Preparation and Application of Plant-Derived Nano-Solutions in Agricultural Disease Control

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Abstract

Global demand for food and threats from plant disease require sustainable tactics for managing pests. Conventional pesticides, though efficient, are plagued with limitations such as persistence in the environment, non-target toxicity, and resistance building up. Green nano-solutions – nanomaterials made or formulated with plant extracts, biomolecules, or botanically derived substances – are an exciting alternative. These "green" nanotechnologies utilize phytochemicals (polyphenols, flavonoids, etc.) as reducing/capping agents to generate metallic or polymer nanoparticles that show strong antimicrobial potency. Nanoformulations (e.g., nanoencapsulated essential oils) can offer bioactive plant constituents with better stability and controlled release. Herein, we discuss procedures for preparing plant-source nano-pesticides (green synthesis, nanoemulsions, encapsulation, stabilization, and characterization) and list recent experimental findings on their ability to control bacterial, fungal, viral, and nematode pathogenesis. Reports indicate strong inhibition of varied pathogens (e.g., Fusarium, Botrytis, Xanthomonas) by nanoparticles made from biological processes. Mechanisms of action are membrane permeabilization, ion release, and oxidizing insult. Significantly, most of these formulations show low phytotoxicity and reduced non-target activity under assayed conditions. From a sustainable agricultural perspective, nano-pesticides made from plants offer efficient control of pests with potentially reduced chemical burden and better selectivity. Here, we discuss their merits (efficacy, biodegradability), limitations (scale-up, regulatory obstacles, incomplete toxicity), ecological concerns (accumulation, soil microbiome effect), and future prospects (sophisticated delivery with precision, field experiments, safety studies with respect to environment). Our review emphasizes that nanotechnologies from plants, compatible with circular-economy philosophy, can further bring down environmentally safe disease control, with proper assessment of their safety and long-term impact.

Keywords

Plant-derived; Nano-solutions; Green; Nanotechnology; Nano-pesticides; Sustainable Agriculture; Plant Disease Management; Green Synthesis; Nanoencapsulation.

1. Introduction

There are two strains of pressure on modern agriculture-increasing food demand and achieving environmentally sustainable practices. By 2050, world population is likely to increase to around 9–10 billion people, requiring a ~50–80% increase in crop productivity. Even today, however, yield losses from plant diseases (caused by fungi, bacteria, viruses, nematodes, and pests) average about 20–40% globally annually. Synthetic agrochemicals (fungicides, insecticides, herbicides) are extensively used for managing these pathogens, but their heavy usage has induced serious concerns.

Overuse of pesticides causes soil and water pollution, affects non-target organisms (including target bene-icial microbes), promotes pest resistance, and increases emissions of greenhouse gases. For instance, persistent pesticide residues decrease soil fertility and cause death of bene-icial soil organisms. Their public health and environmental effects are well known, prompting the quest for alternative approaches.

Nanotechnology holds great promise for these issues through targeted, efficacious delivery of actives. Nanopesticides and nanoformulations can enhance pest control efficacy while lowering chemical loads. For example, nanoparticle carriers can control release of active molecules over hours or days to prevent drift and degradation. Many such nano-enabled formulations show enhanced bioactivity per unit of active ingredient than bulk chemicals do. A recent review noted that nanotechnology can deliver "long-lasting, efficient solutions" for pest control to help environmentally friendly practices by greatly lowering undesirable residues. Moreover, certain nanoparticles (Ag, Cu, ZnO) exhibit intrinsic antimicrobial activity to serve directly as biocidal agents[1].

Taken together, nano-solutions from plants hold out the promise of high efficacy and sustainability: they can potentially demand reduced dosages of active substances, break down harmlessly into products[2], and comply with organic farming practices. Here, we review the state of the art in preparing such nanoformulations and their use for control of plant disease. We outline preparation of green nanoparticles, encapsulating techniques, and analytical characterization techniques. We then catalog recent experimental results on antimicrobial efficacy and safety from laboratory and field studies. Lastly, we consider the advantages and limitations of this tactic, such as possible ecological hazards and future directions for studies.

2. Methods

Preparation of nanomaterials from plants can proceed by several approaches. Most broadly, these are (i) green syntheses of metal nanoparticles by employing plant extracts as reducing/capping agents, (ii) nano-encapsulation of botanical pesticides (e.g. essential oils or plant metabolites) in polymer carriers, and (iii) hybrid or composite procedures (e.g. biopolymer-metal NP quantum dots hybrids). In either case, follow-up stabilization and characterization procedures are necessary. Principal techniques are briefed below.

