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Original Article

Nano-Based Management of Chilli Leaf Curl Virus: A Promising Frontier in Sustainable Agriculture

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INTRODUCTION

Chilli (Capsicum spp.), a vital spice and vegetable crop grown worldwide, faces a major threat from Chilli Leaf Curl Virus (ChiLCV), a begomovirus transmitted by the whitefly Bemisia tabaci. Infected plants show upward or downward leaf curling, vein thickening, stunting, and reduced fruit set, often leading to yield losses of 30–100% depending on infection timing and severity. Traditional control relies on insecticides for vector management, rogueing infected plants, and resistant varieties, but these approaches often fall short due to insecticide resistance in whiteflies, the virus's rapid spread, and limited durable resistance. Nanotechnology is emerging as an innovative, eco-friendly solution for both early detection and direct management of ChiLCV, offering precision, reduced chemical use, and enhanced plant resilience.

Nano-Enabled Early Detection

Rapid and accurate detection forms the foundation of effective disease management. Conventional PCR methods can miss low-level infections or require lab infrastructure. Nanoparticle-based biosensors provide faster, more sensitive field-applicable alternatives (Lavanya and Arun. 2021). Researchers developed an attenuated total reflection-mediated localized surface plasmon resonance (ATR-LSPR) optical platform using aluminum nanoparticles. This detects ChiLCV DNA in small sample volumes (20–40 µL) by monitoring changes in absorbance signals, achieving high sensitivity for early viral load assessment (Das et al. 2021). Gold nanoparticles (AuNPs) functionalized with specific probes (e.g., targeting the coat protein gene of ChiLCV) enable a simple visual detection assay. In field samples from chilli and tomato, this AuNP assay outperformed PCR, detecting begomoviral infections in 77.7% of chilli samples versus 49.4% by PCR. Thiolated probes enhance specificity and versatility across related hosts. These nano-biosensors support on-site diagnostics, enabling farmers to act quickly and contain outbreaks.

Direct Antiviral Action: Nanoparticles as Virus Fighters

Nanoparticles (NPs) combat viruses through multiple mechanisms: direct interaction with viral particles (disrupting capsids or nucleic acids), induction of plant defense responses (e.g., antioxidant enzymes like SOD, POD, CAT), and interference with vector transmission. While specific studies on ChiLCV are emerging and promising results come from related geminiviruses and viruses in chilli/pepper:

- **Zinc Oxide Nanoparticles (ZnO NPs)** — Foliar application of ZnO NPs (100–150 mM) reduces disease severity and viral titers in pepper infected with begomoviruses like Pepper Huasteco Yellow Vein Virus (PHYVV). They activate plant resistance mechanisms and show direct antiviral effects (Acuna et al. 2022).

- **Titanium Dioxide Nanoparticles (TiO_2 NPs)** — In chilli pepper, TiO_2 NPs (150 µg/mL) applied foliarly reduce symptoms and viral load of Tobacco Mosaic Virus (TMV). Pre-incubation with the virus also lowers infectivity, suggesting potential against DNA viruses like ChiLCV.

- **Silver Nanoparticles (AgNPs)** — AgNPs exhibit broad antiviral properties by binding to viral proteins or generating reactive oxygen species. Studies on related pathosystems and foliar/seed applications in chilli show reduced pathogen pressure and boosted plant vigor.

Chitosan nanoparticles and nanocomposites also demonstrate strong inhibitory effects against viruses in pepper, improving yield parameters while boosting phenolic and proline content for defense (Ganainy et al. 2023).

Nanocarriers for Advanced Delivery: RNAi and Beyond

Double-stranded RNA (dsRNA) sprays can silence viral genes via RNA interference (RNAi), but naked dsRNA degrades quickly. Nanocarriers like carbon nanotubes, mesoporous silica, liposomes, or layered double hydroxides protect and deliver dsRNA efficiently into plant cells, enhancing gene silencing against viruses (Vasquez et al. 2025). This approach could target ChiLCV-specific genes (e.g., replication-associated protein) for precise, non-GM control. Combined with vector gene silencing (e.g., whitefly *hsp70*), it disrupts both virus and vector (Chakraborty et al. 2022).

Benefits and Integrated Approach

Nano-based strategies offer:

- Lower environmental impact than broad-spectrum insecticides.
- Targeted action reducing non-target effects.
- Improved plant growth and stress tolerance alongside antiviral effects.
- Scalability through green synthesis using plant extracts for cost-effective, sustainable production.

Farmers can integrate these with cultural practices (e.g., reflective mulches for vector repulsion), vector monitoring, and certified disease-free seeds for robust Integrated Disease Management (IDM) (Shingote et al. 2022).

Challenges and Future Outlook

Safety, regulatory approval, and long-term ecological impacts of NPs require careful assessment. Optimizing concentrations, application timing (often most effective post-inoculation or as preventive sprays), and combining NPs with other tools will maximize efficacy (Wargane et al. 2024). Ongoing research in nanophytovirology, including CRISPR delivery via NPs and advanced biosensors, holds immense promise. For chilli farmers battling ChiLCV, nanotechnology could transform a devastating disease into a manageable one, supporting higher yields and sustainable production in the face of climate-driven pest pressures. As this field advances, nano-enabled solutions are poised to play a key role in securing the future of chilli cultivation globally.

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