Journal of Functional Materials and Applied Engineering

Review Paper

Research Progress on Lignin-Based Microcapsules for Drug Protection and Release

Charlotte Brown[1], Henry Taylor[2], Deepak Atchudan[2,*]

[1] Centro de Química Estrutural, Institute of Molecular Sciences, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[2] Department of Chemistry, Kurukshetra University Kurukshetra, 136119, Haryana, India
*Corresponding author: CharBrown@gmail.com; HenryTaylor@kuk.ac.in; Deepakatchudan@kuk.ac.in

Abstract. In recent years, spherical particles derived from natural bio-based feedstocks have garnered growing interest owing to their distinctive morphologies, structural versatility, and capacity for facile surface functionalisation. Lignin, the most abundant aromatic biopolymer in nature, possesses inherent antibacterial and antiviral activity together with excellent biocompatibility, underscoring its considerable promise for pharmaceutical, cosmetic, and food-sector applications. Preliminary studies have already demonstrated the successful deployment of spherical lignin particles as drug-delivery vehicles—for instance, in the encapsulation of therapeutics for oncological treatment, as well as in the controlled release of insecticides and antimicrobial agents for agrochemical applications. This contribution begins by outlining the fundamental physicochemical attributes of lignin-based drug-loaded microcapsules and the factors governing active-agent release. Detailed discussions of fabrication methodologies, attendant characteristics, and comparative advantages are then presented. Subsequently, recent advances in the utilisation of lignin-based microcapsules within biopharmaceutical and chemical-pesticide contexts are reviewed, together with the critical challenges that remain to be resolved. Finally, prospective directions for the future evolution of lignin-based drug-loaded microcapsules are highlighted.

Keywords: *lignin; microencapsulation; nanomaterials; carriers; biomass*

Received on 02 April 2025, Accepted on 25 April 2025, Published on 11 June 2025

1 Introduction

Microencapsulation technology is a technique that uses polymer materials to encapsulate active components such as solids, liquids, or gases into tiny particles through chemical or physical methods, and the resulting tiny particles are called microcapsules[1-3]. Microcapsules can effectively isolate drugs from the external environment, achieving targeted delivery, anti-photodegradation, and controlled release of drugs[4-5]. The active material wrapped in the microcapsule is usually called the core material, and the selected carrier is called the wall material, whose diameter is usually in the micrometer range[6]. The coating of wall materials can improve the stability of core materials, prolong the reaction time of core materials, and thus achieve control and release of core materials[7-8]. Therefore, microencapsulation technology has attracted widespread attention since its inception.

Microencapsulation offers a versatile platform for altering the physical behaviour of core substances, safeguarding their stability and functional activity, achieving controlled-release profiles, and sequestering volatile components to minimise evaporative losses. Therefore, it is widely used in pesticides, biology, cosmetics, dyes, spices, medicine, coatings, adhesives and other fields[9-11]. The selection of microcapsule wall materials plays a key role in the preparation process and the performance of the final product. The loading efficiency, slow-release ability, and stability of microcapsules mainly depend on the wall materials, which is one of the key issues to be considered in the preparation of microcapsules. At present, the research hotspot on the source of microcapsule wall materials mainly focuses on non-toxic, biocompatible, widely available renewable natural polymer materials, such as chitosan[12], cellulose[13], lignin, etc.[14].

Among them, lignin is one of the three major components of plant skeletons, a biomass resource second only to cellulose in nature, and an important renewable energy source[15]. There are a large number of antioxidant polyphenols and aromatic rings in lignin molecules, which have excellent antioxidant effect and affinity for active drugs. Lignin-based microcapsules made from lignin as a carrier have huge application potential in the fields of antioxidation and drug slow release[16]. Since most drugs, especially chemical pesticides, are insoluble in water, a large amount of organic solvents are needed to dissolve the drugs in the traditional microcapsule preparation process, which has the disadvantages of cumbersome operation steps, high production cost, and long time consumption[17-18]. Using lignin-based materials as wall materials to prepare drug-loaded microcapsules through simple methods can not only solve the problems of difficult degradation and high cost of wall materials, but also reduce pollution to organisms and the natural environment[19-21]. In addition, many studies have shown that drug-loaded microcapsules prepared from lignin-based materials can not only improve the controlled release and light stability of drugs to varying degrees, but also enhance the drug effect[22-24].

In summary, the use of lignin as a wall material to prepare drug-loaded microcapsules is still in the preliminary research stage, but as a new type of drug slow-release carrier, lignin has many advantages over traditional microcapsule wall materials: (1) Lignin and its derivatives, as by-products of pulping and papermaking, are cheap and can effectively reduce the cost of microcapsule preparations; (2) The polyphenol structure and chromophore groups in lignin have the functions of scavenging free radicals and absorbing ultraviolet rays, which can prepare potential light-stable drug-loaded materials; (3) Lignin is non-toxic, renewable, and biodegradable. Pesticides loaded on lignin will be completely released with the degradation of lignin, and the degradation products of lignin can play a role in composting. With the continuous deepening and improvement of research on lignin functional properties, important research results have been achieved in the use of lignin as a carrier in biomedical materials, fine chemicals, and other aspects. Against this backdrop, the present review systematically surveys the key physicochemical attributes, fabrication strategies, and state-of-the-art applications of lignin-based drug-loaded microcapsules. By offering a comprehensive roadmap for lignin utilisation in sustained-release drug delivery, this work holds considerable practical significance for broadening the utility of industrial lignin and enhancing its economic value.

2 Lignin-based drug-loaded microcapsules

2.1 Structure, properties and categories of lignin

In its broadest definition, lignin constitutes an amorphous, three-dimensional biopolymeric network assembled via dehydrogenative polymerisation of three distinct phenylpropanoid precursors. These phenylpropane building blocks are cross-linked through ether (–O–) and carbon–carbon (C–C) bonds within the macromolecular architecture. The constituent monolignols are universally recognised as p-coumaryl, sinapyl, and coniferyl alcohols, which respectively give rise to the p-hydroxyphenyl (H), syringyl (S), and guaiacyl (G) units that define lignin's primary structural motifs (Fig. 1). During lignification, these three basic monomer structures are combined at different positions through C–C or –O– bonds, resulting in different types of connecting bonds in the lignin macromolecular structure.

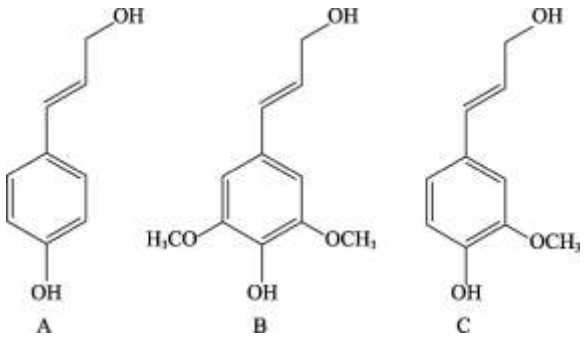

Figure 1 Lignin's basic monomers: p-Coumaryl alcohol (A), sinapyl alcohol (B) and coniferyl alcohol (C)[28]

According to statistics, globally, the amount of lignin synthesized by plant growth each year is as high as 1.5×10^{11} t[29-30]. Lignin entering the environment mainly comes from by-products produced by the pulping and papermaking industry and the bio-ethanol refining industry[31]. However, the current utilization rate of lignin is still very low. Except for being directly incinerated as fuel to provide heat energy, the practical application of lignin in industrial fields, such as surfactants, polymer additives, dye colorants, UV stabilizers, chemical fertilizers, adhesives, etc., is very limited[32-34]. The reason why the application of lignin is limited is essentially due to the complexity and uncertainty of its molecular structure and low molecular accessibility. For lignin from different sources, modification to broaden its application fields has become one of the most popular strategies to improve lignin utilization[35].

The lignin macromolecule is rich in functional moieties—including methoxy, hydroxyl and phenyl substituents [36]. Both the identity and spatial distribution of these groups depend strongly on the botanical origin of the lignin and the specific isolation protocol employed. According to different plant sources, lignin can be divided into gramineous lignin, hardwood lignin, and softwood lignin[37]. According to different production needs and processes, lignin sources are generally divided into two categories (as shown in Fig. 2): Lignin feedstocks broadly fall into two classes. The first encompasses small-batch, laboratory-refined preparations—exemplified by cellulolytic enzyme lignin (CEL), milled wood lignin (MWL), and enzyme-mild acidolysis lignin (EMAL) [38]. The second comprises industrial lignins, which are typically generated as by-products of pulping and papermaking operations [39]. Depending on the specific pulping technology employed, industrial lignin is commonly sorted into four categories: lignosulfonates, kraft lignin, soda lignin, and organosolv lignin [40]. Because botanical origin and isolation protocol differ, the structural architectures, physicochemical behaviours, and functional-group fingerprints of these lignins vary markedly. The rich endowment of reactive handles—methoxy, hydroxyl, and phenyl substituents among others—endows lignin with substantial chemical versatility, enabling transformations such as oxidation, reduction, sulfonation, polycondensation, and graft copolymerisation that prove advantageous during microcapsule fabrication [41]. In addition, lignin also has good biocompatibility and is easily degraded by various biological enzymes, giving it unique advantages as a drug carrier or microcapsule wall material in the field of drug slow release[42].

