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Application of Chiral Nanomaterials in Plant Disease Control: Mechanisms, Progress and Prospects

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Abstract. Chiral nanomaterials are novel functional materials formed by the intersection of chiral chemistry and nanomaterial science. They possess both the stereoselectivity unique to chiral structures and the size effect of nanomaterials, and can achieve precise targeting functions through specific recognition with chiral macromolecules in biological systems. Relying on the characteristics of high targeting and environmental friendliness, they provide new ideas and directions for the prevention and control of plant diseases. Chiral nanomaterials can significantly improve the dispersibility, stability and biological activity of drug-loading systems, and show important application potential in overcoming the functional defects of traditional pesticide formulations, improving the effective utilization rate of pesticides, reducing ecological and environmental risks and other aspects. Taking the control of soybean diseases by chiral nanomaterials as the starting point, this paper systematically elaborates the action mechanism of chiral nanomaterials in plant disease prevention and control, focuses on discussing their application potential and existing bottlenecks in the control of viral diseases of major crops such as soybeans, and hopes to provide certain theoretical references for the research and development of new green pesticides.

Keywords: Chiral nanomaterials, Antiviral agents, Induced resistance, Targeted delivery, Green pesticides, Soybean viral diseases

1. Introduction

Traditional agricultural crops can be used as the main food source for domestic circulation or export, and also as livestock feed and industrial raw materials. Their quality and yield are key indicators to measure the level of agricultural production. As one of the important factors affecting grain yield, plant disease control has long been a key concern for China, a major grain-producing country. There are a great variety of plant diseases with an extremely wide range of involvement, and crop yield reduction caused by disease outbreaks is very common. Taking soybean as an example, it is an important food crop in China, and diseases and insect pests cause a 15%~30% yield loss of soybeans every year [1], and even total crop failure occurs in areas with severe disease outbreaks. Viral diseases are important factors limiting the improvement of soybean yield and quality, directly threatening the sustainable development of the global soybean industry. With the continuous expansion of soybean planting scale, the popularization and application of multiple planting modes, and the changes in cultivation environments such as temperature, humidity and light, the occurrence frequency and types of soybean diseases have increased significantly. In other words, the pathogens of soybean diseases are diverse [1], and the compound infection of multiple diseases occurs frequently, which seriously affects the safety and economic benefits of soybean production. At present, chemical pesticides are still the main means for the control of soybean diseases. However, the drug-loaded particles of traditional pesticide formulations have relatively large particle sizes, low effective utilization rate and large application rate, which usually cause irreversible serious harm to the ecological environment. Therefore, the research and development of new pollution-free and fast-acting green pesticides has become an important research direction in the field of plant disease control. More than 100 plant viruses are known to infect soybeans, among which about 50 can actually infect soybeans in nature [2]. These viruses have caused great harm to China's soybean industry, and even total crop failure occurs in severely affected areas. In recent years, more and more novel studies have been conducted on the use of nanomaterials as plant agents to control plant diseases. For example, nano-Fe_2O_3 can mediate soybeans to develop resistance to root rot and reconstruct the rhizosphere microbial community of soybeans [3]. The relevant research results have laid a solid foundation for the application of nano-agents in the field of plant virus-induced resistance. At the same time, nano-agents also have a good theoretical basis in the field of drone pesticide application [4], and possess promising application prospects in plant virus-induced resistance.

2. Mechanisms of viral damage to plants

2.1. Transmission mode

Soybean mosaic virus (SMV) is a common plant virus, which is mainly transmitted through soybean seeds or mechanical damage on the surface of plants. Seed transmission means that SMV can be stored in the nutritional part of seeds, and soybean plants grown from sown seeds in the next year will directly become infected plants. Mechanical damage transmission is mainly that aphids feed on SMV-infected plants and carry the virus through flight migration, artificial transportation and other ways, thus completing the spread of the virus.

2.2. SMV pathogen characteristics

Soybean mosaic virus belongs to the Potyvirus group. After plant infection, the virus particles are distributed in the nucleus and cytoplasm in linear form. The inactivation temperature of the virus is 55~60 ℃, and its in vitro stability is relatively poor. It can only survive for 1~4 days at room temperature, and the survival time can be extended to 120 days at 4 ℃. SMV has many different strains, and there are significant differences in pathogenicity among different strains and infection stability under low-temperature preservation conditions. Its infectivity is very sensitive to preservation temperature; the universality of preservation at -40 ℃ is very poor, while ultra-low temperature at -80℃ and liquid nitrogen environment at -196℃ can maintain its high infectivity for a long time. After 15 months of preservation, the virus incidence rate and disease index can still reach more than 90.0% and 75.0% respectively [5].

