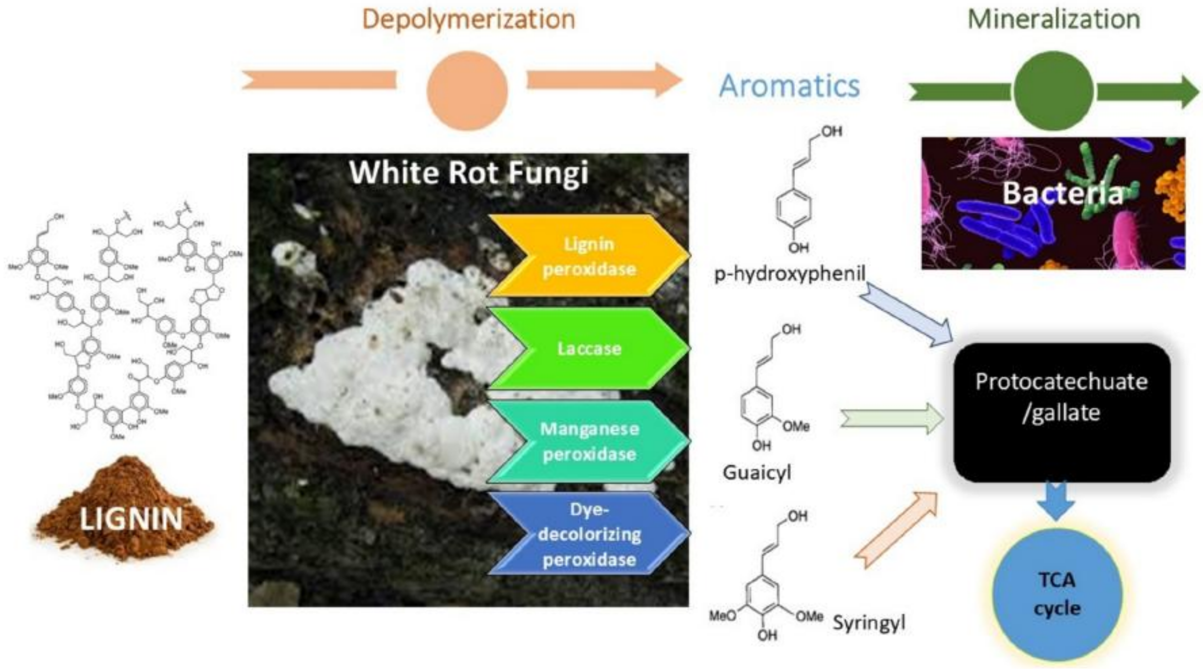


Fig. 6. Different pathways of microbial degradation of lignin. Reconstructed from Iram et al. [**83**].

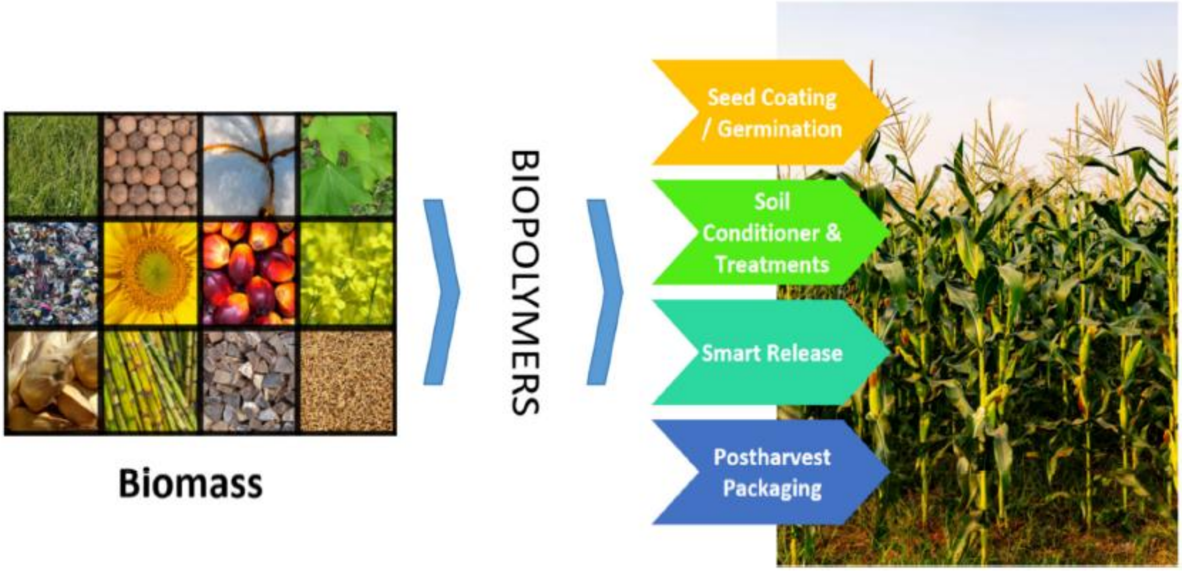


Fig. 7. Future perspectives of biopolymers in agricultural applications. Reconstructed from Fartahi et al. [**104**].