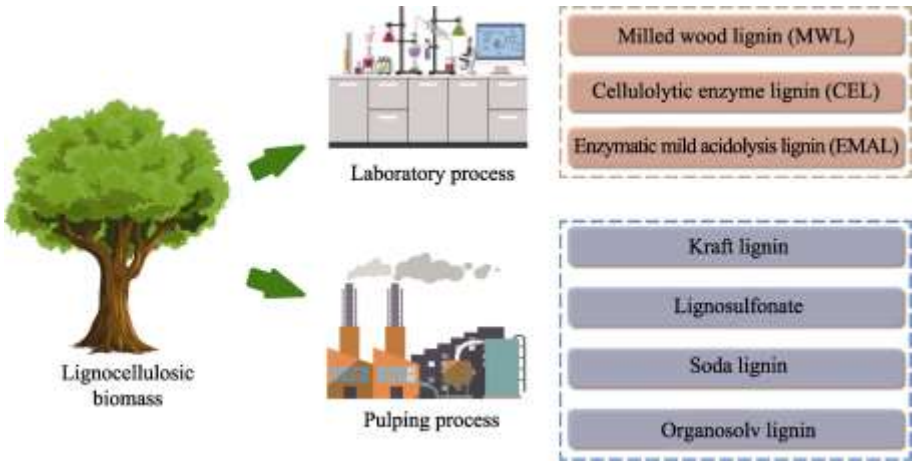

Figure 2 Schematic diagram of lignocellulose preparation by different scale methods

2.2 Characteristics and release influencing factors of lignin-based drug-loaded microcapsules

Lignin is a natural polymer with a three-dimensional network structure and contains various functional groups. It can cross-link with the core material (drug), showing great application potential in drug controlled release[43]. Using lignin and its derivatives as microcapsule wall materials can effectively solve the problems of drug release stability and difficult degradation of microcapsule wall materials[44-45]. At the same time, the light stability mechanism of lignin is similar to that of hindered phenols, mainly because a large number of phenolic hydroxyl groups in the molecular structure can effectively scavenge active free radicals generated in photo-oxidative decomposition[46-47]. Therefore, compared with microcapsules made of traditional carrier materials (such as synthetic and semi-synthetic polymer materials), the addition of lignin makes the microcapsule material have

excellent anti-UV degradation ability, which can effectively protect drugs from degradation in some photosensitive medicines and biological insecticides[48-49]. In addition, lignosulfonate has good compatibility with drugs, wide applicability, and abundant sources. As an anionic surfactant, it can coat the surface of chemical pesticide particles, and use electrostatic interaction and steric hindrance to avoid sedimentation and flocculation of chemical pesticide particles caused by intermolecular forces such as van der Waals force[50-51].

Lignin-based drug-loaded microcapsules are a capsule-like preparation formed by using microencapsulation technology to embed liquid or solid drugs in a lignin-based wall material by embedding method[52]. Since the active ingredient of the drug is wrapped in a lignin-based airtight or semi-airtight wall material as the core material, compared with the original pesticide and traditional microcapsules, the release influencing factors of lignin-based microcapsule preparations are also different. The main influencing factors are as follows: (1) Stability of microcapsule wall material itself. The antioxidant, anti-UV, and light stability of microcapsule wall materials will affect the stability of the material itself, thus affecting the release characteristics of drug-loaded microcapsules. For example: although protein and pectin materials have certain antioxidant properties, they are prone to agglomeration during microcapsule preparation and have certain allergenicity, which often leads to premature release of core drugs at undesired locations or times[53]. Due to its high carbon content, good oxidation resistance, anti-UV, and light stability, lignin can be used as a wall material for drug-loaded microcapsules to improve the dispersion stability and release cycle of drugs that are easily decomposed, oxidized, and have poor light stability[54]; (2) Intrinsic lignin properties. The molecular weight, together with the identity and abundance of functional groups, governs drug release from lignin-based microcapsules. For instance, FERRAZ et al. [55] encapsulated herbicides within six distinct lignin coatings and demonstrated that the diffusion-controlled release profile correlated with both the lignin molecular weight and its hydroxyl/aliphatic hydroxyl content, allowing release kinetics to be tuned by adjusting functional-group density. (3) Microcapsule release environment. Relative to conventional carriers, lignin-derived materials offer the distinct merits of being non-toxic, environmentally benign, highly biocompatible, and inherently biodegradable. Therefore, lignin-based materials as wall materials have a wider range of applications. Studies have shown that microcapsules prepared with lignin as wall material have the effect of prolonging the drug efficacy cycle in both simulated human body environment and harsh tropical natural environment[21,56]. In addition, ZHOU Bin et al.[57] found that the environmental system pH and salt concentration will affect the release rate of chitosan/sodium lignosulfonate microcapsules. The pH and salt concentration of the external environment will affect the charge density on the molecular chain, thereby affecting the thickness of the microcapsule wall material, and then affecting the release rate of the core drug; (4) Preparation conditions of microcapsules. According to the preparation principle of drug-loaded microcapsules and the different chemical properties of lignin, the core-shell structure, size, and shape of microcapsules/particles can be finely adjusted to control the drug loading, encapsulation rate, and release rate to meet different applicable conditions[58-59].

3 Preparation methods of lignin-based drug-loaded microcapsules

At present, the methods for preparing drug-loaded microcapsules using lignin can be roughly divided into Pickering emulsification, physical ultrasonic method, electrostatic self-assembly, and interfacial polymerization. Lignin-based drug-loaded microcapsules prepared from different sources and methods have different characteristics.

3.1 Preparation of lignin-based drug-loaded microcapsules by Pickering emulsification

The preparation of lignin microcapsules by Pickering emulsification refers to dissolving the core active substance in the dispersed phase, using lignin as the main wall material to prepare nano-colloidal particle emulsion. The colloidal particles adsorb around the emulsion droplets and are cross-linked by a certain method (such as physical gel method, electrostatic deposition method, chemical cross-linking method, etc.) to form a continuous and stable shell[60]. Lignin is a natural macromolecule with amphiphilicity. Its own C_6-C_3 hydrophobic skeleton shows unique hydrophobicity, while weakly ionized groups such as phenolic hydroxyl show certain hydrophilicity[61]. WU Wenjuan et al.[62] showed that amine-modified lignin has excellent application potential in emulsified asphalt materials. The mechanism is to graft amine compounds onto lignin to form a lignin cationic emulsifier. In this context, the preparation of microcapsules by lignin Pickering emulsification method has the characteristics of high flexibility, non-toxicity, low cost, and renewability. Therefore, the use of Pickering

emulsification to prepare microcapsules is a very effective method for using natural renewable polymer materials as wall materials for drug-loaded microcapsules.

Wang et al. [63] fabricated thermally stable, irregular flake-shaped lignin nanoparticles (LSNP) by complexing lignin with sodium dodecyl sulfate (SDS). These particles exhibited remarkable amphiphilicity, stabilising both highly polar and moderately polar oil phases within Pickering emulsions. Leveraging this emulsion template, avermectin was entrapped inside lignin microcapsules (LMC) through a tandem ionic-crosslinking and interfacial-polymerisation strategy, ultimately yielding lignin/polyurea composite microcapsules (LPMC) at the oil–water boundary (Fig. 3a; EH denotes the ethylenediamine cross-linker). The resulting LPMC achieved an encapsulation efficiency of 85.4 % and a drug loading of 4.7 %, alongside sustained-release behaviour and marked resistance to photodegradation. This approach offers a streamlined, eco-friendly route to water-dispersible, lignin-based microcapsules for controlled-release applications.

YIAMSAWAS et al.[64] used lignin or sodium lignosulfonate (SL) and NaCl dissolved in water to form a dispersed phase, and then mixed with cyclohexane containing polyglycerol polyricinoleate (PGPR) as an emulsifier. Pre-emulsification was first performed at room temperature, followed by ultrasonic treatment to obtain a stable microemulsion. Cross-linking agent toluene diisocyanate was added to the microemulsion to cross-link lignin or SL at the oil/water interface, and finally lignin-based nanocapsules with a diameter of 150-200 nm were formed. This nanocapsule can be applied to the encapsulation of hydrophilic drug materials, as shown in Fig. 3b. In addition, researchers used laccase as a model enzyme and mixed enzymes extracted from natural fungi to enzymatically degrade lignin nanocapsules. The microcapsules could perform long-term release, but the specific loading drugs and slow-release effects need further investigation.

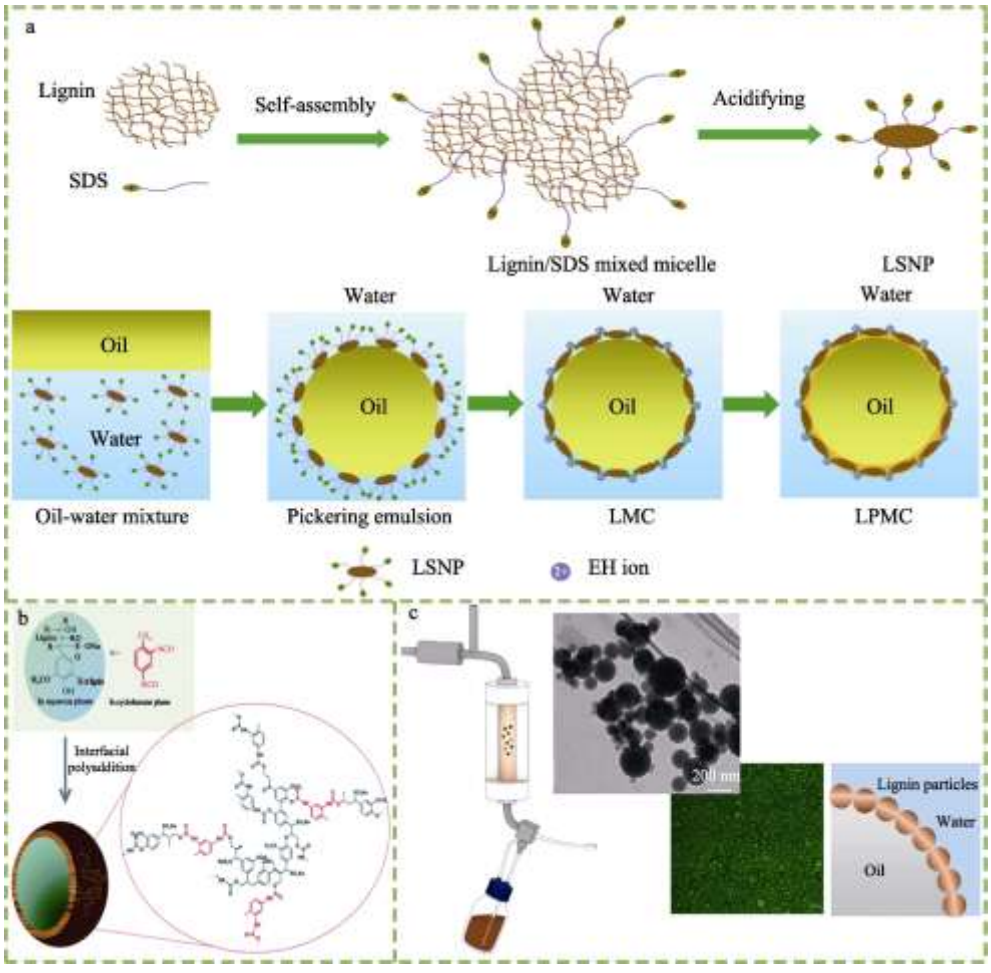

Figure 3 Schematic diagram of LPMC preparation by LSNP[63] (a); Schematic diagram of the preparation of lignin microcapsules[64] (b); Schematic diagram of the preparation of spherical lignin particles[65] (c)

