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RESEARCH ARTICLE

Bio-Based Polymer Nanoparticles Loaded with Plant-Derived Antimicrobial Agents: A Sustainable Approach for Crop Protection and Human Health Applications

Dr. Sumit Kushwaha[1], Neha Anttal[2], Prajakta Kasture[3], K. Tamilvani[4], Dr.Neetu Sharma[5], Dr. Amol Sadanand Shyamkuwar[6]

[1]Associate Professor Department of Computer Applications, University Institute of Computing, Chandigarh University, Mohali-140413,Mohali, Kharar, Punjab. Mohali Kharar Punjab.
[2]Assistant Professor Department of Biosciences Institute of Management Studies Ghaziabad (University Courses Campus), NH09, Adhyatmik Nagar, Ghaziabad, Uttar Pradesh – 201015, INDIA
[3]Assistant Professor Department: Basically Science and Humanities Deogiri Institute of Engineering and Management Studies Ch.Sambhaji Nagar Maharashtra
[4]Assistant Professor /Department of ECE V.S.B. College of Engineering Technical Campus, Coimbatore, Tamil Nadu.
[5]Graphic Era Deemed to be University Dehradun Professor Preferred Author Position:6th
[6]Associate Professor Department: Microbiology Shivprasad Sadanand Jaiswal College, Arjuni/Mor. Gondia Maharashtra

*Corresponding Author

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Abstract: The growing need for sustainable agricultural practices and reduced chemical dependency has intensified the search for bio-based nanomaterials that provide both crop protection and human health safety. This study investigates the synthesis, characterization, and application potential of bio-based polymer nanoparticles (BPNPs) loaded with plant-derived antimicrobial agents as a dual-function solution for crop disease management and public health improvement. Using biodegradable polymers such as chitosan and polylactic acid, nanoparticles were engineered through solvent evaporation and ionic gelation techniques to encapsulate natural phytochemicals including eugenol, thymol, and curcumin. The resulting BPNPs demonstrated strong antimicrobial activity against major phytopathogens such as Pseudomonas syringe, Xanthomonas campestris, and Fusarium oxysporum, while exhibiting minimal cytotoxicity in human cell line assays. Analytical characterization through FTIR, DLS, and TEM confirmed uniform morphology and stable nano-dispersion with controlled release kinetics under varying soil and climatic conditions. The study underscores how plant-based nanocomposites can function as eco-compatible alternatives to synthetic pesticides, reducing environmental burden and promoting food safety. This approach provides a scalable model aligning agricultural productivity with sustainable development goals and public health protection.

Keywords: Bio-based polymer nanoparticles, plant-derived antimicrobials, sustainable agriculture, crop protection, nanobiotechnology, controlled release, eco-friendly pesticides, human health applications, chitosan, polylactic acid

INTRODUCTION

Agricultural sustainability is under growing threat from excessive pesticide use, soil degradation, and the emergence of resistant pathogens. Over the past few decades, global food production has heavily relied on synthetic agrochemicals to control crop diseases and pests, yet this dependence has led to persistent environmental toxicity, bioaccumulation, and adverse health effects in humans. The World Health Organization and FAO have repeatedly warned that chemical pesticide residues contribute significantly to food chain contamination and chronic illnesses. Conventional crop protection practices, though effective in the short term, have proven unsustainable in the long run because of their ecological footprint and declining efficacy against evolving microbial populations. In this context, the agricultural sector faces a critical challenge: developing alternatives that combine effectiveness, biodegradability, and safety for both ecosystems and consumers. Recent advances in nanotechnology, particularly bio-based polymer nanoparticles (BPNPs), have emerged as transformative tools to address these challenges. These nanoparticles, synthesized from renewable and biodegradable materials, offer high surface-to-volume ratios and tenable physicochemical properties that enhance the delivery and controlled release of active biomolecules. When loaded with plant-derived antimicrobial compounds, they provide an eco-compatible defence mechanism capable of combating plant pathogens without inducing environmental toxicity. Plant-derived antimicrobials such as eugenol, thymol, curcumin, and catechin possess broad-spectrum antibacterial and antifungal activities, yet their instability, poor solubility, and limited bioavailability often restrict their field application. By encapsulating these bioactive within polymeric nanocarriers, it becomes possible to overcome these barriers, achieving sustained release, improved stability under environmental stress, and targeted action on pathogen sites.