Table 1. Stability indicators of soybean mosaic virus (SMV) under different storage conditions

Storage Conditions	Survival Duration	Virus Infection Stability	Incidence Rate After 15 Months (%)	Disease Index After 15 Months	Practical Application Value
Room Temperature (25°C)	1~4 d	Extremely Poor	—	—	None
4°C	120 d	Poor	—	—	Short-term Storage
-40°C	Several Months	General	<50.0	<40.0	Medium-term Storage
-80°C	Long-term	Excellent	≥90.0	≥75.0	Long-term Storage
-196°C (Liquid Nitrogen)	Long-term	Optimal	≥90.0	≥75.0	Virus Preservation for Scientific Research

2.3. Disease symptoms

Affected by multiple factors such as soybean varieties and external environment, the individual performance of plants after SMV infection varies greatly. After infecting Hefeng 25 soybean, SMV mainly shows four typical symptoms: mosaic, blister-like protrusion, dwarfing and top necrosis. Mosaic-type plants have slightly uneven leaves with obvious yellow-green mottling, and the overall growth state of the plants is basically normal; blister-like protrusion-type leaves are uneven, dark green with yellow-green mottling; dwarfing-type plants are generally short with shortened internodes, narrow and stiff leaves, and yellow-green mottling and yellow-brown spots; top necrosis is a severe disease symptom, in which the terminal buds gradually yellow and necrose, upper leaves chlorosis and lower leaves die. The diseased leaves are thick, stiff and dark green. The severity of symptoms increases step by step in the order of mosaic, blister-like protrusion to dwarfing and top necrosis, and severe symptoms lead to stagnant plant growth and even death [6]. Seeds produced by plants infected with SMV may have seed coat pigmentation, showing different colors such as black, brown and white spots [7]. It should be noted that the color of seeds is also affected by environmental factors and cannot be used as a marker to judge whether seeds carry the virus.

3. Chiral nanomaterials

3.1. Latest research progress and application examples

Chiral nanomaterials have developed rapidly in recent years. The high specific surface area, unique interface effect and targeted delivery capability brought by the nanoscale have made them a core research direction for the green upgrading of pesticide formulations and sustainable agricultural development. Relevant research has evolved from the early simple nanonization of active ingredients to a diversified system integrating slow-release technology and intelligent carrier design [8].

With their unique physical and chemical properties and action mechanisms, nano-pesticides show targeted application value in soybean production and provide a new technical path for the control of soybean diseases and insect pests and the regulation of growth and development. From the existing research directions, nano-pesticide materials represented by nano-CuO, ZnO and others show significant potential in the control of soybean root rot [9], which can effectively reduce the inhibitory effect of diseases on soybean root growth. At present, nano-agents have been practically applied in many fields. The CQDs/TNTAs composite photocatalyst has a degradation rate of more than 98% for glyphosate wastewater under visible light, and has excellent cycle stability; the degradation efficiency of N-GQD/N-TiO_2/P-g-C_3N_4 nanotubes on ciprofloxacin is 7.9 times that of pure N-TiO_2, which can effectively mineralize pesticide molecules; the rGOA-nZVI/PS system has a degradation rate of more than 99% for organophosphorus pesticides such as phorate in a wide pH range; 3D cornflower-like MoS_2 nanoflowers can degrade 96.5% of neonicotinoid pesticides on tomato surfaces within 15 minutes, and retain the key aroma substances of crops themselves [10]. These application achievements and practical cases fully confirm the broad application prospects and practical feasibility of nano-agents.

3.2. Advantages compared with traditional pesticides

Although traditional pesticides once played a certain role in ensuring the supply of agricultural products in agricultural production, they are also a "double-edged sword". The negative effects caused by unreasonable use are very significant, mainly reflected in the following aspects: First, harm to human health. Traditional pesticides have a relatively high proportion of highly toxic and highly residual varieties. Producers who are exposed to such pesticides for a long time are prone to acute poisoning. Consumers ingest residual pesticides through the food chain, which accumulates in the body for a long time, may induce gene mutations, significantly increase the risk of canceration and deformity, and may also lead to chronic health problems such as nervous system disorders and decreased immunity [11]. Second, environmental pollution. The application efficiency of traditional pesticides is very low, only a small amount acts on target pests, and most of the rest enter the soil, water and atmosphere through droplet drift, rainwater scouring and other ways, forming non-point source pollution. Residual pesticides in the soil will destroy the community structure of soil microorganisms, water pollution will threaten the survival of aquatic organisms, and pesticide particles in the atmosphere can enter the human body through respiration, further expanding the scope of harm [12]. Third, hindering agricultural product trade. The international market has increasingly strict standards for pesticide residues. The problem of excessive residues caused by the abuse of traditional pesticides in China has led to frequent detention and return of exported agricultural products, increasing the cost of storage and inspection, weakening the international competitiveness of China's agricultural products, and causing huge foreign trade losses every year [13]. Fourth, exacerbating the resistance of diseases and insect pests. Irregular use of traditional pesticides such as arbitrarily increasing the concentration and application times will accelerate the development of resistance in diseases and insect pests [14], leading to a continuous decline in the control effect of pesticides, forming a vicious circle of "increasing dosage—enhanced resistance", and further aggravating the problems of pesticide residues and environmental pollution.