AGO et al.[65] first used an aerosol flow reactor to synthesize spherical lignin particles with a given inherent hydrophilicity, with a particle size of 30-2000 nm. After shear redispersion in water or mineral oil, the spherical lignin particles still showed good mechanical integrity. Spherical lignin effectively stabilized oil-in-water (O/W) Pickering emulsions. The size of emulsion droplets depended on the size of lignin particles used for emulsification. Its properties were related to the type and concentration of lignin, and it could be used to stabilize emulsifiers and load chemical pesticides, as shown in Fig. 3c. The team provided a new, scalable manufacturing method to produce spherical lignin particles with controllable size and high yield, providing the possibility for the application of spherical lignin particles in the field of biomedicine and chemical pesticide microcapsules.

3.2 Preparation of lignin-based drug-loaded microcapsules by ultrasonic-assisted method

Lignin molecules contain a large number of phenolic hydroxyl groups, which can generate phenolic free radicals under ultrasonic radiation, promoting intermolecular cross-linking polymerization of lignin[66]. Ultrasonic radiation energy can be used to improve the efficiency and purity of lignin extraction, and also to separate lignin samples and large relative molecular weight lignin. Compared with traditional preparation methods, drug-loaded microcapsules prepared by physical ultrasonic technology have the advantages of long-term stability, dilution stability, high loading efficiency, low toxicity of surfactants, flexible controlled drug release, and convenient preparation. In terms of production cost, processing, and maintenance, physical ultrasonic technology is more advantageous than other technologies. CHEN et al.[67] used ultrasonic-assisted interfacial microemulsion polymerization technology to successfully prepare pH-responsive lignin nanocapsules, as shown in Fig. 4a. The particle size of lignin nanocapsules was between 50-300 nm. This new type of nanocapsule could easily load hydrophobic coumarin-6, with an encapsulation rate of 0.713 mmol/g. At pH = 7.4, the drug release curve of lignin nanocapsules was close to linear, while at pH = 4, the drug release conformed to the Korsmeyer-Peppas curve. Ultrasonic-assisted synthesis of lignin-based nanocapsules offers a facile and sustainable pathway for lignin valorisation, while demonstrating considerable potential for the controlled delivery of hydrophobic cargoes such as pharmaceuticals, essential oils, and antioxidants.

TORTORA and co-workers [68] employed ultrasound irradiation to fabricate lignin microcapsules (LMC) loaded with coumarin (Fig. 4b). The resulting particles displayed a uniform spherical morphology, exhibiting mean diameters ranging from 0.3 to 1.1 μm. In vitro release assessments revealed that these microcapsules remained structurally intact and showed negligible drug leakage during prolonged immersion in pure water. Conversely, complete payload discharge was achieved within 60 min upon exposure to SDS-containing aqueous media. This accelerated release was attributed to the surfactant-mediated diminishment of LMC hydrophobicity, which facilitated rapid coumarin liberation. Comparative analysis indicated that the release profile was predominantly governed by the external medium rather than by intrinsic structural attributes of the microcapsules. Although cytocompatibility investigations furnished substantial theoretical backing for prospective biomedical deployment of LMC, optimisation of release conditions warrants additional scrutiny.

TAN Shanyuan[69] used ultrasonic cavitation method to prepare two lignin microcapsules: prochloraz-lignin (AL-PCZ) and prochloraz-imazalil (AL-PCZ-IMZ), as shown in Fig. 4c. The results showed that the ultrasonic treatment time of AL-PCZ was 3 min, the ultrasonic power was 720 W, and the encapsulation rate of microcapsules was 89.1%, with a drug loading of 90.5%; the ultrasonic treatment time of AL-PCZ-IMZ was 1 min, the ultrasonic power was 480 W, its encapsulation rate was 60.5%, and the drug loading was 69.3%. Both AL-PCZ and AL-PCZ-IMZ were uniform spherical, with particle sizes between 150-500 nm and 200-350 nm, respectively. They could effectively resist UV irradiation, slow down the release rate, and prolong the drug efficacy period. Both microcapsules had certain advantages over ordinary commercial microcapsules in terms of dispersion, storage, broadening of bactericidal spectrum, slow release, prolonging drug efficacy, and reducing drug resistance. However, due to the thin walls of AL-PCZ and AL-PCZ-IMZ prepared, the release stability and safety need to be improved.

PIOMBINO et al.[70] used lignosulfonate as the capsule wall material, and thymol and its derivatives with antibacterial, antioxidant, antifungal, and antiparasitic effects as the capsule core material, and prepared

lignosulfonate microcapsules (SLS-MCs) containing thymol and its derivatives by continuous ultrasonic method, as shown in Fig. 4d. The results showed that several types of lignin microcapsules were spherical structures with a particle size between 3.2-3.4 μm. GC-MS measured that the encapsulation rate of microcapsules was above 40%, among which the encapsulation rate of thymol derivative (T) was as high as 76%. The release study was carried out in acetate buffer at pH = 5.4, and the microcapsules had excellent slow-release effect. The preparation of SLS-MCs used an oligomeric shell system that could act as an antioxidant itself to protect thymol and its derivatives as low relative molecular weight mobile antioxidants and antimicrobial agents, and this new system provided a certain theoretical support for the application of lignin in the biomedical field, but the specific slow-release amount and drug encapsulation rate need further in-depth study.

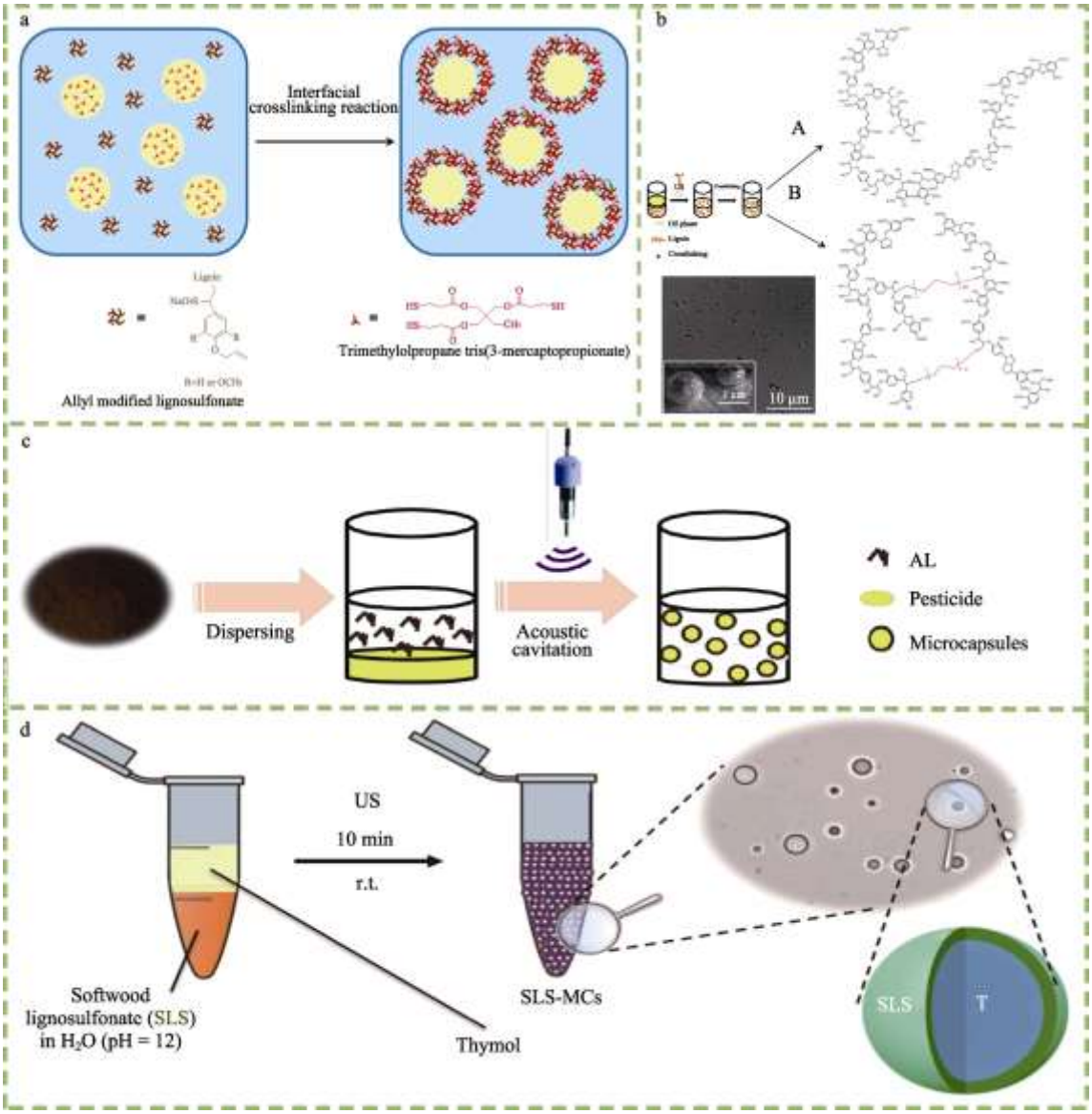

Figure 4 Scheme of preparing pH-responsive lignin based microcapsules[67] (a); Schematic diagram of preparation of lignin microcapsules encapsulated with coumarin by ultrasonic method[68] (b); Schematic diagram of preparation process of AL-PCZ and AL-PCZ-IMZ[69] (c); Schematic diagram of SLS-MCs preparation[70] (d)