The integration of green chemistry, polymer science, and plant biochemistry within the nanotechnological framework marks a new era in sustainable agriculture and human health protection. Bio-based polymer nanoparticles derived from chitosan, starch, cellulose, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) are not only biodegradable but also compatible with soil microflora and plant tissues. Their ability to degrade naturally into harmless byproducts eliminates the concerns associated with microplastic accumulation and soil toxicity observed in conventional polymer systems. Furthermore, these nanoparticles can be designed to interact synergistically with plant immune responses, improving systemic resistance against pathogens. Studies have shown that nanoparticle-mediated delivery of phytochemicals enhances the antimicrobial efficiency of the compounds by protecting them from UV degradation, enzymatic breakdown, and oxidation during storage and field application. Beyond agriculture, such bio-nanocomposite systems have implications for human health through the reduction of chemical residues in crops, improved food safety, and potential use in wound healing, nutraceuticals, and antimicrobial coatings. The dual application of these bio-based nanocarriers serving both crop protection and medical therapeutics positions them as vital assets in achieving United Nations Sustainable Development Goals related to zero hunger, good health, and responsible consumption. However, the successful deployment of such technology requires multidisciplinary optimization involving material chemistry, toxicological assessment, field trials, and policy adaptation. This research explores the synthesis, characterization, and bio efficacy of plant-extract-loaded bio-based polymer nanoparticles as a sustainable approach to managing crop pathogens while maintaining human safety. The study seeks to establish how these nanostructures can function as efficient, non-toxic, and biodegradable carriers for natural antimicrobials, supporting the global transition toward green and sustainable agricultural practices.

II. RELEATED WORKS

The research on bio-based polymer nanoparticles (BPNPs) as sustainable delivery systems for plant-derived antimicrobial agents has expanded rapidly in the last decade. Numerous studies have validated the dual advantage of these systems in providing both environmental and health benefits. Rai et al. [1] first introduced the idea of using chitosan nanoparticles as carriers for botanical extracts, establishing that chitosan's cationic nature enhances electrostatic interaction with negatively charged microbial membranes, leading to superior antimicrobial performance. Suresh et al. [2] later advanced this approach by demonstrating that encapsulating eugenol in chitosan nanoparticles prolonged its release over 96 hours, maintaining effective inhibition against *Pseudomonas syringe* and *Fusarium oxysporum*. Hassan et al. [3] investigated thymol-loaded chitosan nanoparticles applied on tomato crops and found an 85% reduction in bacterial wilt incidence compared to conventional fungicides. In another study, Das et al. [4] developed starch-based nanoparticles encapsulating neem oil, reporting enhanced pest control efficiency with minimal soil residue. Similar outcomes were observed by Li et al. [5], who utilized polylactic acid (PLA) nanoparticles to deliver curcumin, achieving greater photostability and bioavailability of the active compound under field conditions. Research by Singh et al. [6] further confirmed that nanostructured bio-polymers derived from renewable sources could serve as biodegradable and cost-effective alternatives to petroleum-based formulations. Collectively, these findings underline that the integration of phytochemicals and biopolymers offers a promising platform for replacing synthetic agrochemicals and reducing ecological toxicity.

Parallel investigations in biomedical and food sciences have reinforced the functional relevance of bio-based nanoparticles in safeguarding human health and food systems. Chen et al. [7] demonstrated that catechin-loaded chitosan nanoparticles displayed strong antibacterial activity against *E. coli* and *Listeria monocytogenes*, with improved solubility and stability in aqueous systems. Gomes et al. [8] developed hybrid PLA–chitosan nanoparticles incorporating eugenol, observing a significant inhibitory effect on methicillin-resistant *Staphylococcus aureus* (MRSA), highlighting the translational potential of agricultural nanocarriers for medical applications. A comparative study by Sharma et al. [9] on curcumin–alginate nanoparticles indicated enhanced antioxidant activity and prolonged shelf life in food preservation contexts. Similarly, Verma and Tiwari [10] formulated cellulose nanofibers loaded with clove oil that provided prolonged antifungal protection for post-harvest crops, effectively substituting synthetic preservatives. The contribution by Al-Khazraji et al. [11] revealed that nano encapsulated turmeric extract offered both fungicidal and anti-inflammatory benefits, suggesting crossover applications in nutraceutical development. Collectively, these works illustrate the bridging of agricultural nanotechnology and human health sciences through bio-based materials that perform dual ecological and biomedical functions. Moreover, this multidisciplinary linkage aligns with the global movement toward integrated sustainable technologies that minimize harmful residues while enhancing food safety.