As a new type of material with unique physical and chemical properties, nanomaterials show significant application advantages in the field of agricultural production and have gradually penetrated into many key links of agricultural production. Their application can not only help improve crop yield and optimize quality, but also promote plant growth and development and enhance photosynthetic efficiency by regulating plant physiological metabolism. At the same time, they can also play a positive role in enhancing crop resistance to biotic and abiotic stresses, providing new ideas and technical support for the green control of diseases and insect pests and the innovative development of new resistance breeding technologies [15].

Table 2. Performance comparison between traditional pesticides and chiral nano-pesticides in disease control

Evaluation Indicators	Traditional Chemical Pesticides	Chiral Nano-pesticides	Improvement Effect
Effective Utilization Rate	<30%	>60%	Significantly Improved
Target Recognition Ability	None	Stereoselective Recognition	Accuracy Improved
Stability of Drug-loading System	Poor	Excellent	Stability Enhanced
Environmental Residue Risk	High	Low	Pollution Reduced
Resistance Induction	Easy to Occur	Not Easy to Occur	Risk Reduced
Adhesion on Crop Leaves	Weak	Strong	Duration Extended
Impact on Non-target Organisms	Relatively Large	Relatively Small	Safety Improved

4. Application and existing problems of chiral nanomaterials in disease control

4.1. Action mechanism of nano-agents

Nanomaterials have a moderate positive potential on the surface, which can effectively adsorb negatively charged virus particles or RNA, thus hindering the binding and spread of viruses to host cells [16]. SMV infection causes oxidative stress in plants, and active components with good antioxidant properties released by nanomaterials can alleviate this oxidative stress, reduce the level of reactive oxygen species (ROS) in plants, and protect the integrity of organelle structures [17].

4.2. Typical application scenarios and application effects

The application of nanotechnology in agriculture is promoting the transformation of disease and pest control from traditional spraying to precise and intelligent delivery. Both nano-formulations based on formula process improvement and nano-delivery systems based on new carrier materials show significant potential in improving pesticide utilization, reducing application rate and alleviating environmental risks.

In field practical application scenarios, nano-aqueous formulations have shown excellent performance in reducing dosage and increasing efficiency. Experiments conducted by Feng Xiaoxia and other researchers in rice fields in Huoqiu County, Anhui Province showed that the control effect of nano-pesticide aqueous formulations on major diseases and insect pests such as striped rice borer and rice planthopper was higher than that of conventional pesticide treatments and farmers' self-prevention treatments [18]. More importantly, in the three applications throughout the process, the pesticide formulation usage was reduced by 8.54% compared with conventional pesticides of the same composition, and by 16.28% compared with farmers' self-prevention areas. It also effectively solved the problem of poor compatibility of various pesticides in plant protection drone operations.

In the cutting-edge research on the construction of new functional carriers, materials such as metal-organic frameworks (MOFs) and selenium-based nanoparticles have further expanded the intelligent response boundary of nano-pesticides. For example, carriers such as ZIF-8 and MIL-101(Fe) can not only accurately release drugs in the alkaline environment of the target pest intestine or the acidic microenvironment of pathogens, but also supplement trace nutrients for plants by releasing metal ions [19]. Similarly, the selenium-chitosan nano-system (CBZ@Se-CS) constructed for peanut fusarium wilt has verified the feasibility of this design idea: relying on the pH sensitivity of chitosan, the particles achieved efficient targeted release of carbendazim under acidic conditions (pH 5.0) simulating fungal infection, with a cumulative release rate of 85% [20]. From the dosage reduction data of field trials to the controlled release mechanism of laboratory research, the application of nanomaterials in the field of pesticides provides multi-level solutions for sustainable agriculture.

4.3. Existing problems

Although nanotechnology has achieved phased results in the field of pesticide dosage reduction and efficiency enhancement, it still faces multiple technical bottlenecks and cognitive shortcomings in the transformation from laboratory research and development to large-scale field application. The contradiction between production cost and functional stability has not been reconciled. Although intelligent response carriers represented by metal-organic frameworks (MOFs) have multiple functions such as high loading rate, their mainstream synthesis routes still rely on solvothermal or microwave-assisted methods. The synthesis process involves high-purity metal salts, organic ligands and high-energy consumption steps, resulting in the cost per gram of material far exceeding the acceptable value of agricultural inputs [19]. Although nano-formulations prepared by aqueous dispersion process have completed field application verification and cost control, their performance improvement mainly relies on the increased specific surface area and improved adhesion brought by physical particle size reduction, lacking specific response ability to disease microenvironments [18].

