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Chitosan - Silica: A Hybrid Formulation to Mitigate Phytopathogens

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Plant diseases caused by fungi, bacteria and other phytopathogens significantly reduce agricultural productivity worldwide. Chemical pesticides are widely used to control plant diseases, but their excessive application leads to environmental pollution, development of resistant pathogen strains and health hazards. Therefore, eco-friendly alternatives are gaining increasing attention in sustainable agriculture. Chitosan-silica hybrid formulations have emerged as a promising strategy for plant disease management. Chitosan is a biodegradable biopolymer derived from chitin with antimicrobial and plant defense eliciting properties, while silica enhances plant resistance against biotic stresses and improves structural strength. The integration of these two components forms a hybrid material with enhanced stability, bioactivity and antimicrobial efficiency. Chitosan-silica hybrids act through direct inhibition of pathogens and stimulation of plant defense responses. Several studies have demonstrated their effectiveness against major phytopathogens such as *Ralstonia solanacearum*, *Colletotrichum gloeosporioides*, *Botrytis cinerea* and *Fusarium oxysporum*. In addition, these hybrids promote plant growth, seed germination and stress tolerance. This review summarizes the structure, synthesis, mechanisms and agricultural applications of chitosan-silica hybrid formulations in plant disease management.

Key Words: Chitosan, silica, nanocomposite, phytopathogens, plant disease management, sustainable agriculture

Introduction

Plant diseases are a major challenge in agriculture and are responsible for substantial yield losses across various crops. Pathogens such as fungi, bacteria, viruses, phytoplasma and nematodes infect plants and reduce both yield and quality of agricultural produce. Traditionally, disease management relies heavily on chemical pesticides. However, continuous use of synthetic chemicals has resulted in environmental contamination, pathogen resistance and negative impacts on human health (Riseh *et al*., 2023).

In recent years, research has focused on natural and biodegradable materials for disease management. Among these, chitosan has attracted considerable attention due to its antimicrobial properties and ability to induce plant defense responses (Muzzarelli, 1983). Similarly, silicon is recognized as a beneficial element that enhances plant resistance against pests and pathogens.

The combination of chitosan and silica in the form of hybrid formulations provides a synergistic effect that enhances antimicrobial activity and plant growth promotion. Chitosan-silica hybrid materials therefore represent an innovative and environmentally safe approach for sustainable plant disease management.

Chitosan: Structure and Properties

Chitosan is a natural linear polysaccharide composed of 2-amino-2-deoxy-β-D-glucan units derived from the deacetylation of chitin. Chitin is the second most abundant natural polymer after cellulose and is commonly found in the exoskeleton of crustaceans, insects and fungal cell walls (Pandey *et al*., 2018).

SOURCES OF CHITIN

- **Major sources include:**
  - Crustaceans such as shrimp and crab
  - Insects
  - Mollusks
  - Fungi

IMPORTANT PROPERTIES OF CHITOSAN

- **Chitosan possesses several unique characteristics that make it suitable for agricultural applications:**
  - Biodegradable and eco-friendly
  - Non-toxic and biocompatible
  - Antimicrobial activity
  - Ability to induce plant defense responses
  - Film-forming capability

Due to these properties, chitosan has been widely studied for disease control, seed treatment and plant growth promotion.

Silica and Its Role in Plant Health

Silica is primarily composed of silicon dioxide (SiO_2) and is one of the most abundant minerals in the Earth's crust. Silicon is considered a beneficial element for plant growth and stress tolerance. Silicon enhances plant resistance by strengthening plant tissues and acting as a physical barrier against pathogen penetration. It also activates plant defense mechanisms and improves physiological processes such as photosynthesis and nutrient uptake (Kumaraswamy *et al*., 2018).

FUNCTIONS OF SILICA IN PLANT

- Improves plant structural strength
- Enhances resistance to pathogens and pests
- Increases tolerance to abiotic stresses
- Improves photosynthetic efficiency
- Enhances nutrient uptake

Chitosan-Silica Hybrid Formulation

Chitosan-silica hybrids are composite materials produced by combining chitosan with silica nanoparticles. This hybridization improves the biological activity, mechanical strength and stability of the material.

Compared to individual components, the hybrid formulation exhibits improved antimicrobial activity and enhanced plant growth promoting properties (Riseh *et al*., 2023).

CHARACTERISTICS

- Eco-friendly and biodegradable
- Antimicrobial and antioxidant properties
- Improved thermal stability
- Enhanced mechanical strength
- Better compatibility with plants

Production of Chitosan-Silica Hybrid

- The synthesis of chitosan-silica hybrid materials generally involves a sol-gel process.
- **Typical preparation steps include:**

1. Preparation of silica solution using silica, ammonia and water.
2. Dissolution of chitosan in acetic acid to form chitosan solution.

