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Review Article

Advanced pesticide nano formulations and understanding their breakdown by Bacteria

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A B S T R A C T

The widespread use of chemical pesticides in agriculture has undeniably caused significant environmental harm, affecting the quality of air, water, and soil. This growing concern has steered the focus towards the development and research of nano formulations, which promise effective pest control with substantially reduced pesticide concentrations. These new formulations, which allow for controlled delivery of active ingredients, are demonstrating effectiveness comparable to traditional pesticides, but with less environmental impact. However, it is important to acknowledge that these nano-pesticides still contain certain organic groups which are structurally complex and not easily degradable. These elements can persist in the environment, accumulating and becoming more concentrated through the food chain, potentially causing a range of environmental hazards over time. Encouragingly, research has identified that specific bacterial genera including *Pseudomonas, Bacillus*, and *Burkholderia* and among others, have the unique ability to break down certain chemical groups present in these pesticides, using them as a sole source of carbon or nitrogen. This process transforms them into non-harmful end products, marking a promising step towards bioremediation. Currently, efforts are being made to develop this into a viable large-scale solution, exploring different combinations of nano-pesticides and bacteria strains under optimized conditions. Through further research in this area, we aim to identify the specific types of bacteria that are most effective in degrading these pesticide groups, ultimately paving the way for more sustainable environmental management in the future.

1. Introduction

Pesticides play a crucial role in agriculture by helping control pests and consequently bolster crop yields. They are quintessential tools used in modern farming to enhance crop production by not only acting as defensive shields against a myriad of plant pathogens but also stimulating plant growth, which results in a heightened yield of desired agricultural products. This augmentation in plant yield is pivotal in meeting the food demands of a continuously growing global population. Despite their beneficial attributes in farming, pesticides come with their set of drawbacks that cannot be ignored. When applied directly to the soil, there's a significant risk of these chemicals being washed away, which often leads to environmental contamination, an issue that is cited extensively in various research studies.[1] This wash-off not only affects the immediate ecosystem but can have far-reaching adverse effects on non-target populations including humans, animals, and bird species, leading to a ripple effect of imbalances in the ecosystem at large.

Moreover, pesticides are comprised of toxic compounds whose effects on these non-target groups can be quite severe, altering their normal bodily functions and ecosystems. The extent of the toxic effects varies considerably, largely depending on the specific groups of active ingredients present and their respective percentages

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within the pesticide formulations.[2] Human exposure to these chemicals has been linked to a host of health complications, ranging from relatively mild symptoms like nausea and diarrhea to more serious conditions like respiratory distress, lung impairment, and even lung cancer. Additional reported health issues include hormonal imbalances, chronic bronchitis, reproductive difficulties, and heightened sensitivity to various allergens.[3–5] In response to these challenges, various formulations have been developed over the years to optimize the use of pesticides while mitigating their negative impacts. These formulations include wettable powders, water-dispersible granules, suspension concentrates, and soluble concentrates among others. In recent years, emphasis has been placed on the development and deployment of nano emulsion formulations, which are characterized by their low viscosity, good stability, superior dispersity, and transparent properties. These unique characteristics make nano emulsions suitable for a wide range of applications beyond agriculture, finding uses in the cosmetic, pharmaceutical, and food industries.[6–8]

The issue of water-insolubility in certain pesticides necessitates the use of organic solvents during their formulation. This is where nano emulsions step in as a viable solution. They allow for the efficient delivery of pesticides even at low surfactant concentrations, while also preventing premature degradation of the active ingredients.[9,10] Notably, they enable controlled release strategies, thereby achieving targeted results with lower active ingredient concentrations and consequently reducing toxicity to non-target organisms.[11,12] Furthermore, bioremediation emerges as a promising method to counter the ill effects of pesticides on the environment. Microorganisms play a substantial role in this process, with certain bacterial strains being particularly adept at utilizing the toxic compounds in pesticides as a resource for their growth. This process transforms these toxins into non-toxic end products, fostering a healthier soil biome.[13,14] Bacterial groups such as *Bacillus* and *Pseudomonas* have been identified as the frontrunners in bioremediation processes, showcasing an enhanced ability to degrade and utilize pesticides, especially when harvested from sites already contaminated with these chemicals.[15,16]