Green synthesis of metal nanoparticles: Phytochemicals (phenolics, flavonoids, terpenoids, proteins, etc.) in plant extracts are capable of reducing metal salts while capping the formed NP simultaneously. A common process consists of cleaning and ventilation of vegetation material (leaves, flowers, peels or seeds), grinding it, and making an aqueous (or alcohol) extract through boiling or maceration. This extract is filtered to eliminate particulates. This filtered extract is added to a metal precursor solution (e.g., $AgNO_3$, $CuSO_4$, $Zn(NO_3)_2$) in controlled conditions (temperature, pH) to trigger reduction. For instance, 0.1–1 mM of silver nitrate is commonly reacted with plant extract at room temperature or moderate heating, with continuous agitation. A color change (e.g., from yellow to brown for AgNPs) reflects nanoparticle growth owing to surface plasmon resonance. Phytochemicals act as reducing agent by donating electrons to metal cations ($Ag^+ \rightarrow Ag^0$), besides acting as capping agent that hinders agglomeration. Varying plants produce different NP sizes and morphologies depending upon their metabolite profile. Documented illustrations are AgNPs (~15–100 nm) produced from Eugenia, Azadirachta indica, Ocimum sanctum, and numerous others. Common steps in green synthesis are[3]:

- Select plant material (fresh or dried parts), wash and dry.
- Prepare extract (boil or soak in water/alcohol, then filter).
- Combine extract with metal salt solution; stir at controlled temperature/pH.

- Detect reaction by UV–Vis spectroscopy (SPR peak appearance).

Collect nanoparticles by centrifugation and wash to remove unreacted biomolecules.

Encapsulation and nanoformulation of plant bioactives: Many botanical pesticides (essential oils, plant-derived alkaloids, proteins, etc.) are volatile or unstable. Encapsulation within nanocarriers enhances their stability, solubility, and controlled release. Common encapsulation methods include emulsification–evaporation, ionic gelation, and polymerization. For instance, essential oils can be formulated as nanoemulsions using surfactants: by high-shear mixing or ultrasonication with water and emulsifiers (e.g. Tween 80), oil droplets can be reduced to ~10–200 nm nanoscale emulsions. Alternatively, natural polymers (chitosan, alginate) can form nanocapsules via ionic gelation: mixing chitosan with an oil phase (or dissolved active) and cross-linking with tripolyphosphate (TPP) produces chitosan nanoparticles encapsulating the oil. Layer-by-layer assembly can also coat active compounds within polyelectrolyte films. Key steps include[4]:

- Prepare a polymer solution (e.g., chitosan in acetic acid) and dissolve the plant-active (oil, extract).

- Add cross-linker (TPP for chitosan) dropwise under stirring to form nanogels.

- For nanoemulsions, dissolve essential oil in minimum volume of ethanol and emulsify in water with surfactant by ultrasonication.

- Purify resulting nanoparticles/emulsions by centrifugation or dialysis.
- Outline size and encapsulation efficiency.

For example, imidacloprid microcrystals were encapsulated in a chitosan/alginate matrix to generate a controlled-release formulation. Correspondingly, polymer-coated silica or liposomal carriers can be loaded with plant extracts to release pesticidal compounds in a nano-dispersed system.

3. Results

These NPs can be characterized completely by a mix of UV–Vis, XRD, TEM/SEM, and FTIR in most studies. For instance, Malik et al. (2024) verified biosynthesis of AgNPs by UV–Vis (bands at 420–450 nm), XRD (diffraction of silver), SEM (spheres of 80–100 nm), and FTIR (capping of functional groups.

These approaches collectively allow for the production of stable, well-characterized nano-formulations of plant origins. Lastly, we discuss their documented antimicrobial activity and modes of action in managing plant pathogens.

