

# Multiple cross-linking induced lignin-based liquid mulch film for soil stabilization and crop growth promotion

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**Abstract.** In response to the white pollution and microplastic risks caused by the widely used PE film in arid and semi-arid regions of China, this study, guided by the goal of enhancing the utilization value of biomass resources, proposes a new strategy for preparing liquid film based on non-covalent bonding self-assembly. The aim is to develop green biobased covering materials and provide a PE film replacement solution for the conservation of cultivated land in arid and semi-arid areas. Using lignosulfonate sodium, chitosan and polyvinyl alcohol as raw materials, a ternary composite sprayable multi-crosslinked induced lignin-based liquid film (LCP) was prepared by adjusting the mass ratio of chitosan and polyvinyl alcohol. Fourier transform infrared spectroscopy, isothermal drop quantitative calorimetry and rotational rheology were used to characterize the physicochemical structure of LCP; the mechanical properties were tested using a universal testing machine, and the optimal ratio and spraying amount of LCP were determined by evaluating water vapor permeability, crop growth characteristics and soil retention capacity. The synthesis of LCP is mainly driven by hydrogen bonding and electrostatic interaction, and it has significant shear thinning characteristics. When the ratio of LS:CS:PVA (mass ratio of lignosulfonate sodium, chitosan and polyvinyl alcohol) is 10:4:4, the prepared LCP has the best performance, with a mechanical strength of 24.05 MPa, a water vapor permeability of 352.10 g/(m<sup>2</sup>-d), a seed germination rate of 95%, and an average root length of 19.44 mm. Compared with the untreated treatment, when the dry matter spraying amount is 8 g/m<sup>2</sup>, the crop emergence rate, plant height and total biomass are significantly increased by 45.45%, 26.90% and 54.99%, respectively, and the soil retention effect is also significantly enhanced. The liquid mulch film prepared in this study can effectively promote crop growth and enhance soil retention capacity, providing important references for the reduction of PE film usage and the high-value utilization of agricultural and forestry wastes, and has broad application prospects.

**Keywords:** *Sodium lignosulfonate; Chitosan; Polyvinyl alcohol; Liquid mulch film; bio-based materials*

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## 1 Introduction

Arid/semi-arid regions account for more than 45% of China's land area, covering important agricultural production areas such as the northwest and north China, and are key regions for ensuring national food security and ecological security. However, under the dual impact of global climate change and intensified human activities, this region faces severe challenges such as reduced precipitation, intensified evaporation, and soil degradation (e.g., desertification, salinization), leading to low efficiency in agricultural water resource utilization, large fluctuations in crop yield, and further highlighting ecological vulnerability. Agricultural plastic film mulching technology can reduce soil water evaporation, maintain soil moisture, increase soil temperature, inhibit weeds and pests, improve crop growth environment, promote crop growth and yield increase, and is a key measure for ensuring sustainable agricultural development. However, the long-term use of traditional polyethylene mulch film has caused serious "white pollution" and microplastic risks, with increasingly prominent problems such as soil structure destruction and decreased microbial activity, becoming the core bottleneck constraining sustainable agricultural development in arid regions. Therefore, the development of environmentally friendly mulch film alternatives is urgent. Bio-based liquid mulch film has advantages such as easy spraying, reduced labor, and adaptability to complex terrain. The film formed after spraying not only possesses conventional functions of

moisture retention, temperature increase, and weed suppression but also fundamentally eliminates residual pollution. Promoting and applying liquid mulch film is a key path for constructing a green and low-carbon agricultural system and achieving high-quality agricultural development, and also a key measure for implementing the national "dual carbon" goals and ecological protection and restoration.

Lignosulfonate sodium (LS), as a by-product of the pulp and paper industry, is rich in various active functional groups such as hydroxyl, methoxy, and sulfonic acid groups. It is an important resource for promoting green energy and a circular economy and plays a significant role in sustainable industries such as agricultural efficiency enhancement and food packaging. Xu et al. successfully prepared homogeneous polyvinyl alcohol/lignosulfonate sodium composite film. The results showed that the introduction of lignosulfonate sodium significantly improved the mechanical strength of the film and reduced its water vapor permeability. Wang et al. used lignosulfonate sodium/sodium carboxymethyl cellulose/polyvinyl alcohol to prepare a mulch film with good soil water retention, heat preservation effects, and biodegradability. Although LS shows potential for resource utilization in areas like agricultural mulch film, challenges remain in its extreme environmental adaptability (e.g., high temperature and drought), biocompatibility, and excellent mechanical performance enhancement. Chitosan (CS), as another natural biopolymer, with its excellent antibacterial properties, film-forming ability, and degradability, can achieve performance complementarity when combined with LS. CS is mainly a biodegradable biopolymer polysaccharide synthesized from chitin deacetylation, possessing excellent renewability, biocompatibility, antibacterial activity, and non-toxicity, and has received widespread attention in the field of film coating barrier applications. Sun et al. coated glutaraldehyde-crosslinked chitosan with humic acid/urea complex on cellulose/humic acid film, constructing a polysaccharide-based degradable mulch film with high hydrophobicity, thermal stability, UV resistance, aging resistance, and biodegradability, and its heat preservation effect was comparable to that of PE film. However, this film is brittle, with insufficient mechanical properties and single functionality, limiting the application of this functional film in specific agricultural environments. Polyvinyl alcohol (PVA) can effectively improve the brittleness of chitosan while retaining its biocompatibility and antibacterial properties. Due to its excellent biosafety, degradability, outstanding film-forming ability, and mechanical properties, films prepared from it have become a research hotspot in the industrial, agricultural, and food fields. Ma et al. used hydrogen peroxide-oxidized citric acid fermentation waste and PVA to prepare a new biodegradable mulch film. The tensile strength and elongation at break of this film could reach 16.43 MPa and 446.96%, respectively. It could not only effectively improve soil structure but also increase the fracture resistance of the film. Studies have also shown that cast polyvinyl alcohol/regenerated chitosan blend films exhibited improved physicochemical and functional properties as well as barrier (oxygen and water) performance. This characteristic lays a theoretical foundation for constructing functional mulch film materials that combine flexibility and high strength, and shows great potential in the field of soil ecological protection under extreme climatic conditions in arid and semi-arid regions.

