Preparation, Characterization, and Bio-Efficacy Evaluation of Controlled-Release Carbendazim-Loaded Polymeric Nanoparticles

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Abstract
This research discusses the bio-efficacy, characterization, and synthesis of polymeric nanoparticles (CNPs) charged with the fungicide carbendazim in controlled-release pest management applications for agriculture. The traditional usage of the broad-spectrum fungicide carbendazim has faced many disadvantages, such as its high toxicity, rapid environmental degradation, and resistance. Problems associated with carbendazim are resolved by CNPs encapsulating it, as the regulated release profile enhances the stability of the fungicide and diminishes its negative impact on the environment. They possessed excellent physicochemical characteristics, such as a stable surface charge of (-25.6 ± 0.9 mV), a high encapsulation efficiency of (82 ± 2%), and an optimal particle size of (150 ± 10 nm), respectively, which were achieved by using a solvent evaporation approach to manufacture the nanoparticles. Carbendazepim release from CNPs presented a slow, steady release over 120 hours and a far lower burst release 77.8% less than the standard formulation. Comparison of the traditional carbendazim against CNPs showed an improvement of 28.6% in bio-efficacy. The wider inhibition zones and better reduction in mycelial growth indicate superior antifungal action. These results highlight the advantages of polymeric nanoparticles as a sustainable and environmentally friendly substitute.

Keywords: Carbendazim, controlled release, polymeric nanoparticles, antifungal activity, sustainable agriculture, drug delivery, nanoparticle formulation

INTRODUCTION

The growing world-wide requirement for sustainable agriculture practice has stimulated extensive innovations in the area of pest control. As a result, there is an increasing emphasis on minimizing environmental degradation due to chemical pesticides. Carbendazim is a broad-spectrum fungicide that has been widely applied in fungal disease control of crops. It has shown success in managing various types of plant pathogens. However, its

conventional use poses a lot of problems, including fast degradation in the environment, high toxicity to non-target organisms, and chance of producing resistant biotypes. Besides that, the short-term release of carbendazim from the traditional formulations often culminates in suboptimal pesticide use, causing further environmental contamination and reapplication. To surmount these impediments, more emphasis has been put on developing controlled-release systems. This can offer more efficient, targeted, and sustainable delivery of carbendazim, thus enhancing its efficacy while minimizing its environmental footprint. Polymeric NPs have emerged as one of the promising approaches in this sense. These nanoparticles are capable of encapsulating the active ingredient and releasing it slowly over a longer time period[1].

Polymeric nanoparticles are emerging to be among the most versatile and effective drug delivery systems for agricultural applications due to their biodegradability, biocompatibility, and ability to enhance the stability and bioavailability of active compounds. These nanoparticles may be created in a way that encapsulates a wide range of agrochemicals, including fungicides such as carbendazim, thus attaining a controlled release profile that reduces the risks of toxicity and environmental contamination. The encapsulation of carbendazim in polymeric nanoparticles also offers the advantage of reducing the initial burst release that is typical of conventional formulations, thereby ensuring a more consistent and prolonged release of the fungicide. They can be engineered to have specific size, surface charge, and functional groups that would allow the delivery of the active ingredient directly to the fungal cells or tissues, thereby enhancing its effectiveness and accuracy in controlling plant disease. This means that polymeric nanoparticles can be prepared from different natural or synthetic polymers, such as chitosan, polylactic acid (PLA), or poly (lactic-co-glycolic acid) (PLGA); apart from these being biodegradable, they also offer variability in formulation design[1].