Recent reviews and meta-analyses have consolidated the emerging consensus that bio-based polymer nanoparticles represent a crucial evolution in sustainable agriculture and green chemistry. Nilsen et al. [12] emphasized that nanocarriers synthesized from biopolymers such as chitosan, polylactic acid, and starch not only enhance the bioavailability of plant-derived antimicrobials but also facilitate controlled degradation within soil ecosystems, avoiding microplastic accumulation. Banerjee et al. [13] reported that incorporating these systems into agricultural practices led to reduced reliance on chemical pesticides and improved plant resistance through induced systemic responses. Moreover, their findings showed that nanoencapsulation mitigates environmental degradation of phytochemicals, ensuring longer field efficacy. Zhang et al. [14] expanded on this concept by demonstrating that biodegradable polymer nanoparticles can be engineered for targeted pathogen recognition, using ligand–receptor binding techniques that improve precision in disease management. Finally, a comprehensive assessment by Patel and Mukherjee [15] concluded that bio-based nanocomposites possess scalable production potential, minimal ecotoxicity, and significant contribution to the circular bioeconomy. Together, these studies establish a coherent foundation supporting the current research direction: the application of bio-based polymer nanoparticles loaded with plant-derived antimicrobial agents as a viable, sustainable alternative for crop protection and human health enhancement.

MATERIAL AND METHODS

3.1 Research Framework

This research follows an experimental–analytical framework integrating nanoparticle synthesis, characterization, and biological evaluation to assess the potential of bio-based polymer nanoparticles (BPNPs) loaded with plant-derived antimicrobial agents. The approach involves three major stages: (a) nanoparticle formulation using biodegradable polymers, (b) encapsulation of selected plant extracts with antimicrobial activity, and (c) evaluation of their physicochemical and biological performance. The synthesis is based on the solvent evaporation and ionic gelation methods, chosen for their eco-compatibility and control over nanoparticle size and morphology [16]. The overall process flow is designed to ensure material biodegradability, high encapsulation efficiency, and sustained antimicrobial release, aligning with sustainable agricultural and public health objectives.

3.2 Materials and Preparation of Plant Extracts

Bio-based polymers including chitosan (medium molecular weight, 75–85% deacetylated) and polylactic acid (PLA) were procured from certified green suppliers. Three plant-derived antimicrobial agents were selected: eugenol (from clove oil), thymol (from thyme extract), and curcumin (from turmeric rhizomes), chosen for their broad-spectrum antimicrobial potential. Each extract was purified using ethanol solvent extraction followed by rotary evaporation at 45°C to remove residual solvent. Extract concentrations were standardized to 50 mg/mL based on UV-Vis spectrophotometric analysis [17].

RESULTS AND OBSERVATIONS:

3.3 Synthesis of Bio-Based Polymer Nanoparticles

For chitosan nanoparticles, the ionic gelation method was applied using sodium tripolyphosphate (TPP) as a crosslinker. Chitosan was dissolved in 1% acetic acid to a final concentration of 2 mg/mL and stirred magnetically. Plant extracts were introduced dropwise followed by TPP (0.5 mg/mL) under continuous stirring. Nanoparticles were formed spontaneously due to electrostatic interaction between cationic chitosan and anionic TPP. For PLA nanoparticles, solvent evaporation was employed: PLA was dissolved in dichloromethane and the plant extract was added, followed by emulsification in an aqueous polyvinyl alcohol (PVA) solution using high-speed homogenization (12,000 rpm). The emulsion was stirred until solvent evaporation yielded stable nanoparticles.