3.3 Preparation of lignin-based drug-loaded microcapsules by electrostatic self-assembly

Self-assembly describes the spontaneous reorganisation of molecules from disordered states into ordered supramolecular architectures, orchestrated by weak, non-covalent interactions such as hydrogen bonding, van

der Waals forces, electrostatic attraction, hydrophobic association, π–π stacking, and cation adsorption. Not all compounds are intrinsically capable of this transition; successful self-assembly requires two essential elements: a sufficient thermodynamic driving force and an appropriate structural directing template [71]. Because lignin is an amphiphilic macromolecule, it can participate in such self-organisation processes [72], and the resulting modified lignin materials hold considerable promise for fabricating drug-loaded microcapsules. In this vein, Li et al. [73] exploited electrostatic self-assembly between sodium lignosulfonate (SL) and cetyltrimethylammonium bromide (CTAB) to prepare uniform colloidal spheres (AVM@SL–CTAB) loaded with avermectin (AVM), as illustrated in Fig. 5a. The encapsulation efficiency attained 62.58 % ± 0.06 %, with sustained release continuing beyond 70 h and a cumulative release fraction of 49.96 % ± 1.13 %. Adjusting the mass ratio of wall material to core material allowed the release profile to be tuned, while the photolytic half-life (DT_{50}) was prolonged by a factor of 7.35, providing effective photoprotection for the active ingredient. This lignin-based encapsulation approach is cost-effective and procedurally simple; it not only promotes the high-value utilisation of biomass-derived lignin but also offers a sustainable shielding strategy for photolabile agrochemicals, achieving controlled-release functionality. In the nomenclature used herein, C–AVM refers to commercial avermectin microcapsules; O–AVM to the neat technical active ingredient; AVM + SL–CTAB to a physical mixture of avermectin with the SL–CTAB complex; AVM@SL–CTAB to the self-assembled drug-loaded microcapsules; and Two–Films to a bilayer specimen prepared by coating a pre-formed film of O–AVM, AVM + SL–CTAB, or C–AVM with an additional SL–CTAB layer.

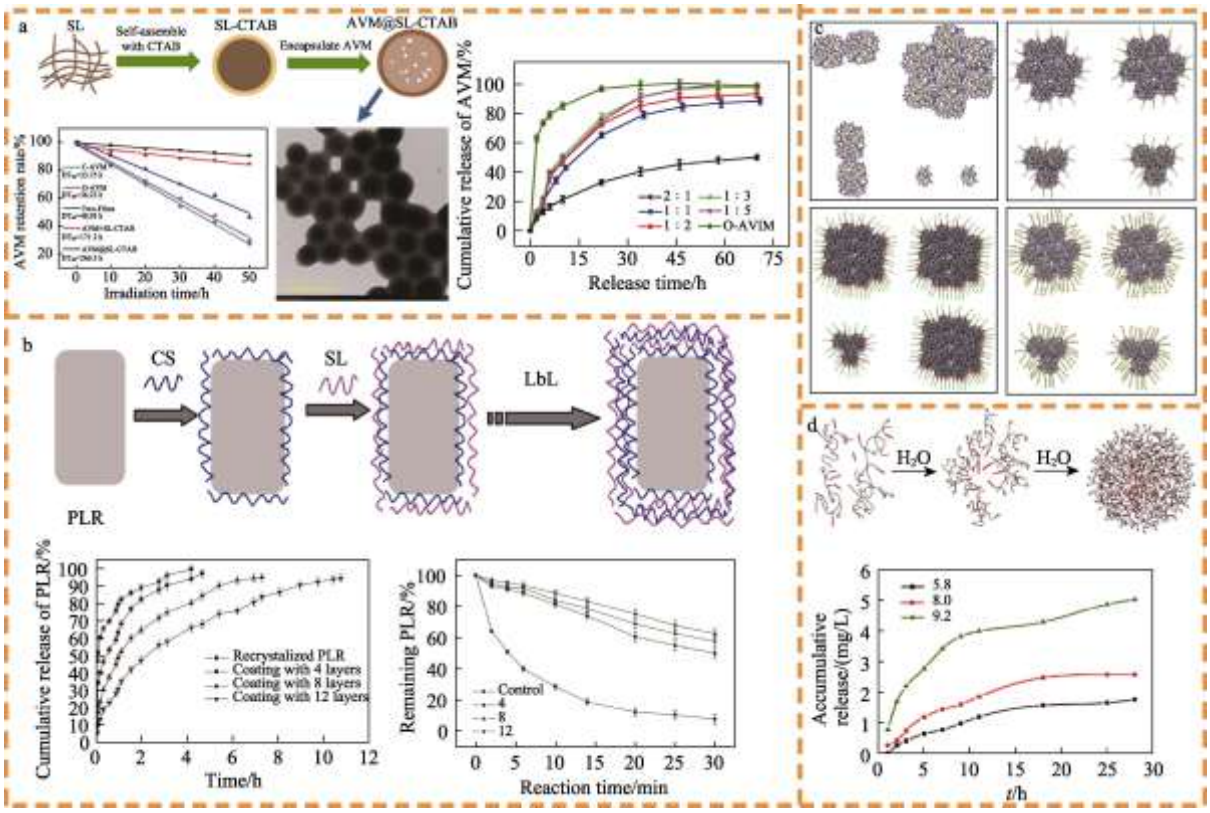

Figure 5 Schematic diagram of AVM@SL-CTAB preparation and different mass ratios of wall to core slow release[73] (a); Schematic diagram of preparation of PLR/(CS/SL) with different assembled layers for slow release and photolysis[59] (b); Schematic diagram of aggregation model of CA-SLS with different ratios of CTAB/SL-PEG in solution[74] (c); Schematic diagram of preparation of drug-carrying microcapsules and in vitro release profiles of drug-carrying microcapsules under different pH conditions[75] (d)

WANG Xiaojing[59] used natural polymer chitosan (CS) and SL as microcapsule wall materials, and used layer-by-layer self-assembly method to successfully prepare PLR/(CS/SL) drug-loaded microcapsules with the herbicide drug picloram (PLR) with poor light stability as the core material, as shown in Fig. 5b. When 12 layers

were assembled, the drug loading and encapsulation rate of PLR/(CS/SL) were 97.4% and 86.2%, respectively. PLR/(CS/SL) prepared by layer-by-layer self-assembly (LbL) can not only effectively reduce the release rate of herbicide PLR, prolong the drug efficacy cycle, and reduce agricultural pollution, but also provide theoretical support for the research and application of lignin self-assembly technology in the field of biological pesticides and chemical fertilizer microencapsulation.

In a study by ZHOU et al. [74], SL was covalently tethered to lengthy polyethylene glycol chains to generate lignin polyoxyethylene ether (SL–PEG). The as-synthesised SL–PEG was then formulated with CTAB at differing mass proportions, producing an array of lignin-based cationic/anionic surfactant systems (CA–SLs). The resulting aggregation behaviours of these CA–SLs in solution, observed across various CTAB/SL–PEG ratios, are illustrated in Fig. 5c. This method can be used to wrap pesticide preparations, and the prepared drug-loaded microcapsules have excellent surface activity and interfacial adsorption performance.

DENG Yonghong et al.[75] successfully prepared lignin-based azo polymer (AL-azo-COOEt) using alkali lignin (AL) from pulping and papermaking industry by-products, and on this basis, successfully prepared regular drug-loaded microspheres with hydrophobic inside and hydrophilic outside using self-assembly colloidal technology. Avermectin was wrapped in the drug-loaded microspheres to obtain microcapsules, as shown in Fig. 5d, with an encapsulation rate as high as 61.49%. Furthermore, the microcapsules displayed markedly superior photostability relative to both the neat active ingredient and commercially available avermectin formulations. Their subdued release kinetics also proved advantageous for therapeutic performance. Concurrently, lignin-derived azo polymers emerge as promising coating candidates for hydrophobic pharmaceuticals.

In summary, lignin-based drug-loaded microcapsules prepared by Pickering emulsification can ensure that the suspended emulsion system formed by drug preparations remains uniform and stable during long-term storage and use, which can not only effectively emulsify fat-soluble drugs, but also give drugs anti-photolysis and thermal stability, while providing a slow-release effect[76]. However, the preparation process usually requires the addition of other auxiliaries, the production cost is high, and the yield needs to be further improved. Lignin-based drug-loaded microcapsules prepared by ultrasonic-assisted method have the advantages of relatively uniform size distribution, small particle size, and high encapsulation rate; some lignins are endowed with new chemical properties after ultrasonic treatment. At the same time, when ultrasonic energy passes through liquid, cavitation will occur in the liquid, which is conducive to drug encapsulation. The preparation is simple and green, and suitable for loading most drugs[77]. This method can not only effectively solve the problems of large amounts of organic solvents used in drug preparation production, low drug loading and encapsulation rate of microcapsules, but also effectively alleviate pesticide photodegradation and short drug efficacy time. However, ultrasonic energy easily causes the sample temperature to rise. In industrial production, heat dissipation and sound energy transmission are difficult, and its application in large-scale industrial production needs further solution. Lignin-based drug-loaded microcapsules prepared by electrostatic self-assembly have the characteristics of uniform size, thermodynamic stability, and controllable release. In addition, the drug-loaded microspheres prepared by this method have higher release stability and controllable release cycle than those prepared by other methods[78]. Although both electrostatic self-assembly and other methods can prepare drug-loaded microcapsules with uniform particle size, compared with other preparation processes, it is necessary to modify the sample and use surfactants, and the technical operation is relatively high, which can easily become an unfavorable factor affecting its application.