In view of this, this study selected lignosulfonate sodium as the raw material, chitosan as the functional modifier, and polyvinyl alcohol as the network crosslinking film-forming promoter. Using a multiple cross-linking induction strategy, a lignin-based liquid mulch film (LCP) with excellent mechanical and water vapor barrier properties was prepared. Physicochemical structure characterization was used to systematically explore the intermolecular interaction mechanisms in the synthesis of the ternary composite liquid mulch film of lignosulfonate sodium/chitosan/polyvinyl alcohol. The responsiveness between its rheological properties, mechanical strength, water vapor barrier performance, and crop growth and soil retention characteristics was studied. The aim is to provide theoretical basis and technical support for the high-value utilization of lignosulfonate and the green transformation of agriculture in arid and semi-arid regions, and it has important practical significance for promoting mulch film reduction, substitution, and sustainable development.

## 2 Materials and Methods

### 2.1 Materials

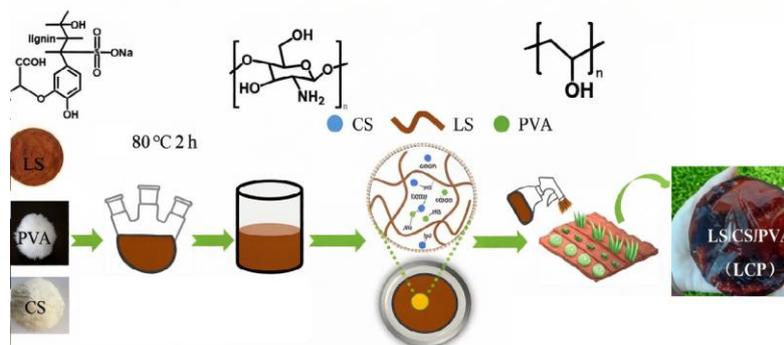
Industrial lignosulfonate sodium (LS), blackish-brown solid powder, purchased from Shandong Tralin Paper Co., Ltd.; Polyvinyl alcohol (PVA1788), polymerization degree 1650~1850, alcoholysis degree 86%~90%, molecular weight 72600~81400, Macklin reagent; Chitosan (CS), viscosity 200 mPa·s, deacetylation degree 90%, molecular weight 800~1000, Macklin reagent; The test vegetable variety is Shanghai pak choi (*Brassica chinensis*).

## 2.2 Preparation of lignin-based liquid mulch film

A certain amount of PVA was added to a three-necked flask containing 82 g of deionized water (the sum of the mass percentages of the three components was fixed at 18%). Magnetic stirring was performed in a constant temperature water bath at 80°C until complete dissolution. After the solution was allowed to stand for 15 minutes, LS and CS were added sequentially, and magnetic stirring was continued for 2 hours to obtain the homogeneous LS/CS/PVA series lignin-based liquid mulch film LCP<sub>x</sub>, where x represents the mass percentage of CS. For example, LCP1 corresponds to a three-component mass ratio of LS:CS:PVA = 10:1:7, and LCP0 is the control group. Detailed sample formulation parameters are shown in Table 1. Using the casting method, 3 g of the prepared homogeneous film-forming precursor solution was poured into a circular mold with an inner diameter of 7.0 cm at room temperature and dried in a 60°C blast drying oven for 2 hours to obtain film samples. The process flow is shown in Figure 1.

**Table 1** Test sample proportioning parameters

Sample	LS (%)	CS (%)	PVA (%)	Water (%)
LCP0	10	0	8	82
LCP1	10	1	7	82
LCP2	10	2	6	82
LCP3	10	3	5	82
LCP4	10	4	4	82
LCP5	10	5	3	82



**Figure 1** Synthesis and preparation process diagram of LCP liquid film mulch

## 2.3 Characterization of lignin-based liquid mulch film performance

### 2.3.1 Chemical functional groups and intermolecular interactions

Fourier Transform Infrared (FT-IR) spectroscopy (Nicolet Is50, Thermo Fisher, USA) was used to measure the FT-IR spectra of LS, LS/PVA, and LS/CS/PVA samples, respectively. The frequency range was 500~4000  $\text{cm}^{-1}$  with a resolution of 4  $\text{cm}^{-1}$ . Isothermal Titration Micro-Calorimetry (VP-ITC, Malvern, UK) was used. At 25°C, 1 mmol/L LS solution was titrated into 0.1 mmol/L CS/PVA solution. The background experiment involved titrating 1 mmol/L LS solution into pure water. The single-site model was selected, sample data were subtracted from background data, and baseline adjustment and model fitting were performed on the heat peak curve measured by ITC.