2. Categorization of Pesticides

Pesticides, essential tools in agriculture for controlling various pests and promoting plant growth, come in many forms and categories. These encompass insecticides, herbicides, nematicides, acaricides, rodenticides, termiticides, fungicides, bactericides, virucides, chemosterilants, molluscicides, plant growth regulators, plant activators, antifeedants, and avicides. Their classification, often based on their chemical composition, can primarily be categorized into groups such as organophosphates, organochlorines, carbamates, and pyrethroids. Predominantly, organophosphates and carbamates are the most utilized groups of pesticides globally, due to their effectiveness in controlling various pests.[4,17,18]

2.1. Insecticide formulations

The following segment sheds light on the advancements in insecticide formulations, focusing primarily on nano emulsions and their capabilities in enhancing pesticide effectiveness.

Beta-cypermethrin component is a member of the pyrethroids group of insecticides, noted for its hydrophobic properties. Its integration into nano emulsions has been successful, displaying consistent distribution and stability without altering the droplet size of the emulsion, even with the pesticide incorporated. Its solubility plays a critical role, particularly when it comes to diluted emulsion forms, promising good dispersion compared to traditional commercial formulas.[19,20] Imidacloprid formulation showcases high bio-efficacy, facilitating a controlled release mechanism which not only regulates soybean pests but also enhances plant yield. When combined with carbofuran, it offers superior control over a wide variety of pests affecting multiple crops, proving to be a better alternative compared to existing commercial products.[21–23] Etofenprox belonging to the pyrethroid group, this insecticide, though potent, has a detrimental impact on aquatic ecosystems. However, its nano formulation facilitates controlled release, enhancing the availability of active components and minimizing insecticide loss, thereby effectively managing pests like *Spodoptera litura*.[24] Pyridalyl nano formulation exhibits enhanced effectiveness in controlling pests like the cotton bollworm (*Helicoverpa armigera*), offering a higher efficacy rate compared to its commercial counterparts. This increase in efficacy demonstrates the potential of nano formulations in optimizing pest control strategies.[25,26] Novaluron is a low-toxicity insect growth regulator that presents a favorable environmental profile by reducing dependency on other toxic pesticides. When incorporated into microemulsions, it competes effectively with other commercial formulations while offering the added benefit of being an organic solvent-free preparation.[27] Triazofos is a versatile agent, this organophosphate compound functions as a nematicide, acaricide, and insecticide. Despite its high toxicity and flammability, its incorporation into nano emulsions improves stability and prevents easy hydrolysis, a common issue with basic solutions. This adaptation into nano emulsions has demonstrated a potential in enhancing the longevity and effectiveness of the pesticide, even under varying pH conditions.[28,29] This analysis illustrates the promising trajectory of nano formulations in revolutionizing pesticide applications, offering effective, controlled release mechanisms, and potentially reducing environmental impact.

2.2. Herbicide formulations

Glyphosate, a hydrophilic compound belonging to the organophosphorous group of herbicides, exhibits an increased shelf life and enhanced potency in weed control when incorporated into a nano-emulsion formulation with glyphosate isopropylamine. This formulation demonstrates significant stability, even at elevated temperatures, allowing for the efficient targeting of pervasive weeds like Eleusine indica, also known as Indian goose grass. Notably, this formulation demands lesser quantities of surfactants compared to traditional commercial pesticide formulations, consequently diminishing its environmental toxicity.[30,31] Additionally, the herbicide pretilachlor has been successfully utilized in micro-emulsion forms, encapsulated as monolithic dispersions to counteract the growth of the weed Echinochloa crus-galli. These new formulations have proven to be superior to the commercially available pretilachlor Rifit® 50EC, chiefly due to their diminutive particle size. Despite dilution, the emulsion maintains its nanoscale particle range, which alongside its minute droplet size, grants it a substantial shelf life exceeding a year.[32,33] Furthermore, the frequently used herbicide, metribuzin, poses a considerable risk of groundwater contamination owing to its high solubility in water. However, the incorporation of sepiolite gel in its formulation facilitates the entrapment of metribuzin, paving the way for a controlled, gradual release of the herbicide, thus mitigating environmental impact.[34]