4 Application categories of lignin-based drug-loaded microcapsules

The development of drug-loaded microcapsules using lignin as raw material can not only solve the special application functions of easily decomposed drugs, but also carry out directional loading and release of biological drugs. According to the functional characteristics of lignin-based drug-loaded microcapsules, they can be divided into biomedical lignin microcapsules and chemical pesticide lignin microcapsules.

4.1 Biomedical lignin microcapsules

The introduction of lignin not only improves the slow-release performance of drugs, but also enriches the special functions of biological drugs. Lignin has good biocompatibility, biodegradability, and renewability, and

lignin-based nanocarriers have been successfully used in drug delivery systems and widely used in cosmetics and biomedical research[79]. At the same time, its high antioxidant and antibacterial activities also expand the potential applications of lignin[80].

Kim et al. [81] fabricated nanospheres from sodium lignosulfonate (SL) and chitosan (CS), as illustrated in Fig. 6a. The resulting microspheres exhibited a mean diameter of approximately 230 nm. Incorporating lignosulfonate into the chitosan nanoparticle matrix conferred enhanced resistance to lysozyme-mediated breakdown, alongside favourable cytocompatibility and antimicrobial efficacy toward human cells. The nanospheres could encapsulate hydrophilic protein-ribonuclease A for drug delivery systems in cosmetics and biomedicine. In vitro release studies on drug-loaded nanospheres showed that at low ribonuclease A concentration during preparation, it would be completely released in a short time, while at high ribonuclease A concentration, it could be slowly released.

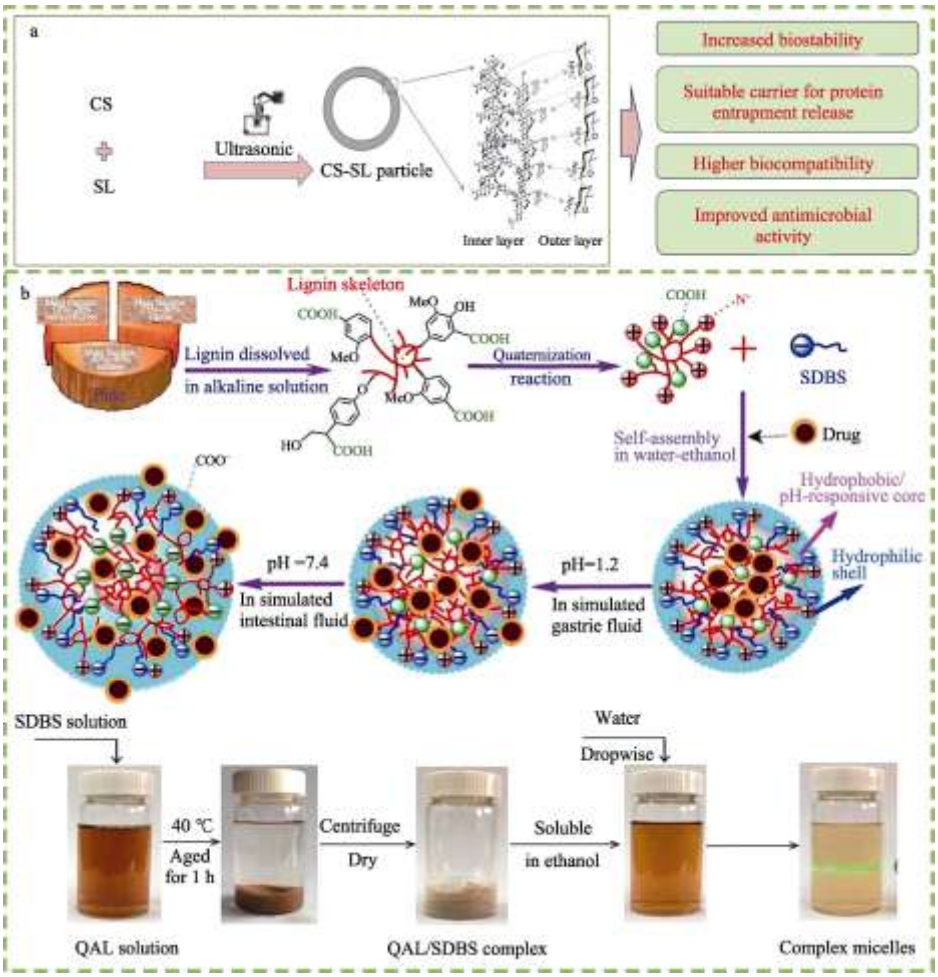

Figure 6 Schematic diagram of preparation of sodium lignosulfonate and chitosan drug-loaded microcapsules[81] (a); Schematic diagram of preparation of lignin-based colloidal microspheres drug microcapsules and digital photos of lignin-based composite micelles[82] (b)

LI et al.[82] used AL and sodium dodecylbenzenesulfonate (SDBS) to self-assemble into lignin composite micelles in ethanol/water mixed solvent, as shown in Fig. 6b. Using ibuprofen (IBU) as a drug model, the encapsulation rate was 74.44%. In simulated gastric fluid (SGF, pH 1.2), over 75 % of the ibuprofen payload remained intact, whereas in simulated intestinal fluid (SIF, pH 7.4) more than 90 % was smoothly released. These findings furnish a novel rationale for engineering oral drug-delivery vehicles and underpin their prospective biomedical utility. In related work, Raschip et al. [83] encapsulated vanillin within gel capsules composed of lignin and xanthan gum. The results showed that increasing the amount of xanthan gum was negatively correlated with the release

rate of gel capsules. When the mass ratio of xanthan gum to lignin was 7:3, the release of vanillin within 100 min was 15%. This was because with the increase of xanthan gum, the intermolecular force of the gel also increased, and lignin played an antioxidant role. The preparation of lignin gel capsules has great application potential in drug controlled release, especially in the treatment of gastritis drugs.

Figueiredo and colleagues [84] engineered a triad of lignin nanoparticle (LNP) formulations: pristine lignin nanoparticles (pLNPs), iron(II)-chelated lignin nanoparticles (Fe-LNPs), and magnetite-embedded lignin nanoparticles (Fe_3O_4-LNPs). These constructs displayed a spherical morphology, accompanied by a tight size distribution and minimal polydispersity, while retaining structural integrity under mildly acidic to neutral conditions (pH < 7.4). Regarding payload accommodation, pLNPs demonstrated exceptional encapsulation efficiency for hydrophobic and cytotoxic therapeutic agents, exemplified by the antineoplastic model compounds sorafenib and benzazulene (BZL). Furthermore, the superparamagnetic characteristics inherent to Fe_3O_4-LNPs unveiled considerable promise for oncological interventions and diagnostic imaging, encompassing magnetically guided drug delivery and magnetic resonance imaging modalities—thereby underscoring the substantial biomedical versatility of lignin-derived nanocarriers.

4.2 Chemical pesticide lignin microcapsules

In recent years, the application potential of lignin has been continuously explored, and the application technology in the agricultural field has been continuously expanded[85]. Since the 20th century, lignin has been used in slow-release nitrogen fertilizer research at home and abroad[86], and on this basis, the research field has been further broadened. Among them, the application of lignin in the field of drug-loaded microspheres is also a very important application direction in the agricultural field[87].

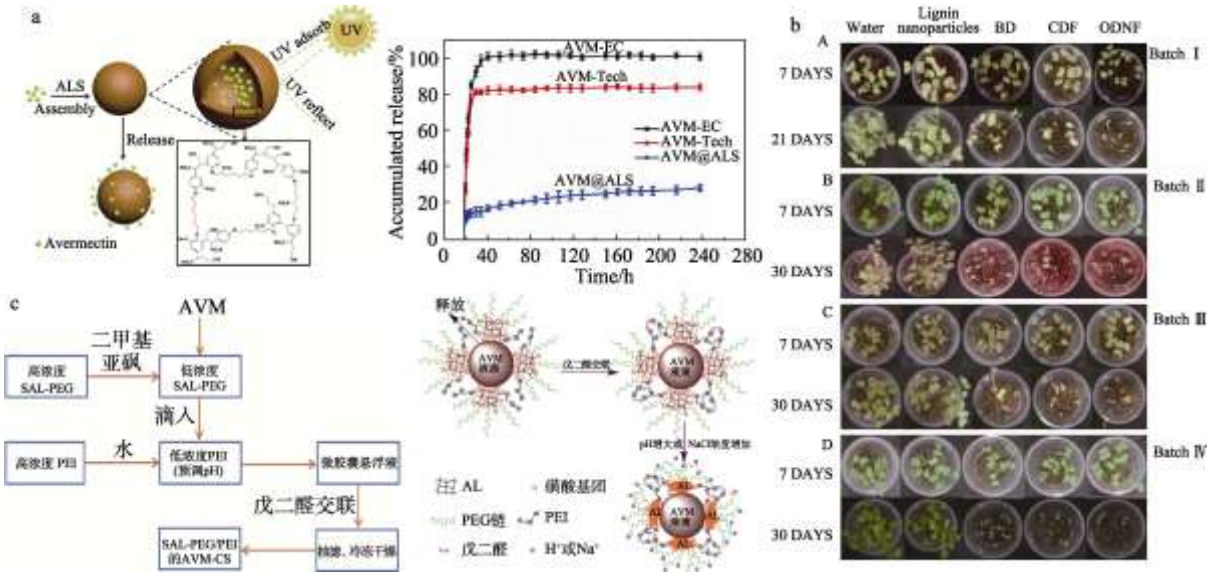

Figure 7 Schematic diagram of AVM@ALS preparation and slow release curve[20] (a); Digital photos of rape seedlings treated by ODNF and other means[88] (b); Preparation flow chart of drug-carrying microcapsules and schematic diagram of effect of sustained release performance[89] (c)

Liu et al. [20] reported a rapid, economical route to fabricate avermectin-loaded microcapsules (AVM@ALS) by self-assembling alkyl-chain-functionalised lignosulfonate polymers around the active ingredient (Fig. 7a). In their nomenclature, AVM-EC denotes the emulsifiable concentrate, whereas AVM-Tech refers to the commercial capsule formulation. The resulting AVM@ALS particles exhibited a substantial payload capacity of 57.01 %, sustained-release behaviour, and resistance to UV-induced degradation. The protocol is straightforward, inexpensive, and relies on renewable raw materials, offering a coating-based strategy that advances the sustainable use of agrochemicals. Nevertheless, only 27.6 % of the entrapped avermectin was released over 241 h; the time to reach release equilibrium and the final equilibrium fraction therefore require further elucidation.