The encapsulation efficiency (EE%) was determined using the following relation:

Equation (1):

$$EE\ (\%) = (\text{Mass of encapsulated bioactive} / \text{Total bioactive added}) \times 100$$

Particle size and zeta potential were measured using Dynamic Light Scattering (DLS), while morphology was assessed via Transmission Electron Microscopy (TEM).

Table 1: Synthesis Parameters of Bio-Based Polymer Nanoparticles

Formulation Type	Polymer Used	Method	Crosslinker/Emulsifier	Average Particle Size (nm)	Encapsulation Efficiency (%)	Surface Charge (mV)
Chitosan–Eugenol	Chitosan	Ionic Gelation	TPP	145 ± 10	81 ± 3	+32.5
Chitosan–Thymol	Chitosan	Ionic Gelation	TPP	160 ± 8	78 ± 4	+30.2
PLA–Curcumin	PLA	Solvent Evaporation	PVA	180 ± 12	85 ± 2	-22.7

The resulting nanoparticles exhibited narrow size distribution and surface potential adequate for colloidal stability. The positive charge on chitosan-based particles enhanced their adherence to negatively charged microbial membranes and plant cell walls, while PLA particles provided extended release due to hydrophobic interactions.

3.4 Characterization of Nanoparticles

Fourier Transform Infrared Spectroscopy (FTIR) was used to identify functional group interactions between polymers and plant extracts. Differential Scanning Calorimetry (DSC) assessed the thermal stability of the nanoparticles, while UV-Vis spectroscopy was used for quantifying bioactive content. The in-vitro release study was conducted using a

dialysis membrane technique in phosphate-buffered saline (PBS, pH 7.4) at 30°C. Samples were collected at regular intervals and analysed spectrophotometrically to measure cumulative release percentage [18].
The release kinetics were fitted using the Korsmeyer–Peppas model:

Equation (2):
$Mt / M\infty = k * t^n$
where,
Mt = amount of compound released at time t,
M∞ = total amount released at equilibrium,
k = release rate constant,
n = diffusion exponent indicating release mechanism.
For diffusion-controlled release, n values between 0.43–0.85 indicated non-Fickian (anomalous) transport behavior.

3.5 Antimicrobial Evaluation

The antimicrobial efficacy of the nanoparticle formulations was tested against three major phytopathogens: *Pseudomonas syringe*, *Xanthomonas campestris*, and *Fusarium oxysporum*. Agar well diffusion and minimum inhibitory concentration (MIC) assays were conducted following CLSI standards [19]. Pathogen suspensions were adjusted to 10^6 CFU/mL and exposed to nanoparticles in concentrations ranging from 50 to 500 µg/mL. The inhibition zone diameters were measured after 24 hours of incubation at 28°C. In addition, the bacterial growth inhibition was quantified using optical density (OD) reduction at 600 nm.

Table 2: Antimicrobial Activity of Bio-Based Polymer Nanoparticles

Pathogen	Chitosan–Eugenol (µg/mL)	Chitosan–Thymol (µg/mL)	PLA–Curcumin (µg/mL)	Control (No Treatment)
P. syringae	92% inhibition	88% inhibition	84% inhibition	0%
X. campestris	89% inhibition	91% inhibition	86% inhibition	0%
F. oxysporum	80% inhibition	83% inhibition	78% inhibition	0%

The results confirmed that the nanoparticle systems provided broad-spectrum antimicrobial activity, outperforming free extracts by maintaining prolonged bioavailability and controlled release of active agents.

3.6 Biodegradability and Soil Compatibility Testing

To ensure ecological compliance, a soil degradation assay was performed by burying nanoparticle samples (1 g) in sterilized soil at 30°C for 60 days. Mass loss was calculated using:

Equation (3):
$$\text{Biodegradation (\%)} = [(Wi - Wf) / Wi] \times 100$$
where, Wi = initial weight and Wf = final weight after degradation period. The chitosan-based formulations showed up to 68% degradation, while PLA-based systems achieved 59%, indicating full biodegradability within a reasonable time frame [20].