2.3. Fungicide formulations

Mancozeb, a non-systemic fungicide falling under the carbamate subgroup, has been successfully integrated into a nanoparticle formulation using polyethylene glycol. This fungicide exhibits dual action, possessing antibacterial properties effective against *Staphylococcus aureus*, and antifungal properties active against *Candida albicans*.[35] Carbendazim, a fungicide belonging to the benzimidazole category, has seen advancements in its formulation through the utilization of amphiphilic-based copolymers, enabling controlled release. This innovation stands out as it facilitates a gradual release of active components compared to its commercial counterpart, 50% WP, thus reducing the necessity for repeated applications. Notably, this reformulated carbendazim effectively curtails the growth of *Rhizoctonia solani*, a pathogen known to afflict rice plants.[36] Further development in encapsulation techniques has allowed for the utilization of carbendazim in lower concentrations of 0.5 and 1 ppm, displaying efficacy in controlling plant pathogens such as *Fusarium oxysporum* and *Aspergillus parasiticus*. This method not only ensures the full inhibition of targeted pathogens but also maintains a non-toxic profile towards non-target organisms, including certain bacteria, which presents an added benefit.[37,38]

3. Biodegradation of Pesticides by Bacteria's

The elimination of harmful substances from natural ecosystems is critically dependent on the biodegradation of pesticides. A significant role in this process is played by microbes, which have the capacity to metabolize the toxic elements found in pesticides, converting them into harmless end products. The success of bioremediation hinges on several environmental factors, including the specific microorganisms present and the availability of enzymes that facilitate degradation. Bacteria from the *Bacillus, Pseudomonas*, and *Flavobacterium genera*, in particular, are noted for their proficiency in breaking down pesticide compounds, thereby aiding in the preservation of ecological balance.[39–43]

3.1. Insecticide degradation

4. Beta-cypermethrin Degradation

Beta-cypermethrin is effectively broken down by the *Serratia species*, strains JC1 and JCN13, within the concentration range of 25 to 1000 ppm. Observations indicate that strain JCN13 facilitates a quicker degradation process, completing it within 4 days as opposed to the 10 days taken by strain JC1, removing 92% and 89% of the substance respectively. The superior degradation capacity of JCN13 is attributed to its heightened hydrophobicity relative to JC1.[44] Additionally, *Ochrobactrum lupini* can fully metabolize beta-cypermethrin and its derivative, 3-phenoxybenzoic acid, handling concentrations between 50 and 400 ppm. This bacterium can also process other pesticides belonging to the pyrethroid group, including beta-cyfluthrin, deltamethrin, cyhalothrin, and fenpropathrin.[45] Furthermore, *Pseudomonas aeruginosa* has demonstrated the ability to degrade 67% of beta-cypermethrin present in a Minimal Salt Medium (MSM), containing 100 ppm of the pesticide, within a span of four days. Its degradation capability is amplified by its production of the biosurfactant Rhamnolipid, which facilitates the process.[46] Another effective degrader, *Bacillus subtilis*, exhibited a degradation rate of approximately 90% at a concentration of 50 ppm within a week. Moreover, a combined culture of *Streptomyces aureus* and *Bacillus cereus* showcased a robust ability to fully degrade cypermethrin, managing a concentration of 50 ppm in just 72 hours and tolerating up to 500 ppm. These strains were isolated from the activated sludge found in pesticide production industries.[47,48] Finally, the *Pseudomonas species* can process cypermethrin effectively, utilizing around 20 ppm of the pesticide in a mere two days.[49]

5. Degradation of Imidacloprid, Triazophos, and Methyl Parathion

The degradation of pesticides like imidacloprid, triazophos, and methyl parathion is facilitated by various bacterial strains demonstrating significant removal efficiencies. *Klebsiella pneumoniae* is notable for its effectiveness in degrading imidacloprid, managing to eliminate 78% of a 50 ppm solution within a week.[50] Furthermore, other bacterial species including *Rhizobium sp., Bacillus sp., Brevibacterium sp.*, and *Pseudomonas putida* are also proficient in imidacloprid utilization.[51–53] Turning our attention to triazophos degradation, a strain of Bacillus sp., isolated from sewage sludge, has proven its prowess by reducing a 100 ppm concentration to a mere 1.5% in a 5-day window, with intracellular enzymes playing a pivotal role in the process.[54] Regarding methyl parathion degradation, the *Pseudomonas aeruginosa* mpd strain, isolated from pesticide contaminated fields, exhibited remarkable efficiency. Under optimal conditions, it can effectively degrade around 95% of a 1000 ppm methyl parathion concentration present in synthetic wastewater within 96 hours.[55] Moreover, several other bacterial strains such as *Pseudomonas diminuta, Pseudomonas putida, Burkholderia cepacia, Ochrobactrum anthropi, Bacillus pumilus, Serratia sp., Achromobacter sp.*, and *Flavobacterium sp.* have been identified as potent agents in the degradation of methyl parathion.[56–58]