YEARLA et al.[88] used nanoprecipitation method to load dichlorvos drug on *Thiobacillus* lignin as a matrix and optimized it to prepare a stable herbicide "diuron nano formulation" (ODNF). The bio-efficacy of ODNF release was tested with rapeseed. Compared with rapeseed seedlings grown in soil without ODNF, rapeseed seedlings grown in soil with ODNF showed signs of leaf chlorosis and death, as shown in Fig. 7b, showing the great potential of lignin as a pesticide controlled-release nano formulation in reducing the harmful effects of herbicides. Among them, BD is herbicide; CDF is a commercial insecticide.

WANG Suya[89] used alkali lignin (AL) as raw material, and obtained sulfonated alkali lignin (SAL) with different sulfonic acid group contents by sulfomethylation method, and grafted polyoxyethylene (PEG) chain on the hydroxyl group of SAL to prepare SAL-PEG with good water solubility, different degrees of cross-linking, and different relative molecular weights. At the same time, SAL-PEG and polyethyleneimine (PEI) were used as wall materials to wrap AVM to successfully prepare drug-loaded microcapsules (SAL-PEG/PEI AVM-CS), as shown in Fig. 7c. After testing, the microcapsules have reached the level of commercial AVM capsules, and at the same time provided a certain theoretical basis for the commercial high-value utilization of lignin.

Table 1 Lignin-based materials used for the entrapment of active substances

Material	Active substance	Encapsulation rate/%	Type	Reference
Wheat straw alkali lignin	Budesonide	35	Respiratory system drug	[92]
Kraft lignin	Sorafenib and benzazulene	68 and 77	Antitumor, cancer drug	[84]
Alkali lignin	Gatifloxacin and doxorubicin hydrochloride	37 and 90	Anticancer, antibacterial drug	[93]
Alkali lignin	Resveratrol	<95	Anti-inflammatory, anticancer and cardiovascular protective drug	[94]
Alkali lignin	Ibuprofen	74	Analgesic and anti-inflammatory drug	[82]
Spruce lignin, organosolv lignin	Atrazine	<78	Agricultural herbicide	[95]
Phenolated alkali lignin	Avermectin	>90	Broad-spectrum insecticide	[96]
Sodium lignosulfonate	Abscisic acid	90	Plant growth hormone	[97]
Thiobacillus lignin	Diuron	74	Agricultural herbicide	[88]
Alkyl chain-coupled lignosulfonate	Avermectin	50	Broad-spectrum insecticide	[20]
Organosolv lignin	Tyrosinase	69	Oxidase	[98]
Kraft lignin	Lipase, cutinase	96	Catalytic, hydrolase	[99]

In summary, lignin is a commonly used microcapsule material for constructing carrier drugs. Because lignin particles not only have the general properties of nanoparticles, but also have antibacterial, antioxidant, biodegradable, and non-cytotoxic characteristics. In addition, the functional groups on lignin molecules make it possible to functionalize nano-lignin. Therefore, it can be used in different drug-loading fields according to the properties of lignin itself, as shown in Table 1.

In the field of biomedicine, lignin-based drug-loaded microcapsules have the characteristics of large specific surface area and easy structure modification, and have good application prospects in drug delivery and tracing, and also have certain research value in drug catalytic loading[90]. When lignin is used as a pesticide microcapsule wall material, the three-dimensional network hydrophobic structure has a large specific surface area, which is easy to attach to the surface of insecticides and auxins, and use the interaction between groups to avoid the

aggregation and precipitation of pesticide particles. Its absorption of ultraviolet rays can stabilize oxygen-sensitive or photosensitive drugs[91]. In addition to being used in medicine and pesticides, lignin microcapsules also have significant application potential in microbiology and industrial applications, such as sensory/protective environmental materials, enzyme or cell synthesis materials[91].

5 Conclusion and prospect

Strengthening the research on high-value utilization of lignin, innovating the development of lignin-based new material industry, and reducing the consumption of fossil energy are important means to achieve China's carbon neutrality goal. As a natural polymer material, lignin has the advantages of green environmental protection, cheap and easy to obtain, and high biodegradability. At the same time, combined with the source and structural characteristics of lignin raw materials, it can be applied to the field of nano-drug loading through different functional designs. The preparation of functional drug-loaded microcapsules using lignin as a carrier has its own unique advantages, for example: the aromatic ring structure in lignin molecules has potential compatibility with hydrophobic drugs, which is conducive to loading or coating drugs; the polyphenol structure and chromophore groups in lignin molecules are conducive to improving the light stability of drug-loaded materials; lignin molecules can undergo a variety of chemical modifications to improve the adhesion, hydrophobicity, and light stability of lignin, which can expand its application in functional drug-loaded materials. From the research progress of lignin-based drug-loaded microcapsules, it can be clearly seen that the richness of functional lignin-based drug materials, preparation processes, and application fields, the diversity of drug-loaded particle shape, structure, and size, and the importance of multidisciplinary intersection of chemistry, materials science, biomedicine, and agronomy.

Although lignin has obvious advantages in drug loading and controlled release, it also faces many challenges at present. Research on the binding mechanism of lignin materials and core drugs, and the evaluation of anti-photodegradation and controlled release durability of microcapsules are still in their infancy. Therefore, in the preparation of drug-loaded microcapsules and drug controlled release applications, there are still some problems that need to be solved urgently: (1) Although lignin has shown good potential in biomedical and agronomic applications, its broad relative molecular weight distribution and extremely complex molecular structure have brought huge obstacles to its in-depth research, standardization, and large-scale production. By accurate fractionation and detailed structural characterization of lignin, and selecting uniform lignin molecules to prepare lignin-based functional materials, this obstacle can be effectively solved. Therefore, the chemistry and processing technology of lignin still need continuous development; (2) At present, the research on lignin-based drug-loaded microcapsules is mainly in the laboratory stage, and has not been scaled up. At the same time, there are problems such as complex preparation processes and low microcapsule yield, which are far from practical application. It is still necessary to explore mature technologies that are easy to prepare, easy to scale up, and multifunctional, reduce the production cost of microcapsules, and improve the competitiveness of drug-loaded microcapsules; (3) The encapsulation rate and drug loading rate of lignin-based drug-loaded microcapsules need to be improved compared with commercial microcapsules. Whether the release conditions are consistent with actual production applications needs further investigation. It is necessary to further improve the stability of encapsulation and controlled release of lignin-based drug-loaded microcapsules; (4) The current deployment of lignin-based drug-loaded microcapsules remains largely confined to agrochemical sectors—namely insecticides, herbicides and plant-growth regulators—while their utilisation for in vivo pharmaceutical delivery is still scarce. Future efforts should therefore diversify their scope, for instance by engineering intelligent, stimuli-responsive lignin vehicles capable of targeted cargo release for precision management of diseases, pest infestations and cancer therapy. (5) Standardisation frameworks for lignin-based microcapsule research remain underdeveloped. Harmonised assessment protocols covering architectural features, morphological attributes, dimensional parameters, functional performance and release longevity must be established to foster the structured, sustainable maturation of this technology within the bio-based materials sector.

References

[1] BOLLHORST T, REZWAN K, MAAS M. Colloidal capsules: Nano- and microcapsules with colloidal particle shells[J]. Chemical Society Reviews, 2017, 46(8): 2091-2126.