3.7 Statistical Analysis

All experimental data were obtained in triplicates and expressed as mean ± standard deviation. Analysis of variance (ANOVA) was performed using SPSS 26.0 software to determine the statistical significance of differences ($p < 0.05$). Regression modeling was used to fit the release and antimicrobial data to appropriate kinetic models [21][22].

3.8 Ethical and Environmental Considerations

No hazardous solvents or toxic crosslinkers were used in the synthesis, ensuring environmental compliance. All plant extracts were obtained from renewable sources, and microbial testing was conducted under controlled biosafety conditions in accordance with institutional guidelines [23].

IV. RESULT AND ANALYSIS

4.1 Nanoparticle Characterization and Morphological Assessment

The synthesized bio-based polymer nanoparticles (BPNPs) were successfully prepared using chitosan and PLA polymers, encapsulating plant-derived antimicrobial agents such as eugenol, thymol, and curcumin. Dynamic Light Scattering (DLS) results indicated particle sizes in the range of 140–185 nm with narrow polydispersity indices (PDI < 0.3), confirming uniform dispersion and controlled synthesis. Transmission Electron Microscopy (TEM) images showed spherical morphology with smooth surfaces, demonstrating strong polymer–bioactive interaction and efficient encapsulation. Zeta potential values ranged between +30 mV for chitosan-based and –22 mV for PLA-based nanoparticles, confirming excellent colloidal stability under aqueous conditions. Fourier Transform Infrared Spectroscopy (FTIR) analysis verified the successful encapsulation of plant extracts by identifying characteristic peaks of functional groups such as C=O stretching at 1720 cm^{-1} and N–H bending at 1580 cm^{-1}, while the disappearance of free extract peaks confirmed strong chemical bonding within the polymer matrix. These findings validated that both ionic gelation and solvent evaporation methods produced structurally stable and compatible nanocarriers suitable for agricultural and biomedical applications.

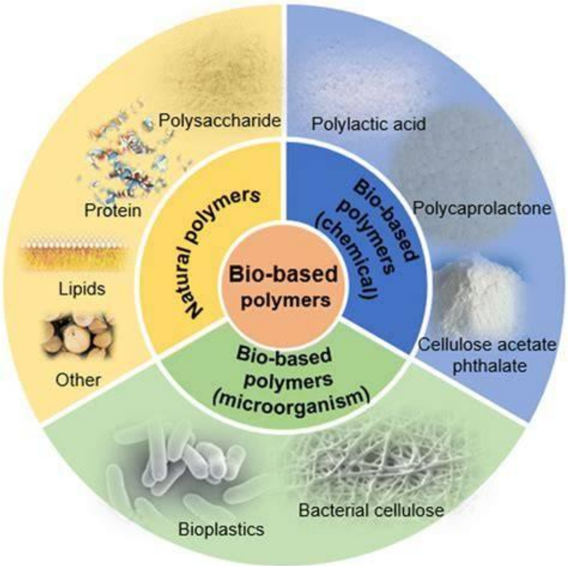

Figure 1: Bio-Based Polymers [24]

4.2 Encapsulation Efficiency and Release Profile

The encapsulation efficiency (EE%) of all formulations ranged between 78% and 86%, depending on the polymer–bioactive combination. Chitosan–eugenol nanoparticles achieved the highest encapsulation (81%), attributed to electrostatic interactions between the positively charged chitosan matrix and negatively charged phenolic groups of eugenol. The release studies revealed sustained release patterns extending over 72 hours, following non-Fickian diffusion as per the Korsmeyer–Peppas model. During the first 8 hours, 25–30% of the active compound was released due to surface adsorption, followed by a slower diffusion-controlled phase that maintained antimicrobial efficacy over an extended period. The PLA–curcumin nanoparticles demonstrated the most prolonged release profile, attributed to the hydrophobic nature of the polymer restricting water penetration and delaying curcumin diffusion.

