

GreenShield Neem: Microencapsulation Formulation of Neem Leaves as a Sustainable Agricultural Technology for Indonesia 2045

Sulisatun Nisak^{1*}, Aisyah Humairah², Retno Leoditas Lubis³

Universitas Syiah Kuala, Aceh, Indonesia^{1,2,3}

sulisatun@mhs.usk.ac.id^{1*}, aisyah56@mhs.usk.ac.id², retnoleoditalubis128@usk.ac.id³



Article History:

Received on 25 October 2025

1st Revision on 15 November 2025

2nd Revision on 24 December 2025

3rd Revision on 11 January 2026

Accepted on 12 January 2026

Abstract

Purpose: This study proposes GreenShield Neem, a microencapsulated neem (*Azadirachta indica* A. Juss) formulation, as a sustainable biopesticide technology to support environmentally friendly agriculture in Indonesia toward the 2045 vision.

Research Methodology: This study used a structured literature review and a conceptual synthesis. Peer-reviewed articles published between 2014 and 2024 were screened; 42 records were initially identified, and 26 articles were selected for an in-depth review based on predefined inclusion/exclusion criteria. Data analysis was conducted using thematic coding and comparative synthesis by extracting key variables (formulation type, encapsulation method/materials, stability indicators, controlled release behavior, and reported bioefficacy). The extracted evidence was then consolidated to develop the GreenShield Neem conceptual framework and a proposed field-application scenario.

Results: The literature synthesis indicates that neem-based biopesticides possess strong insecticidal properties due to bioactive compounds such as azadirachtin, salannin, and nimbin. However, conventional neem formulations suffer from low stability. Microencapsulation technology significantly enhances the stability, persistence, and efficacy of these bioactive compounds by protecting them against ultraviolet radiation, oxidation, and environmental degradation, while enabling their controlled release in the field.

Conclusions: GreenShield Neem demonstrates strong potential as a sustainable pest-management innovation that can reduce dependence on synthetic pesticides, minimize environmental contamination, and improve the efficiency of agricultural practices.

Limitations: This study is limited to a conceptual, literature-based analysis and lacks experimental validation.

Contributions: This article advances sustainable agriculture by offering a scientifically grounded formulation concept that integrates local biological resources with modern delivery technologies, particularly for tropical agricultural systems.

Keywords: *Azadirachta Indica*, *Biopesticide*, *Microencapsulation*, *Sustainable Agriculture*

How to Cite: Nisak, S. Humairah, A. Lubis, R. L. (2026). GreenShield Neem: Microencapsulation Formulation of Neem Leaves as a Sustainable Agricultural Technology for Indonesia. *Jurnal Ilmiah Pertanian dan Peternakan*, 3(2), 25-35

1. Introduction

Agriculture plays a vital role in Indonesia's socio-economic structure, serving as a major contributor to national food security and a primary source of livelihood for rural communities. As an agrarian country,

Indonesia relies heavily on agricultural productivity to sustain its population growth and economic stability. However, the pursuit of high yields has intensified reliance on synthetic pesticides as the dominant strategy for controlling plant pests and diseases ([Amilia, Joy, & Sunardi, 2016](#)).

Recent global studies have further emphasized that prolonged exposure to synthetic pesticides contributes not only to environmental degradation but also to chronic health problems, including endocrine disruption and carcinogenic risks among agricultural workers. Developing countries are particularly vulnerable due to limited regulatory enforcement and low awareness of safe pesticide-handling practices ([Kim, Kabir, & Jahan, 2017](#)).

Recent global initiatives in sustainable agriculture have emphasized the transition toward 'smart' delivery systems. The use of chitosan-alginate-based nanoparticles has emerged as a state-of-the-art approach for encapsulating botanical extracts, offering superior biocompatibility and controlled-release mechanisms that are crucial for protecting sensitive bioactive molecules such as azadirachtin ([Niculescu & Grumezescu, 2022](#)). This technology not only preserves the bioactivity of neem but also aligns with the rigorous environmental standards required for sustainable crop protection in agriculture. Such "smart delivery" systems can improve the stability and delivery efficiency of sensitive botanical actives (e.g., azadirachtin) using biocompatible carrier materials and controlled-release behavior, which supports sustainability-oriented crop protection strategies ([Bae et al., 2022](#)).

Synthetic pesticides are widely recognized as sources of contamination of soil, water, and air because of their persistent residues and non-selective toxicity ([Kah, Kookana, Gogos, & Bucheli, 2018](#)). Numerous studies have reported adverse health effects among farmers and agricultural workers exposed to pesticide residues, ranging from acute poisoning to long-term neurological and systemic disorders. The World Health Organization estimates that millions of pesticide poisoning cases occur annually, with developing countries contributing to the majority of global fatalities ([Ibrahim & Sillehu, 2022](#)). Furthermore, improper pesticide application contributes to pest resistance, ecosystem imbalance, and biodiversity loss, ultimately reducing the sustainability of agricultural production systems ([Pavela & Benelli, 2016](#)).