### 2.3.2 Rheological properties

A rotational rheometer (MAS60, Thermo Fisher, USA) was used to test the steady-state rheological properties of

the LCP liquid gel in rotational mode at 25°C. The shear rate was in logarithmic mode, ranging from 1 to 1000 s<sup>-1</sup>.

### 2.3.3 Mechanical properties

A screen-display intelligent electronic universal testing machine (UTM6503, Sansi, China) was used for detection, performing tensile property tests on the sample films. The liquid mulch film was cut into dumbbell-shaped specimens with a test area width of 4 mm. After pretreatment in an environmental test chamber with 50% relative humidity for 48 hours, the specimens were taken out and tensile strength and elongation at break tests were conducted at a tensile speed of 50 mm/min. Three parallel experiments were set for each treatment.

### 2.3.4 Water vapor permeability

Refer to the literature. The sample film was sealed at the mouth of a weighing bottle containing a fixed amount of deionized water. The initial total mass of each weighing bottle with the sample film was accurately weighed and recorded (denoted as *m*). Subsequently, the samples were placed in a constant temperature and humidity chamber at 23°C and 50% relative humidity. The mass value (denoted as *M<sub>n</sub>*) was measured and recorded every 24 hours for 6 consecutive days. The water vapor permeability (*W*) was determined based on the mass change of the sample film before and after, calculated as follows:

$$W=(M_n-m)/(S \times n)$$

Where: *W* is the water vapor permeability, g/(m<sup>2</sup>·d); *m* is the mass, g; *n* is the number of days, day; *S* is the cross-sectional area of the cup mouth, m<sup>2</sup>.

### 2.3.5 Crop growth characteristics

To determine the effect of lignin-based liquid mulch film on seed safety, double-layer filter paper was laid flat in a culture dish, 10 mL of 1% LCP concentration was injected, 10 Shanghai pak choi seeds were evenly sown, and after sealing with a lid, they were placed in a constant temperature incubator at 28°C for germination experiments. Radicle breakthrough of the seed coat and exposure length ≥1 mm was used as the germination standard. After 72 hours of treatment, the culture dishes were taken out, germination rate was counted, and main root length was measured. Three parallel experiments were set for each treatment, with a culture dish treated with an equal volume of deionized water as a blank control group.

To further evaluate the influence pattern of liquid mulch film on the growth of Shanghai pak choi. Before the experiment, the test soil was air-dried, passed through a 5 mm sieve, and filled into flowerpots with a diameter of 12 cm to ensure uniform soil texture. The initial soil mass water content was adjusted to 20%. 10 Shanghai pak choi seeds were quantitatively sown in each pot. The optimized and screened LCPx (diluted to 1% concentration (w/v)) was fully stirred and mixed, then subjected to different gradient spraying treatments. The spraying effective component dry matter amounts were 2.5, 5, 8, 10.5, and 13.5 g/m<sup>2</sup>, respectively. During the growth period, watering was done daily at fixed times and quantities. After 60 days of continuous seedling cultivation (from 2024.12.29 to 2025.02.28, Jiangsu Academy of Agricultural Sciences greenhouse, temperature 25°C), the Shanghai pak choi seedlings were harvested. Measured indicators included: emergence rate, plant height, and fresh weight, among other related parameters.

### 2.3.6 Soil retention characteristics

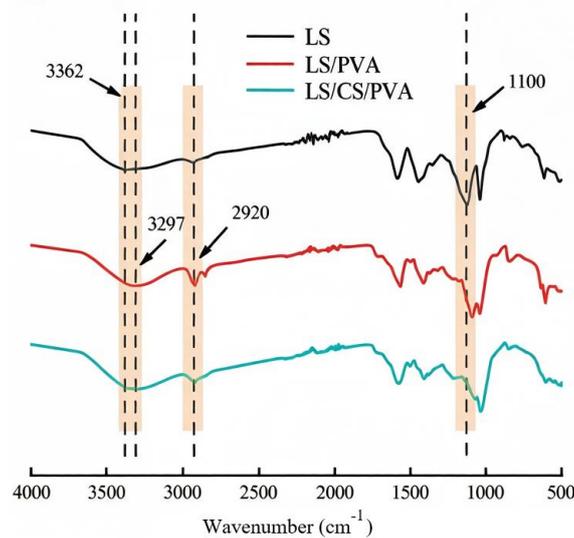
To evaluate the soil retention performance of LCP4, a vertical constant temperature shaker (HZQ-F160, Taicang Huamei Biochemical Instrument Factory) was used to conduct retention tests. Sandy soil samples were treated in an 80°C electric constant temperature drying oven for 12 hours until constant mass, passed through an 80~100 mesh sieve, and evenly filled into glass culture dishes with a diameter of 90 mm to construct test sand cones. Using a precision spraying device, LCP4 material was quantitatively applied to the sand cone surface according to set gradients (effective component dry matter: 4.5, 9, and 13.5 g/m<sup>2</sup>), and dried to constant mass. By adjusting the vibration frequency (160 r/min) to simulate specific intensity dynamic load effects, after continuous vibration for 5 minutes, the change in sand cone repose angle and geometric dimensions were measured. Three parallel experiments were set for each treatment to ensure data reliability.