4.3.6. Other methods

Numerous techniques existed for the preparation of lignin-based hydrogels, mostly emphasizing the integration of lignin with other polymers or crosslinking agents to improve the mechanical and functional characteristics of the hydrogel. In addition to the methods mentioned, several other methods could be used to prepare lignin-based hydrogels, such as amination, oxidation, dynamic redox systems, and polymer blending. **Table 2** summarizes the methodologies for preparing lignin-based hydrogels and their characteristics.

4.4. Influence of process parameters on the synthesis of lignin hydrogels

The following variables were important for lignin synthesis process, namely i) the lignin-to-monomer ratio, ii) the lignin-to-crosslinking agent ratio, and iii) the monomer-to-initiator ratio [**8**]. These factors must be adjusted since the physicochemical structure of the hydrogels could be affected and, in turn, their function.

The choice of solvent was crucial when producing hydrogels by polymerization. A good solvent maximized the yield of polymerization and functioned as a heat sink to promote solution polymerization and crosslinking. Distilled water, ethanol, and their combination were the most frequently adopted methods [**50,72,73**]. In addition to the type of solvent, pH was an important variable.

Changes in the pH of the solution affected the charge, solubility, and other properties of the reagents, which affected the speed at which the reaction proceeded.

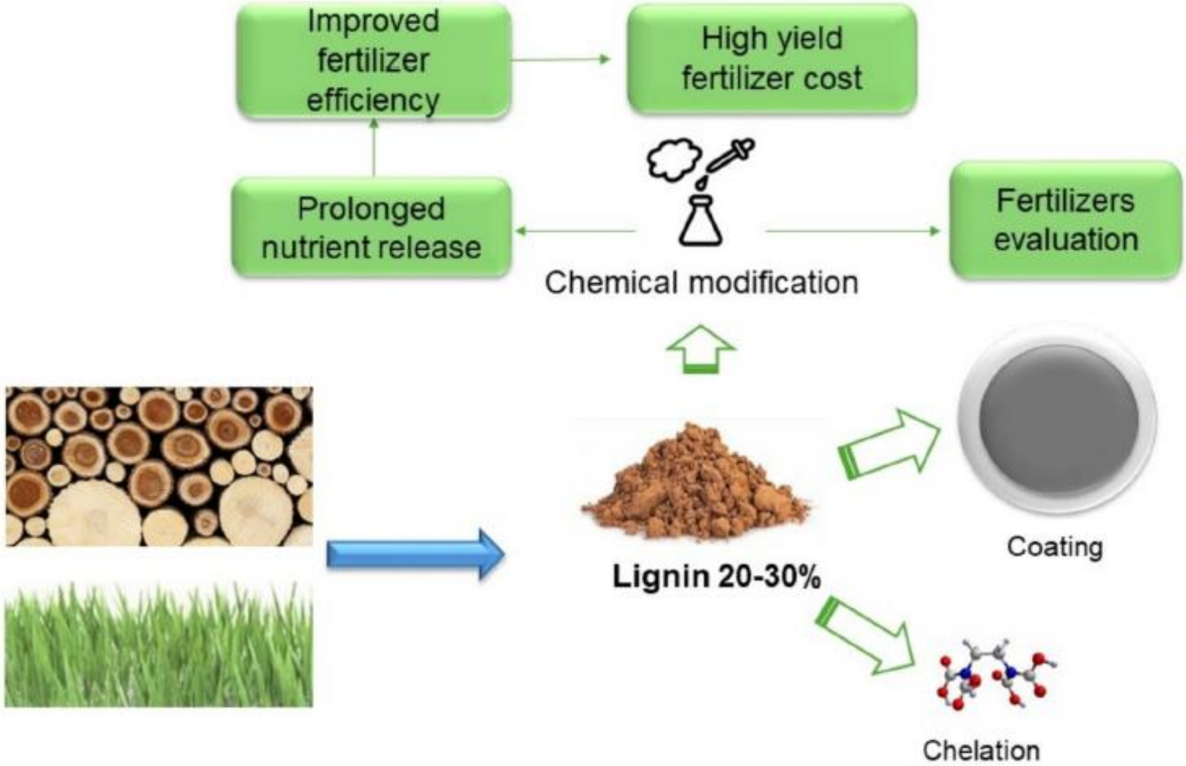


Fig. 8. Role of lignin in the development of fertilizers. Reconstructed from Abbas et al. [**87**].