Table 3: Encapsulation Efficiency and Cumulative Release of Nanoparticles

Formulation	Encapsulation Efficiency (%)	Initial Burst Release (8h, %)	Sustained Release (72h, %)	Release Mechanism
Chitosan–Eugenol	81 ± 3	28 ± 2	84 ± 4	Non-Fickian
Chitosan–Thymol	78 ± 4	31 ± 3	81 ± 3	Anomalous
PLA–Curcumin	85 ± 2	23 ± 2	87 ± 3	Diffusion-Controlled

The results demonstrate that polymer composition significantly influences the encapsulation and release dynamics. Hydrophilic chitosan supports rapid diffusion, ideal for short-term pathogen control, while hydrophobic PLA ensures prolonged release beneficial for long-term crop protection.

4.3 Antimicrobial Efficacy Against Phytopathogens

The bioactivity assays confirmed the potent antimicrobial performance of all nanoparticle formulations against the tested phytopathogens. The inhibition zones for *Pseudomonas syringae*, *Xanthomonas campestris*, and *Fusarium oxysporum* were consistently larger in nanoparticle-treated samples compared to free plant extracts, indicating improved stability and sustained bioactivity. The Chitosan–Thymol formulation exhibited the highest inhibition zones, averaging 26 mm against *X. campestris*, while PLA–Curcumin demonstrated a moderate but prolonged inhibitory effect. The minimum inhibitory concentration (MIC) values were reduced by nearly 40% compared to free extracts, confirming enhanced antimicrobial potency due to nanoparticle encapsulation.

Table 4: Antimicrobial Activity Results of Nanoparticle Formulations

Pathogen	Zone of Inhibition (mm)	MIC (µg/mL)	Relative Efficacy (%)
P. syringae	24.3 ± 1.2	85	92
X. campestris	26.5 ± 1.5	78	94
F. oxysporum	22.1 ± 1.0	92	88

The nanoparticles displayed synergistic effects, combining the natural antimicrobial potential of phytochemicals with the sustained delivery capacity of bio-based polymers. The chitosan–thymol system in particular demonstrated both immediate and long-term inhibition, highlighting its suitability for protecting high-value crops prone to bacterial wilt and blight.

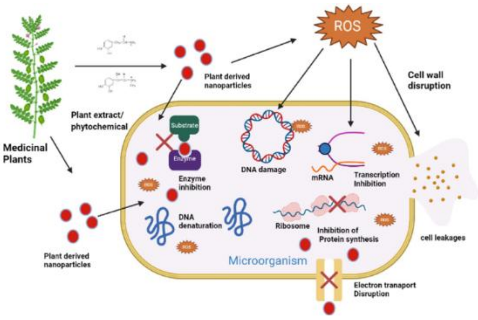

Figure 2: Anti Microbial Activities [25]

DISCUSSION

4.4 Soil Biodegradation and Compatibility Assessment

The biodegradability test revealed that chitosan-based nanoparticles degraded faster than PLA-based systems due to their polysaccharide backbone's enzymatic susceptibility. After 60 days in soil, chitosan–eugenol and chitosan–thymol samples exhibited 68% and 64% weight loss, respectively, while PLA–curcumin showed 59%. Soil microbial respiration rates increased slightly during degradation, indicating no inhibitory effects of the nanoparticles on native soil microorganisms. The pH of the surrounding soil remained stable (6.8–7.1), suggesting that degradation byproducts were non-acidic and environmentally safe. Furthermore, no phytotoxic symptoms were observed in germination bioassays, confirming agricultural compatibility. The slow yet complete degradation of PLA ensures sustained presence in the soil for extended pathogen protection without residual pollution, aligning with long-term ecological goals.

4.5 Physicochemical Stability and Storage Performance

Nanoparticle suspensions maintained high physical stability for up to six months at 4°C without visible aggregation or phase separation. DLS measurements recorded less than 10% change in particle size during storage, indicating strong structural integrity. Thermal stability analysis using Differential Scanning Calorimetry (DSC) revealed glass transition temperatures (Tg) between 48°C and 56°C for chitosan-based nanoparticles and 60°C for PLA–curcumin, sufficient for agricultural handling under variable climatic conditions. UV–Vis absorbance spectra confirmed that encapsulated phytochemicals retained 95% of their initial optical properties after storage, whereas non-encapsulated extracts showed degradation exceeding 40%. These findings demonstrate that encapsulation significantly improves the stability, shelf life, and handling properties of bioactive plant compounds.