### 3 Results and Discussion

#### 3.1 Structure of lignin-based liquid mulch film

##### 3.1.1 Chemical structure characterization

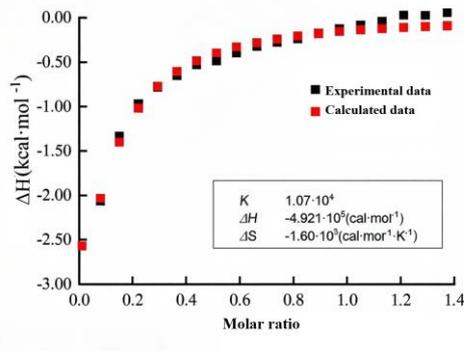
As can be seen from Figure 2, when polyvinyl alcohol was introduced into lignosulfonate sodium, the characteristic peak near  $3362\text{ cm}^{-1}$  shifted to  $3297\text{ cm}^{-1}$ , mainly due to the formation of hydrogen bonds between the large number of hydroxyl groups in PVA and the hydroxyl groups in lignosulfonate sodium. Furthermore, the intensity of the characteristic peak at  $2920\text{ cm}^{-1}$  increased, due to the superposition of the C-H stretching vibration of PVA on the C-H vibration of lignosulfonate sodium. After adding chitosan to this system, the intensity of the broad peak near  $3297\text{ cm}^{-1}$  can be observed to further increase. This is because chitosan contains a large number of amino and hydroxyl groups, which can form more hydrogen bonds with the hydroxyl groups in PVA and lignosulfonate sodium. Simultaneously, the intensity of the characteristic peak of the sulfonic acid group near  $1100\text{ cm}^{-1}$  weakened, originating from the electrostatic interaction between the cationic amino groups in chitosan and the anionic sulfonic acid groups in lignosulfonate sodium.



**Figure 2** FT-IR spectra of LS, LS/PVA and LS/CS/PVA

##### 3.1.2 Intermolecular interactions

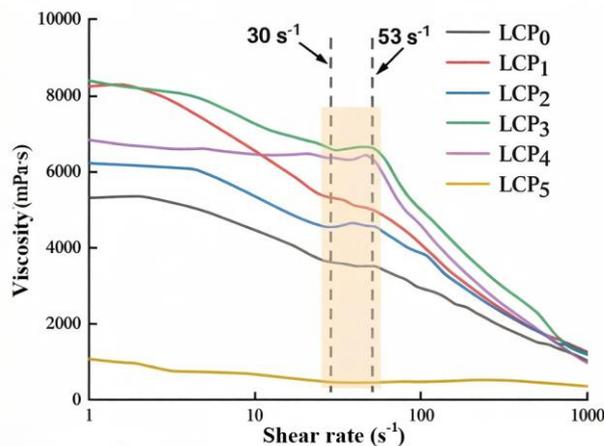
The VP-ITC fitting curve shown in Figure 3 closely matches the experimental data, indicating that the selected model can accurately describe the interaction mechanism between the multi-component molecules. The experimental data is reliable, and the calculated thermodynamic parameters can truly reflect the nature of the binding process. From the figure, the binding constant ( $K$ ) is  $1.07 \times 10^4\text{ M}^{-1}$ , the enthalpy change ( $\Delta H$ ) is  $-4.921 \times 10^5\text{ cal/mol}$ , and the entropy change ( $\Delta S$ ) is  $-1.60 \times 10^3\text{ cal/(mol}\cdot\text{K)}$ , indicating that this is an exothermic and entropy-decreasing process. The reaction reduces the disorder of molecules in the system. From the Gibbs free energy equation  $\Delta G = \Delta H - T\Delta S$ , it can be concluded that  $\Delta G$  is negative, indicating that the reaction is a spontaneous enthalpy-driven process. The three components form a relatively stable intermolecular network structure through electrostatic and hydrogen bond interactions. This thermodynamic data corroborates the characteristic peaks observed in the infrared spectral analysis.



**Figure 3** The relationship between titration molar ratio and reaction enthalpy change in LCP liquid mulch film

### 3.1.3 Rheological properties

In Figure 4, the viscosity of LCP decreases with increasing shear rate, exhibiting shear-thinning characteristics. Compared to LCP<sub>0</sub>, the initial viscosity of LCP<sub>1</sub>, LCP<sub>2</sub>, LCP<sub>3</sub>, and LCP<sub>4</sub> increased from 5324 mPa·s to 8263, 6183, 8360, and 6804 mPa·s, respectively, indicating that the addition of chitosan increased the viscosity of LCP. This is because the amino groups of chitosan and the sulfonic acid groups of lignosulfonate sodium generate electrostatic interactions, forming a dynamic network structure, and hydrogen bonds are formed with the hydroxyl groups of PVA, making the system structure dense and enhancing intermolecular forces, which is also verified in the FT-IR analysis. Furthermore, the sample viscosity exhibits a critical shear rate in the range of 30~53 s<sup>-1</sup>. In the range of 1~30 s<sup>-1</sup>, the viscosity decreases at a lower rate; in the range of 53~1000 s<sup>-1</sup>, the rate of decrease increases. Below this critical value, the interaction of molecular chains forming entanglements and networks dominates, and the viscosity decreases slowly; above this critical value, the entanglements and networks formed by molecular chains are destroyed, gradually orienting along the flow direction, and the resistance between molecules decreases, hence the viscosity decreases faster. The viscosity of LCP<sub>5</sub> is much lower than other samples, possibly due to the low proportion of PVA in the system, which cannot provide sufficient hydrogen bonds to form a complex cross-linked network with lignosulfonate sodium and chitosan.