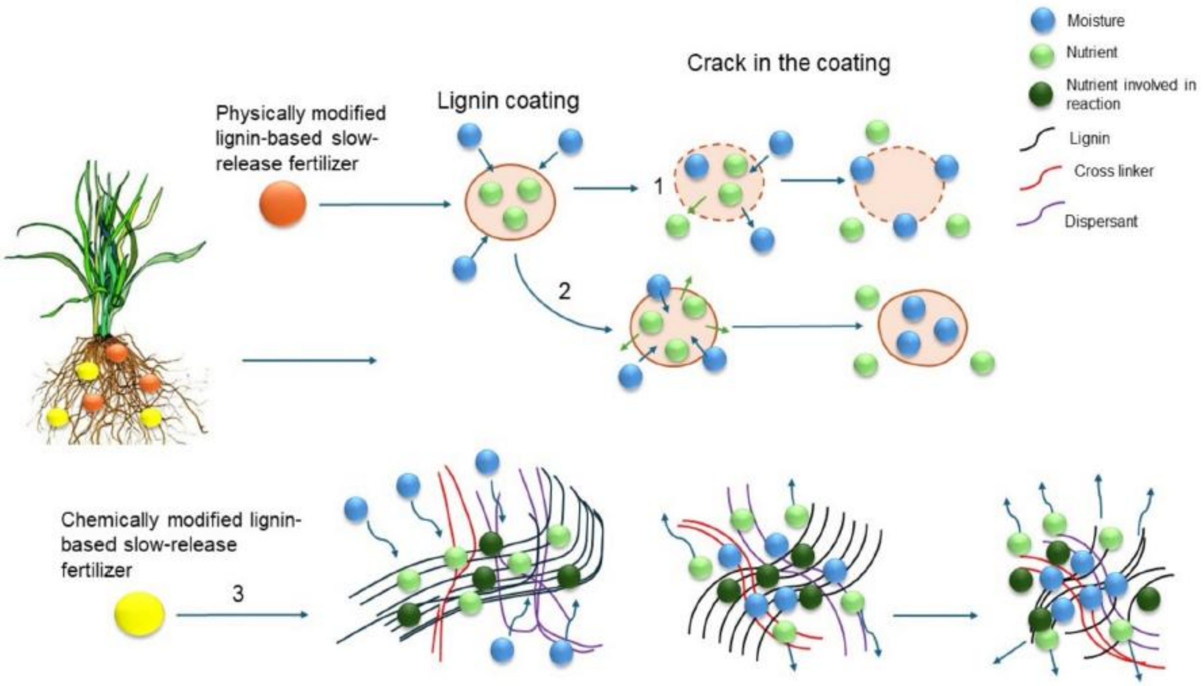


Fig. 9. Schematic representation of the possible release mechanisms of slow-release fertilizer formulations. Paths: a) rupture mechanism, b) diffusion, and c) release from chemically modified materials. The figure has been reconstructed from Firmanda et al. [**111**].