Another important concern for pesticide application is environmental safety. There is a serious lack of long-term fate research on nanocarriers and their degradation products. Most existing field trials only focus on the yield feedback and apparent phytotoxicity of current crops, ignoring the continuous monitoring of the residual dynamics of nanoparticles in soil and water. In addition, whether the continuous oxidative stress pressure induced by nanocarriers on target organisms will accelerate the development of non-specific adaptive resistance is also a blind spot in the sustainable use evaluation of current nanomaterials.

4.4. Potential and challenges in the control of soybean mosaic virus

The control of SMV mainly relies on the breeding of disease-resistant varieties and chemical control of aphids. However, variety breeding is limited by the complex differentiation of SMV strains and easy decline of resistance, while chemical control of aphids is difficult to effectively cut off the virus transmission chain through insecticides due to the non-persistent transmission of viruses by aphids. Coupled with the extreme shortage of specific agents directly targeting viruses, the control of SMV has been in an indirect and inefficient dilemma for a long time. Although there is no effective literature support for the application of chiral nanomaterials in SMV control, its theoretical feasibility can be deduced based on the successful precedent of tobacco mosaic virus (TMV): the research team of Jiangnan University used copper sulfide nanoparticles (D-NP) modified with chiral penicillamine to stereoselectively recognize specific amino acid sequences of TMV coat protein, and site-specifically hydrolyze peptide bonds to disintegrate the virus under photoexcitation, with a virus clearance rate of more than 95% within 3 days [21]. Both SMV and TMV are linear viruses assembled with helical symmetry, and there may be structurally conservative recognizable sites in their coat proteins. This feature has valuable reference value for the application of nanomaterials in the control of SMV.

Table 3. Main mechanisms of chiral nanomaterials in controlling plant viruses

Action Pathway	Specific Mechanism	Control Effect	Ref
Electrostatic Adsorption	Adsorb Negatively Charged Virus Particles and RNA	Prevent Viruses from Adsorbing Host Cells	[16]
Antioxidant Regulation	Scavenge Reactive Oxygen Species (ROS)	Alleviate Virus-induced Oxidative Stress	[17]
Stereoselective Recognition	Specifically Bind to Viral Coat Protein	Site-selective Hydrolysis and Destruction of Viral Structure	[21]
Intelligent Controlled Release	Release Drugs in Response to Disease Microenvironment	Improve Utilization Rate and Reduce Dosage	[19] [20]
Induced Plant Resistance	Activate Plant Defense System	Enhance Overall Disease Resistance	[3] [15]

5. Conclusions and prospects

This review takes SMV as the analysis object and sorts out the action mechanism and research trends of chiral nanomaterials in plant disease control. The application of nanomaterials in the field of plant protection has gradually transitioned from the early simple physical size reduction to function-oriented carrier design, and the research focus has expanded from improving the dispersibility and adhesion of agents to environmental response controlled release, vascular transport, host resistance induction and other aspects. In this research context, the introduction of chiral nanomaterials incorporates stereoselective recognition into the functional category of nano-delivery systems, enabling them to target the spatial configuration of pathogenic biological macromolecules. This is difficult to achieve by traditional chemical pesticides and conventional nano-formulations, and also provides a more precise intervention path for plant disease control. Focusing on the control of SMV, its control dilemma largely stems from the long-term lack of direct action targets: the breeding cycle and resistance stability of disease-resistant varieties are difficult to balance, the chemical control of aphid vectors is limited by the time difference of non-persistent transmission mechanism, and most existing antiviral products are broad-spectrum resistance inducers, lacking the ability to destroy the structure of virus particles themselves. The stereoselective recognition and site-specific destruction potential of chiral nanomaterials can exactly meet this control demand. Relevant findings in tobacco mosaic virus research have initially confirmed that nanoparticles with specific chiral configurations can hydrolyze the conserved peptide bonds of coat proteins under photoexcitation, leading to the disintegration of virus particles [21]. This action mechanism indicates that with the gradual improvement of the structural information of SMV coat protein, the application scope of chiral nanomaterials has the feasibility to expand to such viruses.

At the same time, the influence of chiral structure on the leaf wetting and deposition behavior of pesticides can further improve the actual utilization rate of pesticides. Of course, the transition of chiral nanomaterials from concept verification to field practical application still needs to overcome several key nodes, including the precise analysis of the conserved structural domains of virus targets, the stability of chiral configurations in complex field environments, and the fate behavior of metal components in plant and soil systems. These issues are directly related to the practical applicability and sustainability of chiral nanomaterials in the control of SMV, and are also issues that need to be prioritized in subsequent research.

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