**Figure 4** Rheological properties of LCP liquid mulch film

### 3.2 Mechanical properties of lignin-based liquid mulch film

In Figure 5, the LCP<sub>0</sub> sample exhibited the highest tensile stress and the largest tensile strain. In the process of decreasing the ratio of PVA to chitosan content, the tensile stress and strain of the liquid mulch film gradually decreased (see Table 2). Compared to LCP<sub>0</sub>, the stress of LCP<sub>1-5</sub> decreased to 29.93, 28.51, 25.35, 24.05, and 11.75 MPa, respectively, and the brittleness of the samples showed an increasing trend during testing. This is

mainly because PVA contains a large number of hydroxyl groups, which can form strong intramolecular and intermolecular hydrogen bonds with lignosulfonate sodium and chitosan, thereby enhancing the strength and toughness of the material. However, as the chitosan content increases, the hydrogen bonding between its molecular chains strengthens, to some extent weakening the intermolecular interactions between chitosan and polyvinyl alcohol as well as lignosulfonate sodium. Furthermore, considering the limited compatibility between chitosan and other polymers, even in the presence of hydrogen bonding and other interactions, phase separation may still occur during the film-forming process, thereby weakening interfacial bonding and introducing stress concentration, leading to a decline in the overall mechanical properties of the material. Overall, when the chitosan content is 1%~4%, the stress reduction is 18.00%~34.11%, and the strain reduction is 28.13%~50.00%. When the content exceeds 4%, it causes a significant reduction in the mechanical properties of the mulch film.

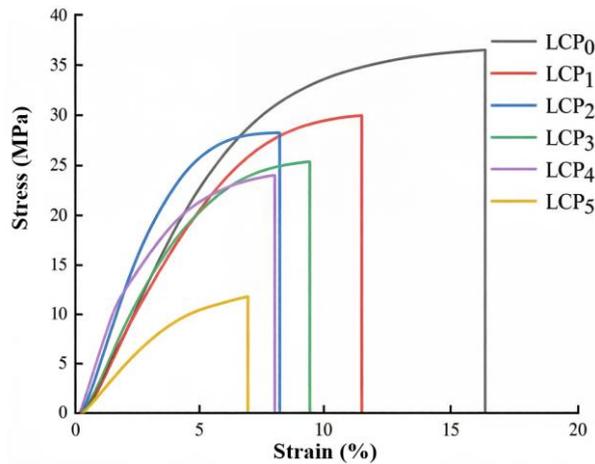


Figure 5 Stress-strain curves of LCP liquid mulch film

Table 2 Maximum stress and maximum strain of LCP liquid mulch film

Sample	Maximum Stress / MPa	Maximum Strain / %
LCP0	36.55	16.00
LCP1	29.93	11.51
LCP2	28.51	8.24
LCP3	25.35	9.41
LCP4	24.05	8.00
LCP5	11.75	6.91

### 3.3 Water vapor permeability of lignin-based liquid mulch film

Water vapor permeability (W) is a core indicator for evaluating the water retention performance of liquid mulch film, directly related to the evaporation rate of soil water and fertilizer and the regulation of the crop microenvironment. As shown in Figure 6, under conditions of room temperature 23°C and relative humidity 50%, the W of the control group without chitosan addition was as high as 366.84 g/(m<sup>2</sup>·d). As the chitosan content increased and the polyvinyl alcohol content decreased, W showed a gradually decreasing trend. The W of LCP<sub>4</sub> was 352.10 g/(m<sup>2</sup>·d), a reduction of 4.02%. This is because chitosan molecules contain a large number of hydroxyl and amino groups, which can enhance the tightness of the local structure to some extent through intermolecular interactions such as hydrogen bonding, thereby hindering the transmission of water vapor. Moreover, as the

chitosan content increases, it may form a relatively continuous barrier phase structure in the system, making the diffusion path of water vapor within the film more tortuous. From a mass transfer perspective, this prolongs the effective diffusion distance of water molecules, thus favoring the improvement of the material's barrier performance. Additionally, reducing the amount of polyvinyl alcohol also helps reduce the adsorption and transmission of water molecules. The synergistic effect of the two enhances the water vapor barrier performance of the composite liquid mulch film. In practical applications, this is beneficial for maintaining the temperature and humidity of the crop growth environment and is of great significance for promoting agricultural water conservation and moisture retention. Although the W of LCP5 is the lowest, its maximum stress and strain are only 11.75 MPa and 6.91%, respectively. To ensure optimal performance for field application, LCP<sub>4</sub> lignin liquid mulch film is preferred, as it can ensure certain mechanical strength while also having good barrier properties.

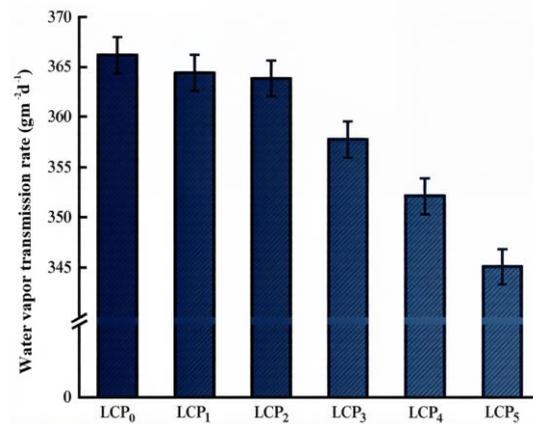


Figure 6 Water vapor transmission rate of LCP liquid mulch film

### 3.4 Effect of lignin-based liquid mulch film on crop growth characteristics

#### 3.4.1 Seed germination rate and root length development

Seed germination rate is an important indicator for evaluating the effect of liquid mulch film on seed germination ability. Figure 7 shows the influence of different LCPs on germination rate and root length. LCP had a certain influence on the germination rate and root length of Shanghai pak choi seeds.