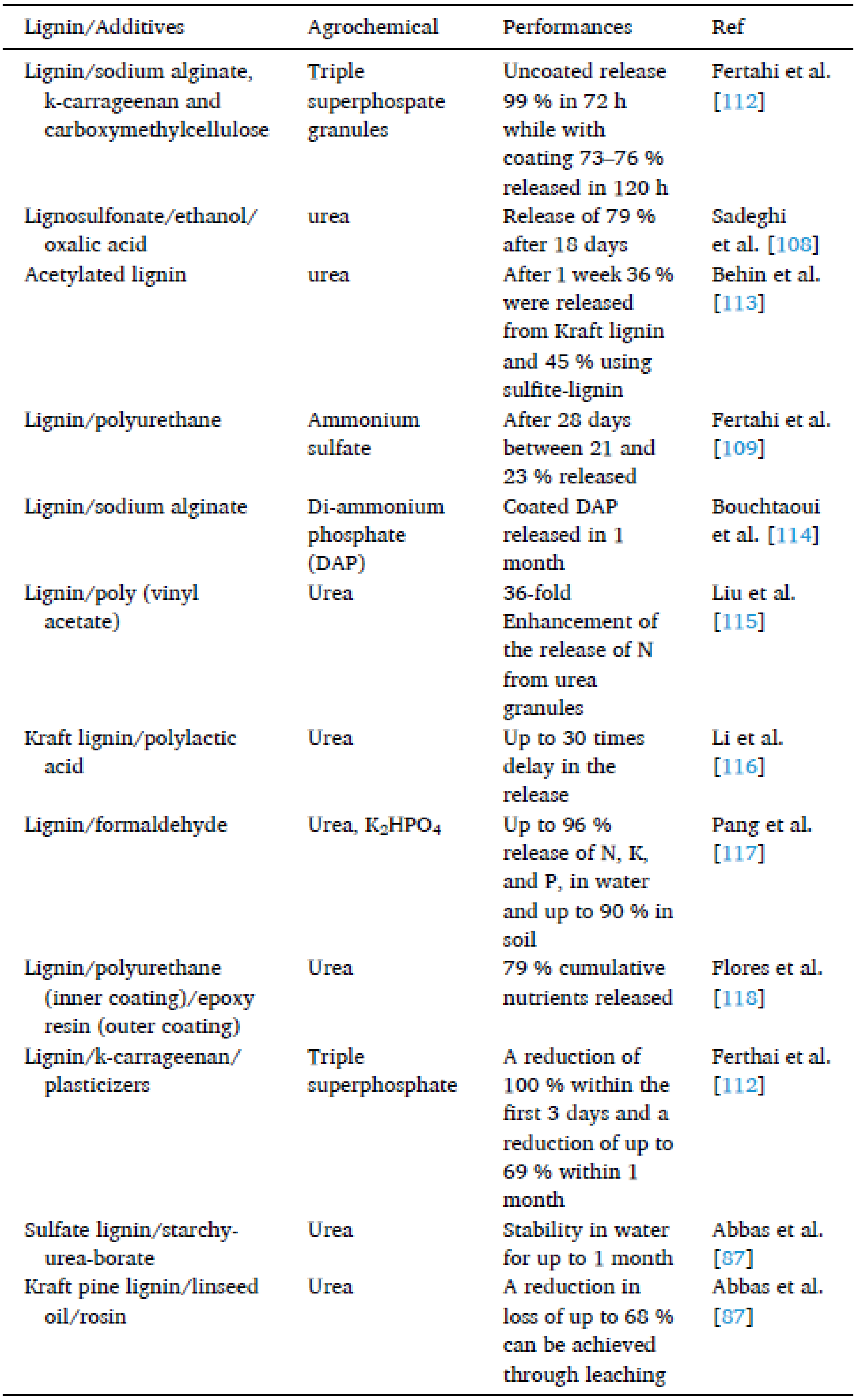
Furthermore, it greatly impacted the swelling index of the hydrogel. In this study, it was crucial to adjust the pH of a solution to increase the yield of hydrogel synthesis [**74**]. The temperature affected both the rate of reaction and the degree of polymerization during the polymerization process used for producing hydrogels. Therefore, a hydrogel's maximum yield needed to be adjusted. The swelling index was also affected because the polymer chains separated more effectively at higher temperatures.

4.5. Lignin-based hydrogels' general properties

4.5.1. Mechanical properties

The concentration of lignin directly influenced the mechanical properties of hydrogels. Furthermore, the loss modulus ($G"$) was used to express energy dissipation, while the dynamic storage modulus (G') was used to convey hydrogel stiffness. As the amount of lignin increased, the storage and loss moduli often also increased [**3**]. In all the selected angular frequency ranges, lignin-based hydrogels frequently presented greater G' values compared to their corresponding $G"$ values because of their stiff network structure. According to Liu and Chung, these outcomes were attributed to the stiff backbone of lignin, which increased the degree of crosslinking and stiffened the network structure. Overall, when the amount of lignin in the hydrogels increased, both the G' and $G"$ values of their mechanical properties tended to improve [**54**]. The results obtained were explained by the strong backbone of lignin, which stiffened the network structure and increased the degree of crosslinking [**54**].

Table 3 Description of lignin-coated fertilizers.