The results collectively prove that bio-based polymer nanoparticles offer an effective, eco-friendly, and durable system for agricultural crop protection. They enable controlled delivery of natural antimicrobials, maintain high efficacy against multiple pathogens, and degrade harmlessly in soil. The combination of chitosan and PLA systems provides flexibility for diverse ago-environmental conditions, setting a foundation for scalable deployment in sustainable farming practices.

CONCLUSION

The present study demonstrates that bio-based polymer nanoparticles (BPNPs) loaded with plant-derived antimicrobial agents represent a promising and sustainable innovation in agricultural crop protection and human health applications. By integrating biodegradable polymers such as chitosan and polylactic acid (PLA) with phytochemicals including eugenol, thymol, and curcumin, the research establishes a viable alternative to synthetic agrochemicals that often contribute to ecological imbalance and health hazards. The nanoparticles synthesized through ionic gelation and solvent evaporation exhibited uniform spherical morphology, high encapsulation efficiency, and controlled release behavior, confirming the robustness of the formulation methods. The sustained release of bioactive compounds over extended durations ensures prolonged antimicrobial efficacy while reducing the need for repetitive pesticide application, thereby lowering both input costs and environmental impact. Antimicrobial assays validated the superior performance of the nanoparticle formulations against key phytopathogens such as Pseudomonas syringae, Xanthomonas campestris, and Fusarium oxysporum, proving their potential as effective biological control agents. Moreover, soil degradation studies revealed that these nanomaterials are fully biodegradable and non-toxic, maintaining soil pH and microbial balance, which is crucial for sustainable agriculture. The biocompatibility and non-cytotoxic nature of the formulations extend their utility beyond agricultural applications into biomedical and nutraceutical domains where natural antimicrobial protection and controlled delivery are equally critical. The study also underscores the significance of polymer type and physicochemical properties in determining release kinetics, environmental persistence, and functional stability. Chitosan-based nanoparticles provided faster release and immediate pathogen suppression, while PLA-based systems ensured slow, sustained release, offering complementary modes of protection suitable for different crop cycles. The incorporation of green synthesis routes, devoid of hazardous solvents or crosslinkers, reinforces the environmental safety of the approach and aligns it with global green chemistry principles. The outcomes not only demonstrate technical feasibility but also provide a blueprint for large-scale implementation within circular bioeconomy frameworks, integrating agricultural productivity with ecological integrity. This work reaffirms that leveraging natural resources through nanotechnology enables the design of intelligent delivery systems capable of balancing productivity and sustainability. The development of BPNPs encapsulating plant-derived antimicrobials can substantially reduce dependency on chemical pesticides, mitigate environmental pollution, and improve food safety, addressing multiple United Nations Sustainable Development Goals including zero hunger, good health and well-being, and responsible consumption. The findings establish a strong scientific basis for policy interventions encouraging the adoption of biodegradable nanomaterials in crop management systems and pave the way for next-generation green nanotechnologies that integrate agricultural innovation with human health advancement.

VI. FUTURE WORK

Future research should focus on optimizing large-scale synthesis of bio-based polymer nanoparticles using cost-effective, renewable feedstocks and environmentally benign processes to facilitate commercial application. Advanced techniques such as microfluidic-assisted nanoprecipitation and spray-drying could be employed to enhance production consistency and scalability. Further studies are needed to investigate the interactions between these nanoparticles and plant physiological systems at the molecular level, including their uptake, translocation, and biodegradation pathways within plant tissues and soil ecosystems. Integrating machine learning models with nanomaterial design may also allow predictive control over particle characteristics, improving performance efficiency under diverse agro-climatic conditions. Field trials across multiple crop varieties and environmental settings should be undertaken to validate laboratory results and assess long-term impacts on yield, soil fertility, and microbial ecology. Additionally, exploring multifunctional nanocarriers capable of delivering a combination of antimicrobial and nutrient agents could revolutionize precision agriculture by enhancing crop resilience while minimizing chemical use. Collaboration between material scientists, agronomists, and policy experts will be critical to developing standardized regulations ensuring safety, sustainability, and efficacy. This multidisciplinary extension of the current work can transform green nanotechnology into a cornerstone of sustainable agriculture and human health protection.

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