Results

The antimicrobial activity of such nano-solutions is multi-faceted. Metallic NPs like Ag and Cu inflict toxicity through a "Trojan-horse" mechanism: nanoparticles attach to pathogen membranes, disrupt integrity, and release metal ions within cells. These metal ions bind to functional proteins and to DNA (e.g., interacting with thiol groups), inactivating enzymes and inducing oxidative stress. At the same time, NPs' large surface area catalyzes ROS generation around cells. This produces lipid peroxidation and DNA lesions. Electron microscopy findings often show NP-induced membrane permeation and cytoplasmic leakage in pathogens. In fungal cells, AgNPs and ZnO-NPs inhibited spore germination and hyphal elongation through similar membrane-ROS mechanisms. For viruses, metallic NPs can adsorb to viral cover protein or nucleic acids, to inhibit host cell entry or replication. For example, AgNPs were reported to inactivate Tobacco Mosaic Virus by attaching to virion glycoproteins and inflicting direct structural lesions.

A fundamental question is do these nanoformulations cause harm to crop plants or desirable organisms? Most studies say that at efficacious rates, NPs from plant origins are relatively safe to plants. In a banana-greenhouse experiment, foliar and drench sprays of a commercial AgNP product (Argovit™) up to 100 mg/L showed no significant growth changes relative to untreated controls, although very high rates (>500 mg/L) inhibited elongation of shoots and roots. A nano-permethrin product (permethrin-encapsulated SiO_2 nanoparticles) showed no detectable phytotoxicity and lesser acute cytotoxicity than bulk permethrin. In stored-grain studies, silica (SiO_2) and alumina (Al_2O_3) NPs effectively managed weevils (Sitophilus oryzae) with no significant toxic residues, contrary to conventional malathion that deposited detectable residues. In general, biogenic NPs derived from edible plants would likely prove to be biodegradable with lessened ecotoxicity. Data for long-term field, however, are still lacking. Reports do issue a warning that any nanomaterial – more especially, carbon-based (CNTs, fullerenes) – can pose environmental risk (genotoxicity, microbial imbalance) once it escapes into the environment without controls. Reports oft times observe that controlled-release nanocarriers would actually limit off-target actives' exposure, lowering overall environmentally related impact.

4. Discussion

The foregoing evidence highlights several advantages of plant-derived nanotechnologies for disease control, as well as caveats and research needs.

The primary benefit is enhanced efficacy with potentially reduced chemical input. By leveraging nanoscale carriers or particles, the active agents (whether metal ions or botanical compounds) are delivered more effectively to the pathogen site[5]. For example, encapsulated pesticides can be released in a pH- or moisture-dependent manner, ensuring activity only in target environments. This "smart" release minimizes runoff and volatilization. Moreover, the high surface area of NPs amplifies interactions with pathogens, meaning lower concentrations achieve the same biocidal effect. In practice, studies have repeatedly shown that nanopesticides require 10–100× lower doses than bulk formulations to achieve equivalent mortality. The controlled-release and targeting also translate to safety: by confining toxic action to pathogens, non-target exposure is reduced[6]. As one review notes, nanobactericides (including plant-derived ones) are generally "relatively less toxic, environmentally safer, and more eco-friendly than conventional bactericides". For instance, ChNPs not only kill fungi directly, but also elicit plant defense responses, effectively double-fighting pathogens. Some nanopesticides can also carry nutrients or growth regulators, combining pest control with biostimulation. Overall, plant-based NPs align with integrated pest management goals: they often degrade into benign residues and can even be derived from agricultural waste, enhancing sustainability. Limitations: Although promising, several limitations apply. The fate of nano-agrochemicals in environments is not adequately known. Even biogenic NPs can end up in soil or water, harming non-target organisms over time. For instance, high levels of silver in waterways are toxic to algae and invertebrates; safe soil threshold levels still must be developed. Scalability of production is also a limitation. Green synthesis with plant extracts is easy at pilot scale in a lab, but larger-scale consistency (particle diameter spread, batch-to-batch differences) can be problematic. In like fashion, natural extracts are seasonal and geographical to a certain extent[7].

5. Conclusion

A novel and sustainable method of controlling agricultural diseases is offered by plant-derived nanosolutions. In comparison to traditional pesticides, these formulations provide improved stability, controlled release, and a lower environmental burden by fusing the accuracy and effectiveness of nanotechnology with the inherent antimicrobial qualities of phytochemicals. Evidence currently available shows that they are highly effective against a variety of pathogens with low phytotoxicity and fewer hazards to organisms that are not their intended targets. Nonetheless, there are still issues with long-term ecological safety, regulatory frameworks, and large-scale production. To guarantee the safe and economical application of green nanopesticides in sustainable agriculture, future studies must concentrate on field validation, standardized testing, and environmental risk assessment.

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