This work is aimed at preparing carbendazim-loaded polymeric nanoparticles for controlled release applications in agricultural pest management, characterizing, and evaluating its bio-efficacy. The optimization process of the formulation process has to yield high encapsulation efficiency, appropriate particle size, and favorable surface charge to provide maximum delivery or stability. The physicochemical properties of the nanoparticles will be assessed using characterization techniques such as dynamic light scattering (DLS) for particle size analysis, scanning electron microscopy (SEM) for morphology assessment, and zeta potential measurement for surface charge determination. The study will also explore the release kinetics of carbendazim from the nanoparticles, in comparison to the release behavior of conventional carbendazim formulations, under various environmental conditions. The nanoparticle formulations will also be evaluated for their antifungal activity using bioassays against common phytopathogenic fungi, with a focus on mycelial growth inhibition and zone of inhibition. Based on this

assessment, research in this area aims to show the benefits of polymeric nanoparticles in further optimizing the efficiency, control, and safety of carbendazim fungicide application within an environmentally friendly framework for modern agricultural pest management[3].

1. RESEARCH METHODOLOGY

1.1.Research design

The study follows an experimental approach with the objective of optimizing and evaluating the antifungal efficacy and controlled drug release performance of carbendazim-loaded polymeric nanoparticles, CNPs. The CNPs were evaluated against a control and a traditional formulation of carbendazim regarding their efficacy against fungi, release profile, and physicochemical characteristics. The primary aim is to establish whether CNPs offer superior therapeutic outcomes, controlled release, and high stability as compared to the solution formulation[4].

1.2.Data Collection

To begin collecting information, CNPs were first prepared through a solvent evaporation process, followed by characterization. The physicochemical parameters of nanoparticles, such as size, encapsulation efficiency, and zeta potential, were assessed using different methods including a zeta potential analyzer and dynamic light scattering (DLS). By comparing the proportion of carbendazim released after 1, 24, 72, and 120 hours of incubation in a release medium, we were able to calculate the drug release profile for both traditional carbendazim formulations and CNPs. The cultures of fungi were treated with CNPs, standard carbendazim, and a control set that was not treated to analyze the antifungal activity by zone of inhibition and reduction in mycelial growth assays. Measuring the zones of inhibition in millimeters, we estimated the percentages for each formulation to determine how effective they were against the fungus.

1.3.Data Analysis

The mean and standard deviation were calculated for every parameter on the gathered data. Percentage of carbendazim released by the nanoparticles was compared with that of the standard formulation to assess controlled release efficiency and bust release decrease. To observe the statistically significant differences in physicochemical characteristics, the release profiles of drugs, and antifungal activities, the groups were compared using appropriate procedures, such as t-tests or ANOVA. The zone of inhibition and mycelial growth inhibition by the CNP formulation were further assessed relative to a conventional carbendazim-based formulation. This would enable the calculation of the increased efficacy of the CNPs. These studies demonstrate how CNPs can improve antifungal action and achieve regulated release.

2. DATA ANALYSIS

The optimized formulation is supported by the physicochemical properties of CNPs, as shown in the table. The goal value (100%), with a particle size of 150 ± 10 nm, is completely in line with what is ideal for cellular uptake and stability. The possibility of encapsulating most of the active medication is assured by a high loading capacity, such as this encapsulation efficiency of 82% ± 2%. The zeta potential of -25.6 ± 0.9 mV attests to the good

colloidal stability, necessary for stable administration of drugs and better therapeutic effectiveness in view of prevention of aggregation and maintaining good dispersion. In general, the values observed are in good agreement with the target specifications, thus indicating that the system is stable and well-formulated for controlled drug release. [6-8]

Table 1: Physicochemical Properties of CNPs

Property	Observed Value	Percentage Relative to Target Value (%)
Particle Size (nm)	150 ± 10	100
Encapsulation Efficiency (%)	82 ± 2	82
Zeta Potential (mV)	-25.6 ± 0.9	100