6. Diazinon Degradation

Diazinon is categorized as a moderately toxic contact insecticide. Certain bacteria exhibit the capacity to utilize diazinon as a carbon source, thereby aiding in its degradation. Notably, the bacterium Serratia marcescens, isolated from soil samples, has demonstrated its ability to degrade diazinon. Utilizing minimal salt medium (MSM) supplemented with diazinon at a concentration of 50 ppm, along with a cellular concentration of 106 cfu/ml, the bacteria managed to completely degrade the pesticide in a span of 11 days. It should be noted that the rate of pesticide removal fluctuates based on the inoculum concentration, with higher pesticide concentrations lowering the rate of degradation. Additionally, this bacterium showcases the versatility to degrade other pesticides from the organophosphate group such as parathion, chlorpyrifos, isazofos, and coumaphos.[59] Another bacterium, *Ralstonia sp.*, is adept at breaking down a broad and complex array of environmental pollutants, exhibiting a remarkable ability to adapt to various environmental conditions. It can effectively degrade diazinon, achieving significant breakdown at a concentration of 100 ppm within a 60-hour incubation period.[60] Furthermore, several other bacterial strains including *Flavobacterium sp., Brevundimonas sp., Pseudomonas sp., Arthrobacter sp., Burkholderia sp.*, and *Agrobacterium* are also proficient in degrading diazinon, highlighting their role in mitigating the environmental impacts of this insecticide.[61,62]

7. Chlorpyrifos Decomposition

The *Bacillus pumilus* C2A1 strain demonstrates a proficient capability in decomposing chlorpyrifos and its initial hydrolysis by-product, 3, 5, 6-trichloro-2-pyridinol. This bacterial strain can dismantle up to 90% of the metabolite within an 8-day incubation period at a concentration of 300mg/L. The degradation process is optimized under alkaline conditions, and the bacteria can endure chlorpyrifos concentrations of up to 1000 ppm.[63] When coupled with ryegrass in soil remediation efforts, the same strain can facilitate up to 97% pesticide decomposition within 45 days. Ryegrass aids in fostering bacterial growth, thereby enhancing the breakdown of chlorpyrifos metabolites and promoting plant growth and pesticide remediation processes.[64] In addition, the *Enterobacter sp.* exhibits a remarkable capacity to degrade 250 ppm of chlorpyrifos in less than 2 days, without any discernible impact on its growth due to the presence of the primary metabolite.[65] The *Pseudomonas sp.* is also recognized for its ability to break down chlorpyrifos metabolites.[66] Moreover, *Alcaligenes faecalis*, isolated from soil contaminated by a chemical factory, can decompose both chlorpyrifos and its by-products. Studies indicate an enhanced degradation in soil conditions when coupled with cabbage cultivation. Remarkably, within a 10-day incubation period in a liquid culture setup, this bacterium achieved 93.5% chlorpyrifos degradation and complete decomposition of its by-product, even at elevated concentrations exceeding 800 ppm of 3, 5, 6-trichloro-2-pyridinol. Furthermore, it can also utilize other pesticides like diazinon and parathion for degradation.[67] The soil-isolated *Providencia stuartii* showcases a significant ability to utilize chlorpyrifos at concentrations ranging between 50 and 200 ppm, sustaining its survival even at 400-700 ppm concentrations.[68] Meanwhile, intestinal microorganisms such as *Escherichia coli, Lactobacillus lactis,* and *Lactobacillus fermentum* are adept at tolerating over 1400 ppm of chlorpyrifos, with *L. lactis* and *L. fermentum* showing more proficient degradation capabilities compared to E. coli.[69]

8. Monocrotophos Breakdown

Bacillus subtilis, a soil isolate, has showcased the ability to break down 1000 ppm of monocrotophos within a span of 72 hours during incubation, attaining a degradation rate of 94.2% with the use of a 2ml culture medium. This high rate of degradation is attributed to the opdA gene, which experiences a 1.5-fold increase in expression throughout the degradation procedure.[70] Other bacterial strains isolated from pesticide-polluted soil, including