[2] PENG W W, YAN X X. Preparation of tung oil microcapsule and its effect on wood surface coating[J]. Polymers (Basel), 2022, 14(8): 1536.
[3] WONG C Y, AL-SALAMI H, DASS C R. Microparticles, microcapsules and microspheres: A review of recent developments and prospects for oral delivery of insulin[J]. International Journal of Pharmaceutics, 2018, 537(1): 223-244.
[4] CHENG J L, ZHANG J D, LIANG M M, et al. Preparation and characterization of pyriproxyfen-ethyl cellulose microcapsule[J]. Agrochemicals, 2021, (12): 882-886.
[5] DU G H, HU J F, ZHOU J H, et al. The study on the mechanical properties of PU/MF double shell self-healing microcapsules[J]. Chinese Journal of Chemical Engineering, 2020, 28(5): 1459-1473.
[6] YOO Y, MARTINEZ C, YOUNGBLOOD J P. Sustained dye release using poly(urea-urethane)/cellulose nanocrystal composite microcapsules[J]. Langmuir: The ACS Journal of Surfaces and Colloids, 2017, 33(6): 1521-1532.
[7] OU M H, ZHANG Y D, LUO X G, et al. Fabrication of electrostatic self-assembly chitosan hollow microcapsules and study of its loading and releasing properties[J]. Chemical Industry and Engineering Progress, 2017, 36(5): 1848-1854.
[8] ABULATEEFEH S R, ALKAWAREEK M Y, ALKILANY A M. Tunable sustained release drug delivery system based on mononuclear aqueous core-polymer shell microcapsules[J]. International Journal of Pharmaceutics, 2019, 558: 291-298.
[9] LIANG B, SHAO J P, YANG S, et al. Preparation and slow release properties of camellia oil microcapsules[J]. Fine Chemicals, 2020, 37(12): 2541-2553.
[10] BAH M G, BILAL H M, WANG J. Fabrication and application of complex microcapsules: A review[J]. Soft Matter, 2020, 16(3): 570-590.
[11] MENG Q Y, ZHONG S L, WANG J, et al. Advances in chitosan-based microcapsules and their applications[J]. Carbohydrate Polymers, 2023, 300: 120265.
[12] LI Z J, XIONG Y M, LIU Y S, et al. Study on the preparation of sweet orange oil nanocapsules by complex coacervation[J]. Journal of Light Industry, 2022, 37(2): 44-50.
[13] LI J, CHENG M M, MENG Y J, et al. Research status of the preparation of microcapsule via Pickering emulsion template stabilized by cellulose nanocrystals[J]. Chemical Research, 2021, 32(2): 183-188.
[14] PANG Y X, SUN Y N, LUO Y L, et al. Preparation of novel all-lignin microcapsules via interfacial cross-linking of Pickering emulsion[J]. Industrial Crops and Products, 2021, 167: 113468.
[15] JIANG T D. Lignin[M]. Beijing: Chemical Industry Press, 2009.
[16] HUANG Y M, HU Q, CUI G Q, et al. Release-controlled microcapsules of thiamethoxam encapsulated in beeswax and their application in field[J]. Journal of Environmental Science and Health, Part B, 2020, 55(4): 342-254.
[17] SHI R F, LUO Q P, HUANG J M, et al. Research progress on preparation and application of microcapsules[J]. Guangzhou Chemical Industry, 2022, 50(14): 17-20.
[18] GRAY A, EGAN S, BAKALIS S, et al. Determination of microcapsule physicochemical, structural, and mechanical properties[J]. Particuology, 2016, 24: 32-43.
[19] PICCININO D, CAPECCHI E, BOTTA L, et al. Layer-by-layer preparation of microcapsules and nanocapsules of mixed polyphenols with high antioxidant and UV-shielding properties[J]. Biomacromolecules, 2018, 19(9): 3883-3893.
[20] LIU Z Q, QIE R T, LI W, et al. Preparation of avermectin microcapsules with anti-photodegradation and slow-release by the assembly of lignin derivatives[J]. New Journal of Chemistry, 2017, 41(8): 3190-3195.
[21] RAO J, CHANDRANI A N, POWAR A, et al. Release behavior of oxyfluorfen polyurea capsules prepared using PVA and kraft lignin as emulsifying agents and phytotoxicity study on paddy[J]. Green Chemistry Letters and Reviews, 2021, 14(2): 204-220.
[22] ZHANG A C, WU X W, OUYANG X P, et al. Preparation of light-colored lignosulfonate sunscreen microcapsules with strengthened UV-blocking and adhesion performance[J]. ACS Sustainable Chemistry & Engineering, 2022, 10(29): 9381-9388.
[23] WU C C, XU J F, HAN W S, et al. Application of lignin in preparation of slow/controlled-release fertilizer[J]. Modern Agricultural Science and Technology, 2021, (6): 176-182.
[24] CHEN J T, WANG M, QIAN Y, et al. Ultrasonic cavitation driven fabrication of organic solvent free lignin/prochloraz nano capsules to promote resistance to photolysis and rain wash, and provide extended release performance[J]. Holzforschung, 2021, 75(9): 869-877.
[25] LAHIVE C W, DEUSS P J, LANCEFIELD C S, et al. Advanced model compounds for understanding

acid-catalyzed lignin depolymerization: Identification of renewable aromatics and a lignin-derived solvent[J]. Journal of the American Chemical Society, 2016, 138(28): 8900-8911.

[26] WANG H L, PU Y Q, RAGAUSKAS A, et al. From lignin to valuable products-strategies, challenges, and prospects[J]. Bioresource Technology, 2019, 271: 449-461.

[27] MANSOURI N E E, SALVAD J. Structural characterization of technical lignins for the production of adhesives: Application to lignosulfonate, kraft, soda-anthraquinone, organosolv and ethanol process lignins[J]. Industrial Crops and Products, 2006, 24(1): 8-16.

[28] CAO L C, YU I K M, LIU Y Y, et al. Lignin valorization for the production of renewable chemicals: State-of-the-art review and future prospects[J]. Bioresource Technology, 2018, 269: 465-475.

[29] MA H Z, FU P L, ZHAO J H, et al. Pretreatment of wheat straw lignocelluloses by deep eutectic solvent for lignin extraction[J]. Molecules, 2022, 27(22): 7955.

[30] ZHOU Y H, ZHANG X H, XIONG W M. Research progress of preparation of aromatic aldehydes

[31] ZEVALLOS TORRES L A, LORENCI WOICIECHOWSKI A, DE ANDRADE TANOBE V O, et al. Lignin as a potential source of high-added value compounds: A review[J]. Journal of Cleaner Production, 2020, 263: 121499.

[32] GAO X, MA Y J, YANG A Y, et al. Research progress in extraction and application of lignin[J]. Liaoning Chemical Industry, 2021, 50(1): 38-41, 45.

[33] LUO T, LYU G J, WANG C, et al. Modification of industrial lignin and its application in composite materials: A review[J]. China Pulp & Paper, 2020, 39(9): 60-67.

[34] LIU C, LI Y, ZHUANG J S, et al. Conductive hydrogels based on industrial lignin: Opportunities and challenges[J]. Polymers, 2022, 14(18): 3739.

[35] FIGUEIREDO P, LINTINEN K, HIRVONEN J T, et al. Properties and chemical modifications of lignin: Towards lignin-based nanomaterials for biomedical applications[J]. Progress in Materials Science, 2018, 93: 233-269.

[36] HUANG C X, HE J, LIANG C, et al. Progress in applications of high value-added lignin materials[J]. Journal of Forestry Engineering, 2019, 4(1): 17-26.

[37] WEI W. Cellulose solvent-based lignocellulose pretreatments and its enzymatic saccharification[D]. Zhenjiang: Jiangsu University, 2017.

[38] ZHU J D, YAN C Y, ZHANG X, et al. A sustainable platform of lignin: From bioresources to materials and their applications in rechargeable batteries and supercapacitors[J]. Progress in Energy and Combustion Science, 2020, 76: 100788.

[39] TU H F. The effect of different pretreatment methods on enzymatic hydrolysis of different cellulosic materials[D]. Wuhan: Hubei University of Technology, 2016.

[40] SCHORR D, DIOUF P N, STEVANOVIC T. Evaluation of industrial lignins for biocomposites production[J]. Industrial Crops and Products, 2014, 52: 65-73.

[41] WANG X H, ZHAO Q. Application of lignin from pulping black liquor in agriculture[J]. Biomass Chemical Engineering, 2004, (2): 36-40.

[42] GARCIAMC, DIEZJA, VALLEJO A, et al. Use of kraft pine lignin in controlled-release fertilizer formulations[J]. Industrial & Engineering Chemistry Research, 1996, 35: 245-249.

[43] VERDINI F, GAUDINO E C, CANOVA E, et al. Lignin as a natural carrier for the efficient delivery of bioactive compounds: From waste to health[J]. Molecules, 2022, 27(11): 3598.

[44] BEISL S, FRIEDL A, MILTNER A. Lignin from micro- to nanosize: Applications[J]. International Journal of Molecular Sciences, 2017, 18(11): 2367.

[45] WIJAYA C J, ISMADJI S, GUNAWAN S. A review of lignocellulosic-derived nanoparticles for drug delivery applications: Lignin nanoparticles, xylan nanoparticles, and cellulose nanocrystals[J]. Molecules, 2021, 26(3): 676.

[46] JIANG Y, WANG Z H, ZHOU L, et al. Highly efficient and selective modification of lignin towards optically designable and multifunctional lignocellulose nanopaper for green light-management applications[J]. International Journal of Biological Macromolecules, 2022, 206: 264-276.

[47] PAULSSON M, PARKAS J. Review: Light-induced yellowing of lignocellulosic pulps-Mechanisms and preventive methods[J]. Bioresources, 2012, 7(4): 5995-6040.

[48] AADIL K R, BARAPATRE A, SAHU S, et al. Free radical scavenging activity and reducing power of Acacia nilotica wood lignin[J]. International Journal of Biological Macromolecules, 2014, 67: 220-227.

[49] CHEN B, WANG Z K, ZHANG M, et al. Research progress of microcapsule wall material[J]. Phosphate & Compound Fertilizer, 2020, 35(8): 50-52.