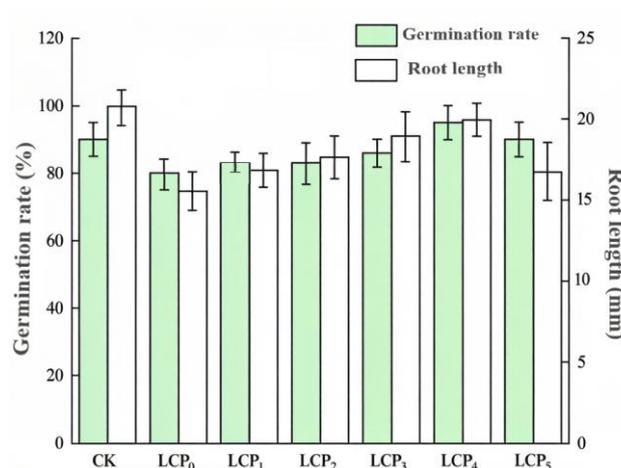
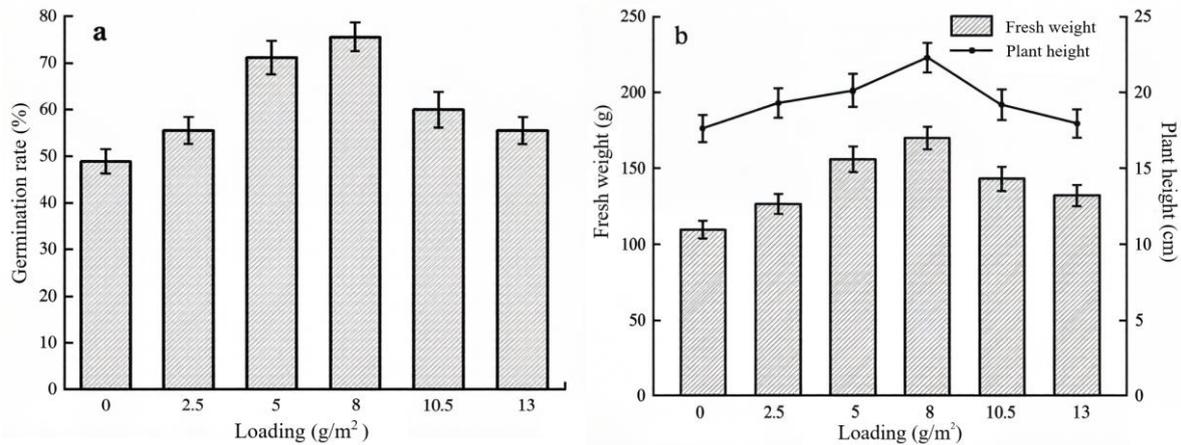


Figure 7 The influence of LCP liquid mulch film on seed germination rate and average root length

The seed germination rate of the CK group was 90%, and the average root length was 20.79 mm. Compared to CK, the seed germination rates of LCP<sub>0</sub>, LCP<sub>1</sub>, LCP<sub>2</sub>, and LCP<sub>3</sub> decreased by 10%, 7%, 7%, and 4%, respectively, and the average root lengths decreased by 5.22, 3.90, 3.15, and 1.82 mm, respectively. The seed germination

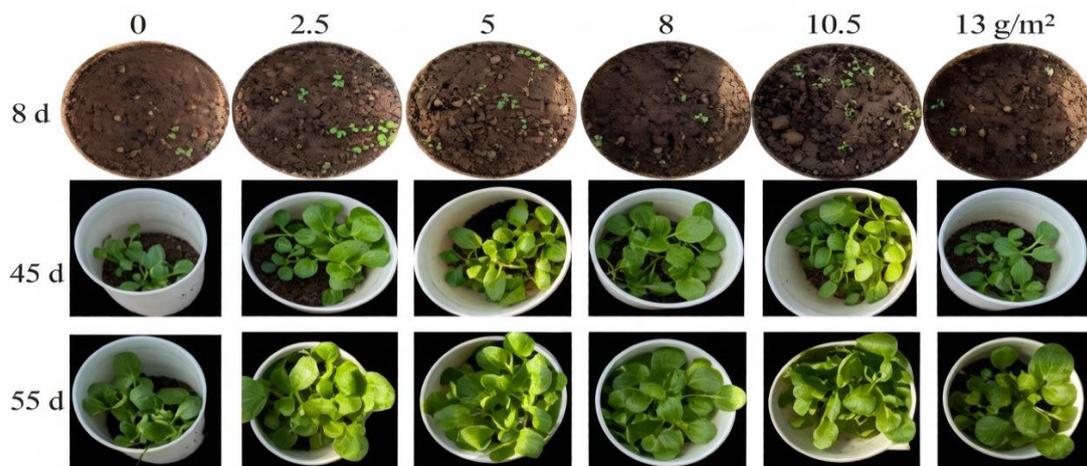
rate of LCP4 reached 95%, an increase of 5% compared to CK; the root length was 19.94 mm, a decrease of 0.85 mm compared to CK (a reduction of 4%). Overall, as the CS/PVA mass ratio increased, the promoting effect of LCP on seed germination rate and root length became stronger, with LCP4 achieving the best effect. This is because an appropriate amount of CS can accelerate seed imbibition and germination initiation by softening the seed coat and enhancing water permeability, and can serve as a functional substance to provide energy and substrate for embryo growth to promote germination (high concentrations inhibit it). Moreover, when forming a suitable ratio with PVA, the LCP film possesses good hydrophilicity and appropriate breathability, thereby maintaining seed microenvironment humidity balance, avoiding water stress, and ensuring oxygen exchange to promote radicle respiration.