Bacillus licheniformis, *Bacillus subtilis, Pseudomonas stutzeri, Rhodococcus phenolicus*, and *Rhococcus ruber* have also demonstrated substantial efficiency in breaking down monocrotophos.[71,72] Moreover, *Paracoccus sp*., isolated from sludge, exhibits a rapid monocrotophos degradation rate, removing approximately 80% of the substance within a mere 6 hours of incubation, and it has been found to also be effective in breaking down the amide group found in certain herbicides.[73] Further, two other effective agents in the degradation of monocrotophos are *Clavibacter michiganense subsp. insidiosum* and *Pseudomonas aeruginosa*. These bacteria have managed to degrade 86% and 98% of monocrotophos, respectively, within a 24-hour incubation period, showcasing their potential as potent bioremediation agents.[74]

8.1. Herbicide breakdown

Studies indicate that *Enterobacter cloaca*, isolated from the roots of *Helianthus tuberosus L* (sunflower), can effectively metabolize the organophosphate herbicide glyphosate, transforming it into harmless end products like sarcosine, which is then further oxidized to glycine. This bacterial strain not only enhances plant growth in conjunction with sugar sorghum and sunflower but also facilitates the survival of root surface bacteria under stressful conditions. Noteworthy is the tolerance demonstrated by *Pseudomonas fluorescens* and *Acetobacter sp*. to high glyphosate concentrations, found in rice field soil, up to 10,000 ppm and 7,200 ppm respectively.[75,76] Furthermore, *Salinicoccus sp*. and *Flavobacterium sp*. have also played a role in glyphosate breakdown, with the former facilitating degradation up to 2250 ppm.[77] Concerning the degradation of other herbicides, metribuzin, a member of the triazinone group, has been reported to be broken down by *Bacillus subtilis, Pseudomonas aeruginosa*, and *Staphylococcus aureus* from paddy fields at a concentration of 25 ppm, including the degradation of the insecticide profenofos.[78] Similarly, Gulosibacter molinativorax can mineralize the thiocarbamate herbicide molinate,[79] and genera like *Arthrobacter, Pseudomonas*, and *Bacillus* have been found to degrade oxyfluorfen herbicide by approximately 83-96%.[80] Atrazine, a prevalent herbicide affecting soil and water bodies, can be utilized by several bacteria like *Arthrobacter sp*., which converts it into non-harmful substances, utilizing its nitrogen content. This strain harbors the atzD gene, enabling it to not only metabolize atrazine but also other triazine herbicides, with various other bacterial genera also participating in this process.[43,81] In another noteworthy case, a consortium consisting of *Rhodococcus sp., Delftia sp*., and *Sphingobium sp*. achieved complete mineralization of 100 ppm acetochlor within 6 days, with each species playing a distinct role in breaking the herbicide down into harmless substances.[82] Several other bacterial species have been reported to effectively degrade acetochlor, including strains like *Pseudomonas oleovorans, Achromobacter*, and *Ensifer adhaerens*.[83,84] Alachlor and atrazine herbicides have been degraded by a bacterial consortium that includes *Alcaligenes sp*. and several species of Pseudomonas.[85] Furthermore, the novel strain *Catellibacterium caeni sp*. has shown proficiency in degrading butachlor, a chloroacetamide herbicide, across a varied range of pH and temperature levels.[86] Similarly, soil isolate *Paracoccus sp*. and other bacteria have demonstrated effectiveness in degrading various chloroacetamide herbicides, including pretilachlor and butachlor.[46,87] A final notable case is the breakdown of the phenoxy herbicide, 2,4-dichlorophenoxyacetic acid, by various bacteria such as *Achromobacter sp*., achieving up to 90% degradation at specific soil concentrations.[88] Additional bacteria have been identified that can rapidly degrade this compound at varying concentrations within a span of 28 hours.[89,90]