Lignin/Additives	Agrochemical	Performances	Ref
Lignin/sodium alginate, k-carrageenan and carboxymethylcellulose	Triple superphospate granules	Uncoated release 99 % in 72 h while with coating 73–76 % released in 120 h	Fertahi et al. [112]
Lignosulfonate/ethanol/oxalic acid	urea	Release of 79 % after 18 days	Sadeghi et al. [108]
Acetylated lignin	urea	After 1 week 36 % were released from Kraft lignin and 45 % using sulfite-lignin	Behin et al. [113]
Lignin/polyurethane	Ammonium sulfate	After 28 days between 21 and 23 % released	Fertahi et al. [109]
Lignin/sodium alginate	Di-ammonium phosphate (DAP)	Coated DAP released in 1 month	Bouchtaoui et al. [114]
Lignin/poly (vinyl acetate)	Urea	36-fold Enhancement of the release of N from urea granules	Liu et al. [115]
Kraft lignin/polylactic acid	Urea	Up to 30 times delay in the release	Li et al. [116]
Lignin/formaldehyde	Urea, K_2HPO_4	Up to 96 % release of N, K, and P, in water and up to 90 % in soil	Pang et al. [117]
Lignin/polyurethane (inner coating)/epoxy resin (outer coating)	Urea	79 % cumulative nutrients released	Flores et al. [118]
Lignin/k-carrageenan/plasticizers	Triple superphosphate	A reduction of 100 % within the first 3 days and a reduction of up to 69 % within 1 month	Ferthai et al. [112]
Sulfate lignin/starchy-urea-borate	Urea	Stability in water for up to 1 month	Abbas et al. [87]
Kraft pine lignin/linseed oil/rosin	Urea	A reduction in loss of up to 68 % can be achieved through leaching	Abbas et al. [87]

4.5.2. Surface morphology and pore structure

The lignin content had a direct effect on the surface morphology and porosity of a hydrogel. An intriguing investigation [**75**] demonstrated how lignin altered the surface of a hydrogel from smooth and honeycomb to rough and irregular. This study demonstrated that lignin concentrations of up to 5 % (w/w) in hydrogels produced denser porous structures. Defects in the structure resulting from the creation of irregular holes occurred at lignin concentrations greater than 5 % (w/w) [**76**]. The impact of lignin, which was extracted through an organosolv method, on the hydrogel surface structure was assessed. These findings indicated that when the concentration of lignin increased, the density and compactness of the hydrogels also tended to increase. When lignin was introduced, the surface morphology of lignin tended to change from a honeycomb to a sheet [**77**].

According to Yang et al. [**2**], lignin nanoparticles produced by hydrochloric acidolysis were identified as agents for the creation of holes in chitosan/PVA composite hydrogels. Lignin nanoparticle-containing hydrogels had a structure resembling a honeycomb. By preventing PVA molecules from disintegrating and migrating into the solution, the hydrophobicity of lignin, and the robust interactions between the nanoparticles and the PVA/chitosan units, the crosslinking effect was further enhanced. According to Zhang et al. [6] there was a direct relationship between the crosslinking that occurred during hydrogel preparation and the utilization of nanoparticles in the manufacture of lignin-cellulose hydrogels. Compared with lignin-free hydrogels, the hydrogel network formed a uniform structure with smaller pores and a larger surface area. A distinct study examined the impact of the pore network structure of the hydrogel on a lignin-based hydrogel network, which consisted of macropores and layers that contained lignin nanoparticles due to the elevated concentration of lignin nanoparticles. As a result, the specific surface area and porosity of the hydrogel decreased [**78**].

4.5.3. Retention and water uptake

The 2 primary applications of hydrogels were water retention and absorption. Furthermore, 2 main aspects influenced water absorption and retention in lignin-based hydrogels, namely (i) the hydrogel structure, which included the pore size, and (ii) the surface morphology. Kalinoski et al. [**78**] reported that the hydroxyl and carboxyl group contents and pore size affected the swelling ratio. Larger holes were distributed less densely with higher swelling ratios. Lignosulfonate grafting enhanced the quantity of free hydroxyl groups at active binding sites, facilitating the incorporation of more hydrophobic functional groups and bioactive compounds into the hydrogels, while also establishing a more porous $3D$ network structure. [**79**].