### 3.4.2 Effect of soil surface coverage on crop growth



**Figure 8** The effects of LCP liquid mulch film on the germination rate, plant height and total biomass of bok choy under different spraying amounts

Figure 8 shows the effect of LCP4 mulch film on the emergence rate and growth of Shanghai pak choy. The results showed that under different spraying amount treatments, the emergence rate of Shanghai pak choy seeds on the 8th day showed significant differences (Figure 8a), indicating that LCP4 liquid mulch film coverage promotes seed germination. Compared to the control group without LCP4 spraying, the emergence rate of Shanghai pak choy sprayed with LCP4 gradually increased, from 48.89% to 55.56%, 71.11%, 75.56%, 60.00%, and 55.56%. The highest value of 75.56% was reached at a spraying amount of 8  $\text{g/m}^2$ , then gradually decreased.



**Figure 9** The influence of different spraying amounts of LCP liquid mulch film on the growth of Chinese cabbage

By the 55th day of seedling growth, compared to Shanghai pak choi not sprayed with LCP4, the plant height of Shanghai pak choi sprayed with LCP4 increased, from 17.62 cm to 19.32, 22.36, 20.15, 19.19, and 17.95 cm, respectively. The total biomass also increased from 109.72 g/pot to 126.81, 156.14, 170.06, 143.26, and 132.54 g/pot (Figure 8b). Among them, the plant height and total biomass increase rates for the 8 g/m<sup>2</sup> spraying treatment were 26.90% and 54.99%, respectively, superior to the untreated control. The analysis of the reason is that during the cultivation of Shanghai pak choi, the temperature was too high, and the water loss rate of the potted soil was fast. The LCP mulch film, through the dense network structure constructed by the ternary composite system, has good water vapor barrier properties, effectively reducing soil water evaporation and maintaining stable humidity in the root zone. Moreover, the polyphenol structure of LS in LCP can scavenge free radicals, alleviating oxidative damage induced by high temperature, mitigating high-temperature stress, forming a microenvironment beneficial for the growth and development of Shanghai pak choi, thereby promoting crop growth (Figure 9). In summary, when the spraying amount is 8 g/m<sup>2</sup>, the emergence rate, plant height, and total fresh weight of Shanghai pak choi achieve an optimal balance.

### 3.5 Effect of lignin-based liquid mulch film on sand soil structure stability and wind erosion prevention/soil fixation efficiency

The test results for the soil retention performance of LCP4 are shown in Figure 10. After surface treatment with LCP4, the sand cone model's cone angle increase showed a dosage-dependent characteristic. The cone angle increases for low, medium, and high application rates were 16.51%, 19.05%, and 18.35%, respectively (Figure 10b~d), while the cone angle of the untreated LCP4 increased from 123° to 180° (Figure 10a), an increase of as high as 46.34%. This indicates that the LCP4 film can achieve improvement in sand soil consolidation efficiency by enhancing the cementation between sand particles. Its surface morphology observation showed that when the LCP4 spraying amount was 4.5 g/m<sup>2</sup>, a dense protective film layer could form on the sand cone surface, effectively blocking the transmission of vibration energy to the internal loose soil body and maintaining the geometric integrity of the model. As the LCP4 application amount increased stepwise, the bonding strength between sand particles showed a pattern of first strengthening and then leveling off. The medium and low application rate treatments mainly relied on the LCP's multi-component synergy, enabling the formation of a thin yet tough "adhesive film" on the sand soil surface, thereby achieving the fixation effect, significantly enhancing wind and sand erosion resistance. In contrast, the high application rate solution had significantly enhanced fluidity on the soil surface, unable to form a uniform cementation layer due to local accumulation or seepage. In practical applications, the application amount of LCP4 can be adjusted as needed. The study confirmed that the LCP4 surface spraying technology can form a synergistic mechanism of physical barrier and chemical consolidation, and its wind erosion prevention efficiency improved by 58.90%~64.37% compared to the unsprayed treatment (difference percentage in cone angle change range), providing a favorable environment for cultivated land conservation and crop survival in semi-arid and arid regions.

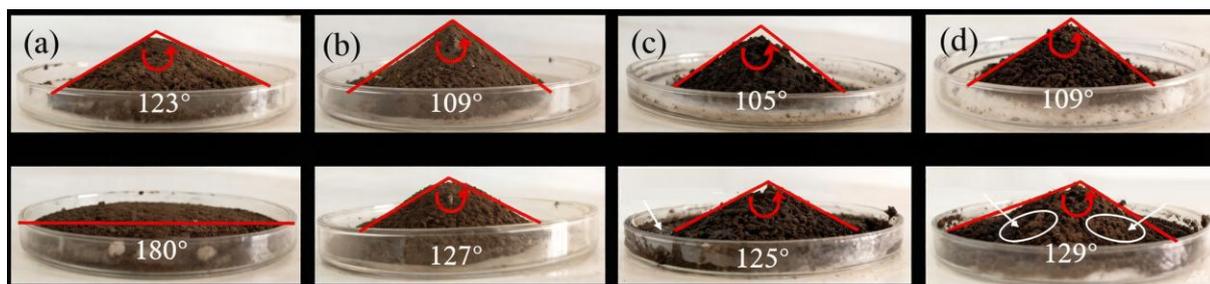


Figure 10 The soil retention effect of LCP liquid mulch film

### 3.6 Production cost and application prospects of lignin-based liquid mulch film

To address the microplastic risk challenge in agricultural production in arid and semi-arid regions, this study innovatively developed a lignin-based multiple cross-linking induced liquid mulch film (LCP). Through batch cost accounting, the production cost of this LCP is approximately 5.70 RMB/kg. Combined with an application rate of 4~5 kg/mu and a mechanical spraying cost of 20 RMB/mu, its comprehensive application cost is about 42.8~48.5 RMB/mu. Field experiments indicate that: LCP mulch film can not only effectively maintain soil structure, inhibit

