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Nanotechnology: A New Hope for Controlling Plant Viral Diseases

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Plant health is directly linked to global food security and farmers' livelihoods, and among the various biotic stresses affecting crops, plant viral diseases are some of the most destructive and difficult to manage. Viruses such as Tomato mosaic virus (TMV), Citrus yellow mosaic virus (CiYMV), and Banana bunchy top virus (BBTV) cause severe yield losses and quality deterioration in many economically important crops. Unlike fungal or bacterial pathogens, plant viruses cannot be controlled effectively once infection occurs, as curative chemical treatments are largely unavailable, and management mainly depends on preventive measures such as vector control and resistant varieties. In this scenario, nanotechnology has emerged as a promising and innovative approach for plant viral disease management. The integration of nanotechnology with plant virology, often referred to as nanophytovirology (Elmer & White, 2018; Wang et al., 2020), explores the use of nanoparticles for rapid virus detection, targeted delivery of antiviral agents such as dsRNA, enhancement of plant immune responses, and even direct inhibition of viral replication. Nanotechnology involves the manipulation of materials at the nanoscale (1–100 nm), where they exhibit unique physicochemical properties including high surface-area-to-volume ratio, enhanced reactivity, improved stability, and better bioavailability (Rai et al., 2014). These characteristics make nanoparticles highly suitable for precision agriculture and sustainable plant disease management, positioning nanotechnology as a new hope for controlling plant viral diseases in modern agriculture. For farmers, especially small and marginal growers, viral diseases often lead to severe economic losses because infected plants cannot be cured. The development of nanoparticle-based antiviral strategies could reduce crop losses, minimize excessive pesticide use, and improve farm sustainability.

Preparation of green synthesized metal nanoparticles

The green synthesis of nanoparticles using plant extracts is gaining attention as an eco-friendly and sustainable approach. In this method, bioactive compounds present in plant extracts act as reducing and stabilizing agents for nanoparticle formation, eliminating the need for toxic chemicals. This approach not only reduces environmental risks but also makes nanoparticle production more suitable for agricultural applications (Iravani, 2011) as shown in Fig:1

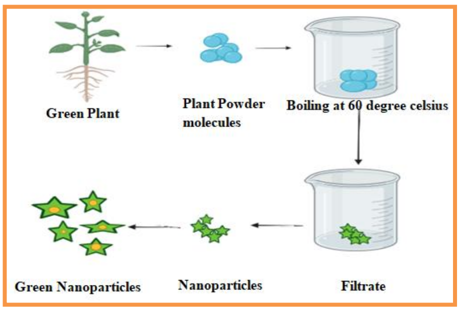

Fig 1: Preparation of green synthesized metal nanoparticles

Role of Nanoparticles in Enhancing Plant Resistance to Viral Diseases

Nanoparticles play a multifunctional role in managing plant viral diseases by directly targeting viral particles as well as indirectly strengthening host defense systems. Due to their ultra-small size and high surface-area-to-volume ratio, nanoparticles can interact efficiently with viral coat proteins, nucleic acids, and host cellular components. Several metallic nanoparticles have demonstrated strong antiviral activity against plant viruses. Among them,

- **Silver nanoparticles (AgNPs)** have been shown to attach to viral coat proteins and inhibit viral replication in plants infected with Tomato mosaic virus, thereby reducing viral load and symptom severity (Cai et al., 2019; Elbeshehy et al., 2015).
- **Zinc oxide nanoparticles (ZnO-NPs)** are known to induce the production of reactive oxygen species (ROS) at controlled levels, which activate antioxidant enzymes and trigger systemic acquired resistance (SAR), enhancing plant tolerance against viral infection (Faizan et al., 2021).
- **Silica nanoparticles** have been reported to stimulate defense-related enzymes such as peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT), which strengthen cell walls and improve stress resilience (Suriyaprabha et al., 2012).

Beyond direct antiviral effects, nanoparticles can also act as carriers for antiviral molecules such as dsRNA, ensuring targeted delivery and prolonged stability within plant tissues. Thus, nanoparticles function through multiple mechanisms including viral inhibition, defense activation, and enhanced physiological resilience, making them promising tools for sustainable plant viral disease management.