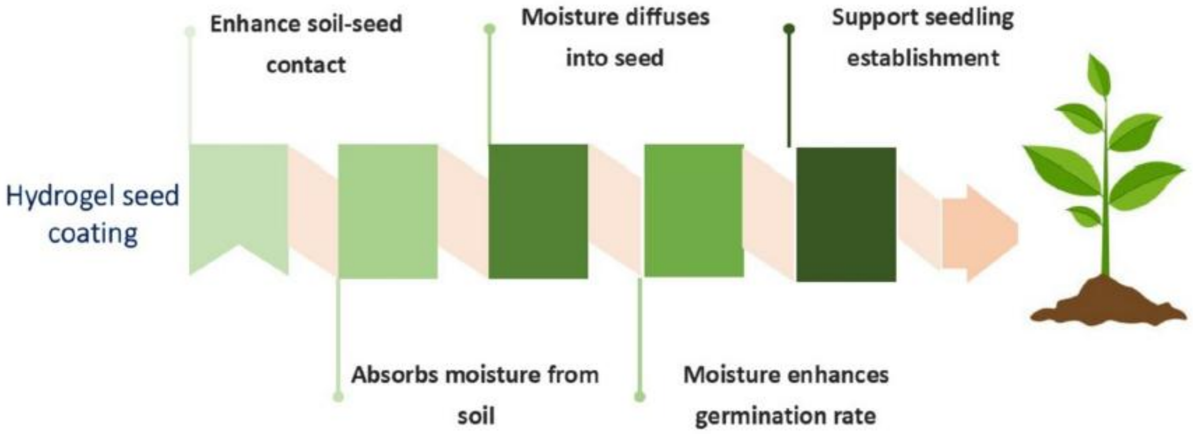


Fig. 10. Hydrogels in a seed coating. Reconstructed from Kaur et al. [**32**].

4.5.4. Lignin-based hydrogel biodegradation

Lignin had the slowest rate of biodegradation among the biobased substances used for making biodegradable hydrogels. The reason for the limited lignin breakdown was that most soil microbes did not use the carbon in lignin, instead, the carbon in the hydrogel was assimilated. Low biodegradation rates, according to Horwath [**80**], were caused by their hydrophobicity, complex and nonspecific structure, and dense nature. Due to its highly branched, cross-linked, and nonuniform chemical structure, lignin made it difficult for soil microorganism enzymes to break down into smaller fragments that could then undergo further decomposition [**81**].

This was because most soil microbes had a limited number of specific enzymes, which prevented their ability to efficiently break down lignin due to its complicated structure [**82**]. Furthermore, the strong hydro-phobicity of lignin made it less accessible to soil microbes and increased its resistance. The mechanism of microbial breakdown of lignin is depicted in **Fig. 6**.

4.6. Lignin-based hydrogel application in agriculture

In a variety of contexts, such as soil moisture retention, lignin-based hydrogels proved to be beneficial. The remarkable capacity of hydrogels to retain water could be particularly beneficial in semiarid and dry environments [**84**]. By improving soil moisture retention, these hydrogels maintained the perfect growing environment for plants, minimizing the need for frequent watering and protecting water resources [**85**]. A further field where lignin-based hydrogels had shown potential was nutrient release. A sustained-release nutrient system could be produced by mixing lignin with fertilizers. This method ensured that plants obtain essential nutrients over a longer period while minimizing nutrient leakage and adverse environmental impacts [**86**]. This slow-release capability was crucial for optimizing fertilizer use efficiency and promoting sustainable agricultural practices [**87**].

Hydrogels were shown to have some potential for preventing soil erosion. According to Bagheri et al. [**88**], adding lignin-based hydrogels to the soil structure could improve soil aggregation and reduce erosion. This stabilization was vital for maintaining soil health and productivity, especially in vulnerable agricultural landscapes.

Another area where hydrogels were gaining popularity was seed coating [**31**]. Hydrogels based on lignin could be used as successful seedcoating materials, providing moisture to seeds to facilitate germination and protection against infections [**89**]. Increased germination rates and greater crop establishment resulted from this treatment.

Lignin-based hydrogels represented a biodegradable substitute for plastic [**90**]. Given concerns over plastic pollution in agriculture, increasing lignin-based hydrogels represented a sustainable option. These biodegradable materials were used in many applications, such as mulching and seed trays, in place of traditional plastics.

The primary benefits of using lignin as a component in hydrogel preparation for agricultural applications included i) The sustainable use of lignin, a renewable and often discarded resource, was consistent with sustainable agricultural practices. This approach supported the circular economy by repurposing industrial byproducts. ii) Cost-effectiveness: Lignin-based hydrogels were more affordable for farmers because of the comparatively low cost of lignin extraction. iii) Environmental impact: By minimizing fertilizer runoff and consuming less water, lignin-based hydrogels reduced the environmental impact of agricultural practices. iv) Increased crop yields. Several studies indicated that the application of lignin-based hydrogels could increase plant growth and yields through improved water and nutrient availability [**8,84,91**].