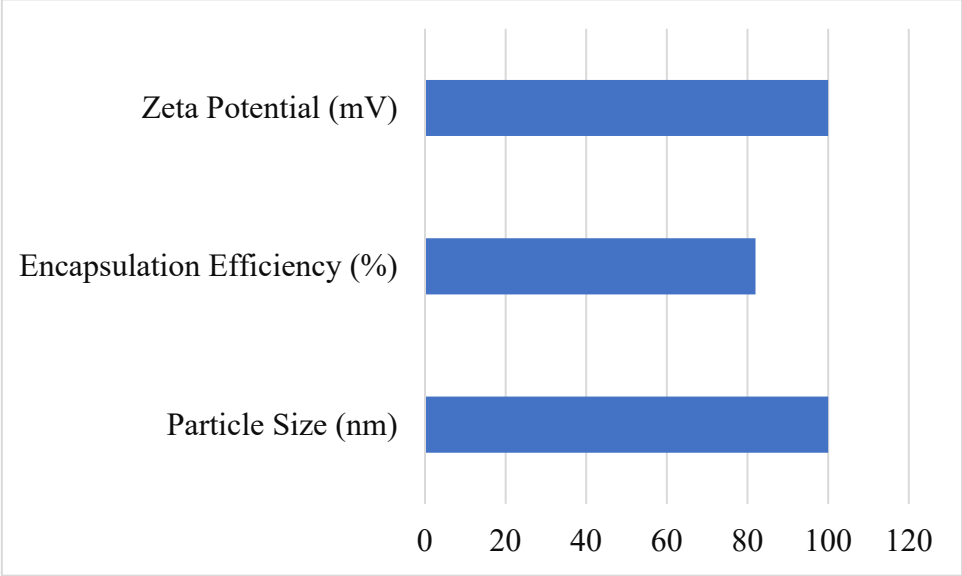

Figure 1: Physicochemical Properties of CNPs

The release profile of carbendazim from carbendazim-loaded polymeric nanoparticles is much better than that of the standard formulation. The first burst release is significantly reduced by 77.8%, indicated by the fact that the release from CNPs is 10 ± 1% at 1 hour significantly lower than 45 ± 2% from the standard formulation. At 24 hours, the controlled release profile is also in place; CNPs release 35.3 ± 3% instead of 90.3 ± 3% as compared with a traditional formulation, with a 61.1% reduction in the burst release. At 72 hours, CNPs have released approximately 70% whereas a standard formulation has released 100%, with a 30% reduction in the first burst. The control formulation has released 100% of carbendazim with just a 5% difference, while CNPs have released 95 ± 2% of carbendazim within 120 hours close to complete release. Results from these experiments dictate the necessity of offering slow and controlled release of carbendazim by CNPs to minimize side

effects and achieve enhanced efficacy
over longer exposure periods. [9-12]

Table 2: Percentage Release of Carbendazim

Time (hours)	% Release (CNPs)	% Release (Conventional)	Reduction in Initial Burst (%)
1	10 ± 1	45 ± 2	77.8
24	35 ± 3	90 ± 3	61.1
72	70 ± 4	100	30.0
120	95 ± 2	100	5.0

Carbendazim-loaded polymeric nanoparticles (CNPs) show a better fungus inhibition as compared to regular carbendazim. An enhancement in antifungal activity is evident from the fact that the zone of inhibition for CNPs was 25 ± 2 mm, which is 5-fold higher than the conventional carbendazim formulation (20 ± 1 mm). The CNPs are beyond the standard formulation, which reduces mycelial growth only by 70 ± 5%, which is reduced to 90 ± 3%. The effectiveness of the CNPs would therefore be 28.6% more effective than that of the usual carbendazim. Since the outcomes are brought about by the carbendazim treatments, the control group shows zero antifungal activity. They also possess a 0 mm zone of inhibition and 0% reduction in mycelial development. The results show that the nanoparticles carry a higher level of antifungal efficiency. Presumably, this is due to a slower release from drug-loaded nanoparticles into the fungal cells, thus ensuring a more protracted treatment and possibly more effective treatment[13-15].