[50] SUDARMOYO, SWADESI B, ANDINI A N, et al. Laboratory study: The development of a sodium lignosulfonate (SLS) surfactant formulation for light oil reservoir to improve oil recovery[J]. AIP Conference

Proceedings, 2018, 1977(1): 030033.
[51] HUANG Y M, LI X Y, XIONG Q P, et al. Preparation and insecticidal activity evaluation of emamectin-Lignin sulfonic acid conjugate with antiphotolysis property[J]. ACS Omega, 2022, 7(33): 29046-29053.
[52] GUO M H, BAI L L, SHEN T W, et al. Research advance in chitosan/lignin composite[J]. World Forestry Research, 2016, 29(5): 33-36.
[53] CAO J A, WANG J P, XU Y L, et al. Application of natural biodegradable polymer wall materials in Micro-capsules[J]. Materials Reports, 2023, (18): 1-36.
[54] LI X, WANG Y B, WANG B J, et al. Antibacterial phase change microcapsules obtained with lignin as the Pickering stabilizer and the reducing agent for silver[J]. International Journal of Biological Macromolecules, 2020, 144: 624-631.
[55] FERRAZ A, SOUZA J A, SILVA F T, et al. Controlled release of 2,4-D from granule matrix formulations based on six lignins[J]. Journal of Agricultural and Food Chemistry, 1997, 45(3): 1001-1005.
[56] RAHDAR A, SARGAZI S, BARANI M, et al. Lignin-stabilized doxorubicin microemulsions: Synthesis, physical characterization, and in vitro assessments[J]. Polymers, 2021, 13(4): 641.
[57] ZHOU B, ZHAO J. Microencapsulation and Release kinetics of abamectin by layer-by-layer polelectrolyte self-assembly[J]. Fine Chemicals, 2008, (7): 625-627, 635.
[58] WANG M, ZHAO Y D, LI J B. From hollow lignin microsphere preparation to simultaneous preparation of urea encapsulation for controlled release using industrial kraft lignin via slow and exhaustive acetone-water evaporation[J]. Holzforschung, 2020, 74(1): 77-87.
[59] WANG X J. Preparation and properties of chitosan/sodium lignosulfonate microcapsules formulated by layer-by-layer self-assembly[D]. Beijing: Beijing University of Chemical Technology, 2013.
[60] LUO Y L. Application of lignin particles in the preparation of Pickering emulsions and microcapsules[D]. Guangzhou: South China University of Technology, 2019.
[61] WANG R Z, SONG L M, LIU P, et al. Study of lignin-based surfactant[J]. Biomass Chemical Engineering, 2020, 54(3): 61-68.
[62] WU W J, YI Y G, WANG C, et al. Research progress on application of lignin in asphalt[J]. Transactions of China Pulp and Paper, 2017, 32(4): 60-65.
[63] WANG S W. Preparation of lignin/sodium dodecyl sulfate composite nanoparticles and their application in microcapsules[D]. Guangzhou: South China University of Technology, 2018.
[64] YIAMSAWAS D, BAIER G, THINES E, et al. Biodegradable lignin nanocontainers[J]. RSC Advances, 2014, 4(23): 11661-11663.
[65] AGO M, HUAN S Q, BORGHEI M, et al. High-throughput synthesis of lignin particles (30 nm to 2 μm) via aerosol flow reactor: Size fractionation and utilization in Pickering emulsions[J]. ACS Applied Materials & Interfaces, 2016, 8(35): 23302-23310.
[66] SCHIEPPATI D, DREUX A, GAO W J, et al. Ultrasound-assisted carboxymethylation of LignoForce kraft lignin to produce biodispersants[J]. Journal of Cleaner Production, 2022, 366: 132776.
[67] CHEN N S, DEMPERE L A, TONG Z. Synthesis of pH-responsive lignin-based nanocapsules for controlled release of hydrophobic molecules[J]. ACS Sustainable Chemistry & Engineering, 2016, 4: 5204-5211.
[68] TORTORA M, CAVALIERI F, MOSESSO P, et al. Ultrasound driven assembly of lignin into microcapsules for storage and delivery of hydrophobic molecules[J]. Biomacromolecules, 2014, 15(5): 1634-1643.
[69] TAN S Y. Preparation of prochloraz/lignin microcapsules by ultrasonic cavitation and their application performance exploration[D]. Guangzhou: South China University of Technology, 2019.
[70] PIOMBINO C, LANGE H, SABUZI F, et al. Lignosulfonate microcapsules for delivery and controlled release of thymol and derivatives[J]. Molecules, 2020, 25(4): 866.
[71] ZHANG Q, DING W, YANG Z X, et al. The development and application of self-assembly[J]. Applied Chemical Industry, 2017, 46(3): 555-558.
[72] BARTZOKA E D, LANGE H, THIEL K, et al. Coordination complexes and one-step assembly of lignin for versatile nanocapsule engineering[J]. ACS Sustainable Chemistry & Engineering, 2016, 4(10): 5194-5203.
[73] LI Y X, ZHOU M S, PANG Y X, et al. Lignin-based microsphere: Preparation and performance on encapsulating the pesticide avermectin[J]. ACS Sustainable Chemistry & Engineering, 2017, 5(4): 3321-3328.
[74] ZHOU M S, WANG W L, YANG D J, et al. Preparation of a new lignin-based anionic/cationic surfactant and its solution behaviour[J]. RSC Advances, 2015, 5(4): 2441-2448.
[75] DENG Y H, LIU Y F, ZHANG W J, et al. Formation of colloidal spheres from a lignin-based azo polymer[J]. Acta Physico-Chimica Sinica, 2015, 31(3): 505-511.
[76] GENG L, PAN Y L, CHEN L F, et al. Investigated on the emulsification influenced by emulsifier[J]. DEStech

Transactions on Engineering and Technology Research, 2017, 2(19): 396-403.
[77] LI A, PENG K D, FENG W, et al. Optimization of process parameters on the preparation of nutritional oil nano-emulsion for infant formula using ultrasound[J]. Journal of the Chinese Cereals and Oils, 2017, 32(3): 110-117.
[78] TANG Q Q, ZHOU M S, QIU X Q, et al. Effects of cationic cetyltrimethylammonium bromide on the aggregation behavior of sodium lignosulfonate (NaLS) in concentrated solutions and preparation of uniform lignosulfonate-based colloidal spheres[J]. Journal of Agricultural and Food Chemistry, 2020, 68(35): 9451-9460.
[79] GAGOSIAN V S C, CLARO F C, SCHWARZER A C D A P, et al. The potential use of kraft lignins as natural ingredients for cosmetics: Evaluating their photoprotective activity and skin irritation potential[J]. International Journal of Biological Macromolecules, 2022, 222: 2535-2544.
[80] CHEN J S, AN L L, BAE J H, et al. Green and facile synthesis of aminated lignin-silver complex and its antibacterial activity[J]. Industrial Crops and Products, 2021, 173: 114102.
[81] KIM S, FERNANDES M M, MATAMA T, et al. Chitosan-lignosulfonates sono-chemically prepared nanoparticles: Characterisation and potential applications[J]. Colloids and Surfaces B: Biointerfaces, 2013, 103: 1-8.
[82] LI Y Y, QIU X Q, QIAN Y, et al. pH-responsive lignin-based complex micelles: Preparation, characterization and application in oral drug delivery[J]. Chemical Engineering Journal, 2017, 327: 1176-1183.
[83] RASCHIP I E, HITRUC E G, OPREA A M, et al. In vitro evaluation of the mixed xanthan/lignin hydrogels as vanillin carriers[J]. Journal of Molecular Structure, 2011, 1003(1): 67-74.
[84] FIGUEIREDO P, LINTINEN K, KIRIAZIS A, et al. In vitro evaluation of biodegradable lignin-based nanoparticles for drug delivery and enhanced antiproliferation effect in cancer cells[J]. Biomaterials, 2017, 121: 97-108.
[85] AZADI P, INDERWILDI O R, FARNOOD R, et al. Liquid fuels, hydrogen and chemicals from lignin: A critical review[J]. Renewable and Sustainable Energy Reviews, 2013, 21: 506-523.
[86] LU J J, CHENG M Y, ZHAO C, et al. Application of lignin in preparation of slow-release fertilizer: Current status and future perspectives[J]. Industrial Crops and Products, 2022, 176: 114267.
[87] YIAMSAWAS D, BAIER G, THINES E, et al. Biodegradable lignin nanocontainers[J]. RSC Advances, 2014, 4(23): 11661-11663.
[88] ase agrochemical nanoformulations: A case study with herbicide diuron[J]. Environmental Science and Pollution Research, 2016, 23(18): 18085-18098.
[89] WANG S Y. Solution behavior of sulfonated alkali lignin polyethenoxy ether and its applications in two pesticide formulations[D]. Guangzhou: South China University of Technology, 2016.
[90] ZHOU Y. Structural regulation of enzymatic hydrolysis lignin-based hollow nanoparticles and its drug carrying ability[D]. Chinese Academy of Forestry, 2019.
[91] SIPPONEN M H, LANGE H, CRESTINI C, et al. Lignin for nano- and microscaled carrier systems: Applications, trends, and challenges[J]. ChemSusChem, 2019, 12(10): 2039-2054.
[92] SIPPONEN M H, LANGE H, AGO M, et al. Understanding lignin aggregation processes. A case study: Budesonide entrapment and stimuli controlled release from lignin nanoparticles[J]. ACS Sustainable Chemistry & Engineering, 2018, 6(7): 9342-9351.
[93] CHEN L, ZHOU X, SHI Y, et al. Green synthesis of lignin nanoparticle in aqueous hydrotropic solution toward broadening the window for its processing and application[J]. Chemical Engineering Journal, 2018, 346: 217-225.
[94] DAI L, LIU R, HU L Q, et al. Lignin nanoparticle as a novel green carrier for the efficient delivery of resveratrol[J]. ACS Sustainable Chemistry & Engineering, 2017, 5(9): 8241-8249.
[95] TAVERNA M E, BUSATTO C A, LESCANO M R, et al. Microparticles based on ionic and organosolv lignins for the controlled release of atrazine[J]. Journal of Hazardous Materials, 2018, 359: 139-147.
[96] YU X N, CHEN S S, WANG W C, et al. Empowering alkali lignin with high performance in Pickering emulsion by selective phenolation for the protection and controlled-release of agrochemical[J]. Journal of Cleaner Production, 2022, 339: 130769.
[97] WANG J, FAN Y X, WANG H L, et al. Promoting efficacy and environmental safety of photosensitive agrochemical stabilizer via lignin/surfactant coacervates[J]. Chemical Engineering Journal, 2022, 430: 132920.
[98] CAPECCHI E, PICCININO D, DELFINO I, et al. Functionalized tyrosinase-lignin nanoparticles as sustainable catalysts for the oxidation of phenols[J]. Nanomaterials, 2018, 8(6): 438.
[99] SIPPONEN M H, FAROOQ M, KOIVISTO J, et al. Spatially confined lignin nanospheres for biocatalytic ester

synthesis in aqueous media[J]. Nature Communications, 2018, 9(1): 1-7.