3. Mixing of silica filtrate with chitosan solution.
4. Formation of hydrogel structure.
5. Treatment with hexamethyl-disiloxane solution.
6. Washing with ethanol and heptane.
7. Drying at approximately 80°C to obtain the hybrid material (Ebisike *et al*., 2020).

Mechanism of Action Against Phytopathogens

DIRECT ANTIMICROBIAL ACTIVITY

Chitosan-silica hybrid formulations directly inhibit pathogens by damaging their cellular structures. The positively charged amino groups of chitosan interact with negatively charged microbial cell membranes, resulting in increased permeability and leakage of cellular contents (Ke *et al*., 2021).

- **The hybrid material can:**
  - Disrupt fungal cell walls
  - Inhibit spore germination
  - Reduce mycelial growth
  - Interfere with bacterial cell membrane integrity

INDUCTION OF PLANT DEFENSE RESPONSES

Chitosan-silica hybrids also act as elicitors of plant immune responses. They stimulate the production of defense-related enzymes and pathogenesis-related proteins.

- **These responses include:**
  - Activation of peroxidase and polyphenol oxidase
  - Production of phenolic compounds
  - Induction of chitinase and glucanase enzymes
  - Strengthening of plant cell walls

These mechanisms enhance plant resistance against pathogen invasion.

ROLE IN SEED GERMINATION AND PLANT GROWTH

Chitosan-silica nanomaterials have been shown to improve seed germination and plant growth. Seed priming with these materials increases germination percentage and vigor index. The enhancement occurs due to increased activity of enzymes such as α-amylase and proteases, which help in the mobilization of stored nutrients (Kumaraswamy *et al*., 2018). Additionally, these materials improve photosynthetic efficiency by increasing chlorophyll content and stomatal activity.

APPLICATIONS IN DISEASE MANAGEMENT

CONTROL OF AIR-BORNE PATHOGENS

Foliar application or fruit coating with chitosan-silica hybrids effectively controls airborne pathogens and post-harvest diseases (Riseh *et al*., 2023).

CONTROL OF SOIL-BORNE PATHOGENS

The hybrid formulation has shown strong inhibitory effects against several soil-borne pathogens including:

- *Pythium aphanidermatum*
- *Phytophthora capsici*
- *Fusarium oxysporum*
- *Rhizoctonia solani*

These pathogens are responsible for major diseases such as damping-off, root rot and wilt.

MANAGEMENT

MANAGEMENT OF BACTERIAL WILT IN TOMATO

Application of chitosan and silica significantly reduced bacterial wilt caused by *Ralstonia solanacearum* in tomato plants. (Kiirika *et al*., 2013).

CONTROL OF ANTHRACNOSE IN CHILI

Combined application of chitosan and nano-silica effectively reduced anthracnose caused by *Colletotrichum gloeosporioides*, resulting in lower disease severity (Dzung *et al*., 2017)

GROWTH PROMOTION IN CHILI

Treatment with oligochitosan and nano-silica improved shoot length, fresh weight and chlorophyll content of chili plants (Nguyen *et al*., 2017)

CONTROL OF BROWN SPOT IN DRAGON FRUIT

Chitosan-silica hybrid formulations significantly reduced the severity of brown spot disease in dragon fruit plants (Tuan *et al*., 2019).

POST-HARVEST DISEASE CONTROL IN GRAPES

Chitosan-silica nanocomposites suppressed gray mold caused by *Botrytis cinerea* and reduced post-harvest losses during storage (Youssef *et al*., 2019).

ANTIFUNGAL ACTIVITY IN GUAVA

A mixture of chitosan (44.5 kDa) and nano-silica showed strong antifungal activity against pathogens isolated from guava fruits, including *Chrysosporium*, *Cladosporium*, *Aspergillus* and *Colletotrichum* species (To *et al*., 2022).

Advantages

- Eco-friendly and biodegradable
- Effective against a wide range of pathogens
- Promotes plant growth and yield
- Enhances stress tolerance
- Reduces dependence on chemical pesticides
- Improves soil health

Limitations

Despite its advantages, several challenges remain:

- High production cost
- Limited large-scale field trials
- Stability issues under extreme conditions
- Lack of farmer awareness
- Limited commercial availability

Conclusion

Chitosan-silica hybrid formulations represent an innovative and sustainable solution for plant disease management. The synergistic interaction between chitosan and silica enhances antimicrobial activity, induces plant defense mechanisms and promotes plant growth. Numerous studies have demonstrated their effectiveness against various phytopathogens in both pre-harvest and post-harvest conditions. Therefore, these hybrid materials hold great promise for reducing chemical pesticide use and supporting sustainable agricultural practices.

Future Prospects

Future research should focus on optimizing synthesis methods, reducing production costs and evaluating field-level performance of chitosan-silica hybrids. Integration of these materials with integrated disease management strategies could enhance their effectiveness. With increasing demand for sustainable agriculture, chitosan-silica hybrid formulations have significant potential as eco-friendly alternatives to conventional pesticides.

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