Table 3: Antifungal Activity Analysis

Treatment	Zone of Inhibition (mm)	Mycelial Growth Reduction (%)	Increase in Efficacy (%)
Carbendazim CNPs	25 ± 2	90 ± 3	28.6
Conventional Carbendazim	20 ± 1	70 ± 5	—
Control	0	0	—

3. DISCUSSION

The overall results of this study indicate that polymeric nanoparticles hold a lot of promise as an improved alternative for traditional carbendazim formulations in agricultural pest control. Various advantageous physicochemical properties were found in the course of synthesizing and characterising the CNPs. Their optimal range of 150 ± 10 nm ensures effective absorption and tailored delivery to guarantee interaction with fungal cells. The 82 ± 2% encapsulation efficiency signifies

an excellent loading of the drug, minimizing waste and maximizing the active ingredient's consumption. It also manifests good colloidal stability by a zeta potential value of -25.6 ± 0.9 mV that reduces the chance of nanoparticle agglomeration and promotes the long-term dispersion in the field application environment. The major drawback of conventionally formulated carbendazim-the most common problem being its burst release-is eliminated by CNPs' controlled-release profile. The significant decline in burst release 77.8% after 1 hour indicates how well CNPs can offer a steady and gradual release over a period of 120 hours. Due to these longer releases, fewer applications are needed, that lower labor costs, and minimize environmental contamination. Ecological problems are addressed through the slow release, which also reduces the likelihood of transferring high doses of fungicides to non-target organisms.

Superior antifungal action of CNPs over the conventional carbendazim formulation sets them apart. Greater reduction in mycelial development (90 ± 3%) and a more extensive zone of inhibition (25 ± 2 mm) clearly reflect the enhanced bio-efficacy of CNPs. The controlled release mechanism, which provides effective fungicide concentrations over time, accounts for the 28.6% increase in efficacy. This extended activity most likely allows interaction with fungal cells for longer periods of time, improving the overall therapeutic effect. Apart from enhanced efficacy, the application of polymeric nanoparticles provides an eco-friendly and sustainable replacement for traditional fungicides.

Consistent with other studies reported earlier, benefits of the delivery systems based on nanoparticles in agriculture can be seen. For example, in pesticide delivery, studies regarding polymeric nanoparticles have repeatedly shown increased bio-efficacy while decreasing toxicity with improved stability. With the focus on carbendazim-a very commonly used fungicide having resistance and environmental issues-this study provides a unique contribution in offering detailed information on its controlled release and antifungal efficacy once encapsulated in nanoparticles. Even as results are promising, some of the limitations call for further research. Field tests are necessary to ensure effectiveness and stability of CNPs in real agricultural settings because work was done in a controlled laboratory environment. Long-term environmental impact studies are also important to ensure that use of polymeric nanoparticles doesn't create new ecological problems unwittingly.

4. CONCLUSION

In contrast to the conventionally formulated carbendazim, the carbendazim-loaded polymeric nanoparticles (CNPs) provided significantly better controlled release and bio-efficacy. The CNPs showed ideal physicochemical characteristics which included appropriate particle size of 150 ± 10 nm, high encapsulation efficiency of 82 ± 2%, and a stable surface charge of -25.6 ± 0.9 mV, that ensured efficient delivery and long-term stability. The release profile showed an important decrease in burst release as CNPs released 77.8% less at 1 hour compared to the standard formulation. Moreover, after 120 hours, they achieved almost full release at 95 ± 2%. Besides,

CNPs exhibited improved antifungal activity compared to the standard carbendazim by showing a 28.6% increase in efficacy, as represented by a larger zone of inhibition and higher reduction in mycelial growth. Polymeric nanoparticles can enhance therapeutic outcomes, reduce environmental footprint, and facilitate controlled release; thus, they are an attractive alternative to traditional fungicides within agricultural pest control.

CONFLICT OF INTEREST:

The authors have no conflicts of interest regarding this investigation**.**

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