4.6.1. Lignin-based controlled delivery fertilizers

Controlled-release fertilizers ($CRFs$) were formulated to release active nutrients in a controlled manner to efficiently reduce nutrient loss from the soil. This was an appropriate response to the current problems that the agricultural sector was facing [**92**]. $CRFs$ provided nutrients gradually and efficiently over an extended period, reduced fertilizer-related potential risks such as water body contamination and leaf burning, and decreased labor expenses by reducing the need for recurrent fertilizer application [**93**].

Although CRF had advantages, its global share of soil fertilizers was just 0.25 %, of these, 1 % were used in the USA, and 8 to 10 % in Europe [**94**]. However, 70 % of polymer-coated $CRFs$ in Japan were used for rice production [**95**]. When nutrients were needed by plants, a variety of mechanisms, including hydrolysis, diffusion, and degradation, were required in the regulated release of those nutrients [**94**].

Several studies reported the use of $CRFs$ with a variety of coating materials, such as sulfur [**96**], polyacrylamide [**97**], acrylic acid-coacrylamide [**98**], chitosan [**99**], starch [**100**], carboxymethyl cellulose [**101**], and lignin [**102**]. Due to the substantial quantity of synthetic polymer that remained in the soil after nutrient absorption, synthetic polymer-based $CRFs$ had several disadvantages. Legal restrictions also apply to materials that contained resins, sulfur, or thermoplastic materials that were either nondegradable or difficult to degrade in soil [**103**]. With continued fertilizer use, residual coating ingredients accumulated over time, resulting in new types of pollution. Consequently, several authors have concentrated on the development of innovative polymeric coatings that were both ecologically favorable and biodegradable.

Lignin had gained popularity throughout the past 20 years for the development of $CRFs$, with great potential for application in agriculture (**Fig. 7**). By adsorbing nutrients, lignin was used as a physically hindered fertilizer with a controlled release function. To facilitate progressive release, van der Waals forces could be established on the surface of nutrients through physical adsorption [**105**]. Meanwhile, chemically modified fertilizer could be produced by altering the active groups of lignin to bind the groups that contained nutrients in the molecular structure. Lignin-based fertilizers were broadly classified into 3 categories, namely (i) physically coated; (ii) lignin-based chemical reactions, in which lignin was used as a raw material to create fertilizer; and (iii) lignin-based chelates (**Fig. 8**) [**86**]. To make lignin-coated fertilizers, nutrient granules were sprayed with an appropriate combination of lignin and other additives in a rotating drum [**86**]. According to Jiao et al. [**106**], lignin was being used by study teams as a covering material for CRF production. Because of their high nutritional value and sophisticated production process, coated fertilizers were the most widely used type of CRF on the market. Coating materials offered high degrees of hydrophobicity, bonding strength, and film-forming qualities [**107**]. The release behavior of coated CRF was highly influenced by the characteristics of the coating polymers, such as their thickness, porosity, elasticity, cross-linking mode, and water absorption [**87**].

Fertilizer coatings could be applied by chemical or physical techniques to minimize nutrient release. Physical procedures such as pan coaters, fluidized bed technologies, and spray coating with a revolving drum were well-developed, well-known, and prevalently used. In a fluidized bed column, Sadeghi et al. [**108**] coated urea granules with acetylated lignosulfonate and reported a significant delay in the release of nitrogen from the urea. Using the fluidized bed method, Behin and Sadeghi coated urea granules with acetylated lignin.

Fertahi et al. [**109**] used varying ratios of PEG and carrageenan as film-forming materials to spray triple superphosphate to produce lignin-coated phosphatic fertilizer. After 6 h, the triple superphosphate coated with lignin, carrageenan, and PEG released 13.51 % of the phosphorus that was contained, while the untreated sample released 72 %. To reduce the number of hydrophilic groups and enhance the coating ability, Behin and Sadeghi [**108**] used acetylate sulfite lignin and acetic acid on a urea coating. Coated urea was prepared by spray coating through a fluidized bed technique. However, this approach did not significantly enhance the hydrophobic characteristics of sulfite lignin, and within 7 days, 45.35 % of the urea was released. Under monitored conditions, a kinetic experiment was used to examine the electrical conductivity (EC) and phosphorus release of these coatings. According to the P release pattern, 1.5 g of $BL - CA$-coated or uncoated MAP was added to 50 mL of H_2O. The indirect release of P from a coated MAP was studied with the use of EC. The BL coating exhibited superior performance in suppressing phosphorus release compared to the CA coating, with a slower phosphorus release correlating with a higher coating ratio (1.0 % and 2.0 %). Avelino et al. [**110**] used thorough physicochemical, structural, and morphological characterization to examine the impact of polyurethane (PU) lignin coatings on ammonium sulfate release behavior.