wind erosion, improve soil hydrothermal conditions and physicochemical properties, but also promote microbial community diversity, improve crop yield and quality, and possesses complete biodegradability. It has important engineering application value and research significance for promoting sustainable green and low-carbon agriculture.

Based on the content of the provided document, the performance enhancement mechanism of the developed lignin-based liquid mulch film (LCP) primarily stems from the synergistic molecular interactions within its ternary composite system and the resultant optimized material properties. The film is synthesized from lignosulfonate sodium (LS), chitosan (CS), and polyvinyl alcohol (PVA). Its enhanced performance is fundamentally driven by multiple non-covalent interactions, specifically hydrogen bonding and electrostatic forces. The hydroxyl groups from PVA and LS form extensive hydrogen bonds, while the cationic amino groups of CS interact electrostatically with the anionic sulfonic acid groups of LS. This creates a reinforced molecular network described as "PVA dynamic hydrogen bond skeleton support, LS/CS electrostatic network anchoring, and LS/PVA/CS hydrogen bond-hydrophobic toughening." This cross-linked structure is responsible for the material's improved mechanical strength (24.05 MPa at optimal ratio) and reduced water vapor permeability (352.10 g/(m<sup>2</sup>·d)). Furthermore, the LCP exhibits significant shear-thinning behavior, which lowers viscosity under high shear rates during spraying, facilitating easy field application and forming a uniform protective layer on the soil surface (Figure 11).



**Figure 11** The influence of LCP liquid mulch film on the growth of cabbage

The enhanced functional performance is realized at a specific mass ratio of LS:CS:PVA = 10:4:4 (denoted as LCP4) and an optimal dry matter spraying amount of 8 g/m<sup>2</sup>. The synergistic mechanism translates into direct agronomic and environmental benefits. The dense network acts as an effective barrier, reducing soil water evaporation and maintaining stable rhizosphere humidity, which alleviates environmental stress on crops. Concurrently, the film strengthens soil structure by cementing soil particles, significantly enhancing soil retention and resistance to erosion. In practice, this leads to a substantial promotion of crop growth: compared to untreated soil, the application of LCP4 at 8 g/m<sup>2</sup> significantly increased seedling emergence rate, plant height, and total biomass of Shanghai pak choi by 45.45%, 26.90%, and 54.99%, respectively. Therefore, the performance enhancement is a holistic outcome of the molecular-level multi-crosslinking that imparts superior material properties, which in turn creates a conducive micro-environment for soil stabilization and crop growth promotion, offering a viable biodegradable alternative to conventional PE mulch films.

## 4 Conclusion

This study proposes a synthesis strategy for a lignin-based liquid mulch film (LCP) induced by multiple cross-linking of lignosulfonate sodium, chitosan, and polyvinyl alcohol. It achieves high-value utilization of biomass resources while effectively avoiding the microplastic pollution risk of traditional mulch films, providing a new green and sustainable approach for crop mulching in arid and semi-arid regions. The main conclusions of the

study are as follows.

(1) Lignosulfonate sodium/chitosan/polyvinyl alcohol, through synergistic cross-linking via hydrogen bonds and electrostatic interactions, constructed a reinforced molecular structure of "PVA dynamic hydrogen bond skeleton support, LS/CS electrostatic network anchoring, LS/PVA/CS hydrogen bond-hydrophobic toughening". This multiple non-covalent synergy mechanism is key to enhancing the interface fusion and mechanical properties of LCP.

(2) LCP exhibits obvious shear-thinning characteristics, facilitating spray application on the soil surface and significantly improving agricultural production applicability. It has a positive promoting effect on seed germination, root development, and crop growth. When the spraying amount reaches 8 g/m<sup>2</sup>, crop emergence rate, plant height, and total biomass are significantly increased, showing good biostimulant effects and reasonable economic costs. It is an effective agronomic mulching material protection measure for arid and semi-arid regions.

(3) Applying LCP liquid mulch film to the soil surface can quickly form a stable protective film layer, which can block the transmission of vibration energy to the internal loose soil, reduce soil particle displacement, enhance the cementation between sand particles, and improve soil retention capacity in arid and semi-arid regions.

This study provides new ideas for the reduction and substitution of PE mulch films and the high-value utilization of agricultural and forestry waste. However, the study only evaluated the mechanical properties, crop growth, and soil retention characteristics of LCP. Future work needs to focus in-depth on the microenvironmental response and degradation characteristics of LCP in arid and semi-arid regions, as well as a comprehensive evaluation of its growth promotion mechanism and soil structure improvement effects. Subsequent research can further combine multidisciplinary knowledge from materials science, soil science, ecology, etc., to deeply explore the interaction mechanisms between LCP and different soil types and climatic conditions, and develop more targeted and adaptable liquid mulch films, which have broad value for promoting the application of new mulch films in sustainable scenarios.

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