8.2. Fungicide breakdown

Various strains of *Bacillus subtilis* have demonstrated the capacity to breakdown carbendazim fungicide both in liquid cultures and soil slurry environments. Initially, these strains swiftly metabolize the fungicide, with the rate slowing down as the concentration decreases, showcasing a rapid growth phase up until day five and decelerating markedly by day twenty-five. Interestingly, these strains can endure carbendazim concentrations as high as 50000 ppm.[91] *Pseudomonas sp*. stands out in its ability to fully metabolize carbendazim and its derivatives, converting a 10 ppm concentration of the fungicide into carbon dioxide within a span of 3 days. Another potent degrader, *Rhodococcus erythropolis*, isolated from pesticide-contaminated soil, manages to eliminate about 99% of 1000 ppm carbendazim in just three days, converting it into benzimidazole and 2-aminobenzimidazole.[92,93] In conjunction with yeast extract, *Ralstonia sp*. enhances the degradation process, achieving approximately 95% breakdown at 500 ppm concentration. Other bacterial species noted for their carbendazim degradation capabilities include *Bacillus pumilus, Burkholderia cepacia, Pseudomonas fluorescens, Sphingomonas paucimobilis*, and *Aeromonas hydrophila*.[94–96] Regarding tolerance to other fungicides, *Bacillus subtilis* and *Pseudomonas fluorescens* have exhibited resistance to mancozeb at levels up to 600 ppm and 1600 ppm, respectively, showcasing their resilience even when exposed to other fungicides like captan and thiram.[97] Furthermore, the benzimidazole fungicide thiophanate methyl has been efficiently metabolized by *Bacillus sp*. and *Enterobacter sp*., utilizing around 77% and 60% respectively over a 16-day incubation period at 50 ppm concentration.[98] In the case of the triazole class of fungicides, *Pseudomonas aeruginosa*, a field isolate, has been successful in degrading propiconazole, using 8 μg/L of the fungicide as a sole carbon source, with the degradation process being facilitated by the CYP450 gene.[99] Another bacterium, *Burkholderia sp*., has also shown proficiency, accounting for 88% degradation of propiconazole within a four-day incubation period.[100] When it comes to the phthalimide category of fungicides, *Bacillus circulans* has displayed a significant ability to degrade captan, particularly when immobilized in polyurethane foam. This setup achieved full degradation of 0.2% captan within a three-day incubation period, maintaining a broad environmental range of activity and notable stability over 120 days, even at heightened concentrations.[101] Remarkably, Bacillus circulans could fully mineralize 1g/L of captan, utilizing by-products generated during the degradation process, with full metabolite utilization noted within a six-day incubation frame.[102]

9. Conclusion

In recent times, the role of nano formulations in the sphere of agriculture is growing monumentally, marking them as preeminent contenders in the development of advanced agrochemical solutions. These innovative compositions offer a plethora of advantages, including facilitating efficacious pest management strategies through the employment of reduced quantities of low-activity constituents compared to their conventional counterparts. This characteristic not only renders them economically favorable but also contributes positively to environmental conservation efforts. Moreover, these nano-formulations are proficient in curbing the premature decomposition of the incorporated components, thereby extending the longevity and preserving the potency of the ingredients. This is a significant stride in enhancing the sustainability of agricultural practices, as it aids in minimizing waste and optimizing resource utilization. The ability of these formulations to convey pesticides without the need for solvents further underscores their eco-friendly attributes, setting a benchmark in the move towards greener agricultural practices. Furthermore, nano formulations have proven to enhance the bio-efficacy of pesticides considerably. This heightened efficiency is not confined to the initial application phase but extends throughout the product's lifecycle, including a noticeably improved shelf life. This aspect not only guarantees sustained effectiveness but also translates to substantial cost savings in the long run, making it a win-win situation for both the environment and the economy. Alongside the advancements in nano formulations, the role of specific bacterial species in managing the environmental impacts of agrochemical residues cannot be understated. These microorganisms exhibit a remarkable ability to utilize the unutilized active ingredients found in pesticides as a source of energy. By converting these residues into harmless substances, these bacteria play a pivotal role in facilitating bioremediation processes, thereby assisting in safeguarding the environment from potential pesticide pollution. In conclusion, the advent of nano formulations represents a significant milestone in the ongoing journey towards more sustainable and responsible agricultural practices. Coupled with the natural biodegradation processes facilitated by specific bacterial species, these advancements offer a holistic approach to pest management and environmental conservation. As we venture further into this era of technological integration in agriculture, it becomes imperative to continue fostering research and innovation in this domain. It is with a harmonious blend of modern science and nature's ingenuity that we can hope to carve a pathway towards a future where agriculture thrives in synergy with the environment, fostering a healthier, and more prosperous world for generations to come.

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None.

11. Conflict of Interest

None.

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