According to the results of the nutrient release experiments, the 2 formulations of lignin-based PUs exhibited remarkably similar behavior in terms of SO4-2 and NH4+ release rates in both release media, despite their differences in features. **Fig. 9** and **Table 3** presented some of the most current lignin-based coated fertilizers together with their release methods.

4.6.2. Controlled release of water

The soil type was one of the many variables that influenced water retention or controlled release. For example, infertile soils had a lower water retention capacity. However, when supplemented with hydrogels, a substantial quantity of water could be retained to facilitate plant growth. Hydrogels based on lignin were demonstrated to improve soil water retention [**105**]. As the crosslinking density increased, the water content, including the overall water content of the hydrogels, decreased [**119**]. The degree of cross-linking had an impact on the hydrogels' characteristics and gelation time, allowing for a substantial amount of controlled water. A reduced crosslinking density led to a notable decrease in the equilibrium-swelling ratio of lignin-based hydrogels. The diffusion of solvents and water throughout the hydrogel network substantially influenced the application of complete copolymer hydrogels. By adjusting the amount of lignin present, copolymer hydrogels had varying degrees of hydrophobicity. Upon reaching equilibrium, lignin-based hydrogels demonstrated less shrinkage than lignin-free hydrogels did. However, when lignin was added to a hydrogel, the mechanical characteristics of the hydrogel improved after swelling. Lignin itself had antibacterial and antioxidant qualities, as it was a complex natural polymer containing phenolic groups [**120**].

4.6.3. Seed coating

Seed coating, a technique used by seed producers for many years, required covering seeds with a specific formulation of materials [**121**]. These coatings aimed to render the seeds more readily available for seedling development and germination in the soil after sowing (**Fig. 10**). The importance of these materials was attributed to the coating materials, which influenced the germination and subsequent development of the resulting seedlings. Published works indicated that the use of hydrogels as materials in seed coatings was positively correlated with germination and seedling development [**46,122,123**].

Most of the published works concerning hydrogels used for seed coating focus on natural polysaccharide-based hydrogels, such as chi-tosan, cellulose, starch, and guar gum, into which nutrients or growth promoters were incorporated [**124-127**]. Hydrogels swell and change in viscosity in the presence of water and could increase their germination speed and percentage while reducing the harmful effects of NaCl on seedling development and seed germination. The extent of the coating can be tailored according to the seed and hydrogel material used, even with the possibility of controlling hydrophilicity or hydrophobicity. Hydrogels were suggested as crucial materials for seed encapsulation because of their properties. However, there was a dearth of published studies on the subject, and additional investigations were recommended.

5. Limitations

Although the integration of lignin into hydrogel formulations for agricultural purposes offers advantages, numerous limitations related to lignin and the overall application of hydrogels require attention. To fully realize the potential of hydrogels in agriculture, it was essential to consider and enhance features such as durability, high biodegradability, resistance to osmotic and mechanical stress, cost, and techniques of synthesis and application. Furthermore, it was advisable to refrain from the use of contaminated reagents or possibly hazardous cross-linking agents [**128**]. The application and quantity of hydrogels required must be customized according to the specific crop species and soil type. Affordability was an important factor for farmers, as it was the economic aspect of hydrogel synthesis and market utilization. Investigating lignocellulosic derivatives could leverage the cost-effectiveness and sustainability of these naturally occurring resources. The evolution of lignocellulose-based hydrogel technology represented notable progress in the formulation of biodegradable matrices for sustainable crop protection within contemporary biopolymer hydrogel methodologies. Although a single hydrogel struggled to excel in all situations, significant progress in hydrogel-mediated sustainable agriculture was inevitable as long as studies and innovation persisted [**32**].

6. Conclusions and future perspective

In conclusion, the abundance of lignin, which was the primary byproduct of the cellulose and paper industries, resulted in a significant increase in interest in lignin-based products. Recently, multiple research teams have engineered lignin hydrogels, as lignin has emerged as the most compelling renewable raw material to produce diverse value-added goods. Lignin-based hydrogels had significant potential for enhancing agricultural practices. These could be used to formulate hydrogels that increase soil health, water retention, and nutrient availability. The sustainable attributes of these materials provided suitable substitutes for synthetic materials, enhancing ecologically friendly farming systems. However, further investigation was necessary to overcome current limits and fully exploit their potential across several agricultural settings. The agricultural sector is seeking sustainable solutions to tackle the challenges presented by a growing population and climate change, with lignin-based hydrogels potentially serving a crucial role in the future of agriculture.

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