When nanoparticles are applied to plants, they initially interact with the leaf surface and enter through stomata or root tissues and subsequently translocate via apoplastic and symplastic pathways. Once internalized, nanoparticles can induce a transient burst of reactive oxygen species (ROS), which functions as a signaling mechanism activating plant defense responses (Rico et al., 2011; Dimkpa et al., 2012). This ROS-mediated signaling enhances antioxidant enzyme activities such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), strengthening cellular defense systems (Faizan et al., 2021; Suriyaprabha et al., 2012). Studies have also shown that nanoparticles modulate phytohormonal pathways including salicylic acid and jasmonic acid signaling, thereby inducing systemic acquired resistance (SAR) and improving stress tolerance (Cai et al., 2019). However, excessive nanoparticle accumulation may result in oxidative damage, membrane lipid peroxidation, chlorophyll degradation, and growth inhibition, indicating potential phytotoxic effects at higher concentrations (Rico et al., 2011; Dimkpa et al., 2012). Therefore, plant responses to nanoparticles are dose-dependent and influenced by their physicochemical properties.

Application of Nanotechnology in Plant Virus Management

Plant viruses are particularly difficult to control because they replicate within host cells and utilize the plant's own cellular machinery, rendering conventional chemical pesticides largely ineffective. Once infection is established, curative management options are extremely limited, and disease control primarily depends on preventive strategies. In recent years, nanotechnology has emerged as a promising tool in crop protection due to its precision, efficiency, and multifunctional properties (Khot et al., 2012). The unique physicochemical characteristics of nanoparticles, including their small size and high surface-area-to-volume ratio, enable them to penetrate plant tissues, move through cellular spaces, and interact with viral particles at the molecular level (Tripathi et al., 2017).

Beyond direct antiviral interactions, nanoparticles can enhance plant defense responses by modulating antioxidant enzyme activity and strengthening innate immunity. Certain nanomaterials have been reported to influence signaling pathways associated with stress tolerance and systemic resistance. Furthermore, nanoparticles can function as advanced nanocarriers for the targeted and controlled delivery of antiviral biomolecules such as double-stranded RNA (dsRNA), improving their stability, bioavailability, and persistence within plant tissues (Nuruzzaman et al., 2016).

By combining direct viral inhibition, activation of host defense mechanisms, and smart delivery systems, nanotechnology offers a more precise and environmentally sustainable strategy for managing plant viral diseases.

Table:1 Antiviral properties of potential nanoparticles

Nano particle	Size	Target virus	Host plant	Effect
Silver nano particles (AgNPs)	12.6 ± 5 nm	Tomato spotted wilt virus (TSWV)	*Solanum tuberosum*	Reduction in disease severity and TSWV concentration
Zinc oxide NPs (ZnONPs)	18 nm	Tobacco mosaic virus (TMV)	*Nicotiana benthamiana*	Suppression of speed of TMV invasion
Iron oxide NPs (Fe3O4)	15–30 nm	TMV	*Nicotiana benthamiana*	Induction of plant resistance and activation of antioxidants against TMV by upregulation of SA genes
Graphene oxide-silver NPs (GO AgNPs)	50–100 nm	Tomato bushy stunt virus (TBSV)	*Lactuca sativa*	Decrease in virus concentration, infection percentage, and disease severity

Conclusion

Nanotechnology is emerging as a promising and innovative strategy for managing plant viral diseases, which are otherwise difficult to control through conventional methods. Nanoparticles such as silver, zinc oxide, iron oxide and silica have demonstrated significant antiviral activity by directly inhibiting viral replication and by enhancing plant defense mechanisms, including antioxidant activity and systemic resistance responses. The concept of nanophytovirology highlights the growing potential of nanomaterials in virus detection, targeted delivery of antiviral agents and sustainable crop protection. Although laboratory results are encouraging, further research on biosafety, environmental impact, field level validation and regulatory frameworks is essential for large-scale agricultural application. With responsible development and interdisciplinary research, nanotechnology could play a crucial role in strengthening plant health and ensuring future food security.

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