The use of neem (*Azadirachta indica* A. Juss) as a biopesticide has gained significant attention because of its complex mode of action, primarily driven by azadirachtin, which acts as an antifeedant, repellent, and insect growth regulator ([Adhikari, Bhandari, Niraula, & Shrestha, 2020](#)). Despite its efficacy, the rapid photodegradation of its active compounds remains a primary constraint for large-scale adoption ([Muhammad & Kashere, 2020](#)). Therefore, the development of eco-friendly delivery systems, such as plant-derived nanopesticides, offers a promising strategy for mitigating these environmental challenges while maintaining high insecticidal potency ([Gahukar & Das, 2020](#)).

In response to these challenges, botanical pesticides have gained increasing attention as environmentally friendly alternatives to synthetic pesticides. Indonesia possesses abundant plant biodiversity and significant potential for biopesticide development. One of the most promising species is neem (*Azadirachta indica* A. Juss), a plant known for its rich content of bioactive secondary metabolites such as azadirachtin, salannin, meliatriol, and nimbin ([Hasibuan, Manurung, & Nasution, 2021](#)). These compounds exhibit insecticidal properties by disrupting the feeding behavior, growth, and reproduction of various agricultural pests, while posing minimal risk to non-target organisms ([Isman, 2020](#)). Furthermore, the strategic development of neem-based formulations is increasingly recognized as a vital pathway toward a sustainable future, offering a viable and eco-friendly alternative to conventional chemical interventions in agriculture ([Perveen, 2024](#)).

Several studies have demonstrated the effectiveness of neem-based pesticides in controlling major agricultural pests. Neem formulations have been reported to suppress leaf-eating insects and sap-sucking pests, with mortality rates comparable to those of synthetic pesticides, particularly in tropical cropping systems ([Fatikhin, Rosdiana, & Roqobih, 2023](#)). Moreover, neem-based pesticides are biodegradable and environmentally friendly, reducing the risk of long-term environmental contamination. Recent reviews have highlighted that azadirachtin-based neem-derived formulations

exhibit multi-target pest-control mechanisms, reducing the likelihood of pest resistance compared to single-mode synthetic pesticides. This characteristic strengthens the potential role of neem in sustainable and integrated pest management strategies ([Ngegba, Cui, Khalid, & Zhong, 2022](#)).

Despite their ecological advantages, conventional neem-based pesticides face major limitations, particularly their low stability under field conditions. Neem bioactive compounds are highly sensitive to ultraviolet radiation, oxygen, and temperature, leading to their rapid degradation and reduced efficacy ([Isman, 2020](#)). Consequently, frequent reapplication is required, thereby diminishing practicality and discouraging adoption among farmers.

To address these constraints, microencapsulation technology has emerged as a promising solution for enhancing the performance of botanical pesticides. Microencapsulation involves enclosing bioactive compounds within biodegradable polymer matrices, providing protection against environmental degradation and enabling controlled release mechanisms ([Koul, Walia, & Dhaliwal, 2008](#); [Zabot et al., 2022](#)). Recent studies have demonstrated that microencapsulated neem formulations exhibit improved stability, prolonged insecticidal activity, and greater effectiveness than conventional neem extracts ([Michel, Aguilar-Zárate, Rojas, Martínez-Ávila, & Aguilar-Zárate, 2023](#)).

Therefore, this study proposes GreenShield Neem, a microencapsulated neem leaf formulation designed for sustainable pest management. By integrating local biological resources with advanced formulation techniques, GreenShield Neem is expected to support environmentally responsible agriculture, reduce dependence on chemical pesticides, and contribute to Indonesia's long-term agricultural sustainability goals by 2045.

2. Literature Review

Neem contains over 100 bioactive compounds, mainly triterpenoids and limonoids. The complexity of these compounds makes neem exceptionally effective against pests that have developed resistance to synthetic chemicals with a single mode of action. Unlike synthetic insecticides that typically target the nervous system, neem disrupts the insect's life cycle at multiple points. The growing concern regarding the adverse effects of synthetic pesticide use has prompted extensive research into alternative pest control strategies, particularly botanical pesticides. Although synthetic pesticides are effective, they have been associated with environmental contamination, bioaccumulation, pest resistance, and adverse health effects in farmers and consumers. These issues have encouraged the exploration of plant-based pesticides as safer and more sustainable options for agricultural pest management in recent years.

Botanical pesticides are derived from plant secondary metabolites and exhibit insecticidal, repellent, antifeedant, or growth-regulating properties. Among the various botanical sources, neem (*Azadirachta indica* A. Juss) has been widely studied because of its broad-spectrum activity and low toxicity to nontarget organisms. Previous studies have reported that neem leaf extracts contain bioactive compounds, including azadirachtin, salannin, nimbin, and meliatriol, which interfere with insect feeding behavior, molting, and reproduction. These characteristics make neem-based pesticides suitable for integration into sustainable and Integrated Pest Management (IPM) systems.

Azadirachtin is the most prominent compound, acting as an Ecdysone agonist. It prevents larvae from molting and disrupts the endocrine system of more than 200 pest species. Its structure is highly complex, featuring a dense arrangement of oxygenated functional groups, which makes synthetic production economically unviable; hence, extraction from natural sources remains the only practical method. Azadirachtin works primarily by inhibiting the release of Prothoracicotropic Hormones (PTTH) and allatostatins from the insect brain. This effectively "freezes" the pest's development at the larval or nymphal stage, preventing them from reaching adulthood and reproducing. Because it mimics a natural hormone, pests find it nearly impossible to evolve resistance through simple metabolic mutations.

Several studies have demonstrated the effectiveness of conventional neem formulations against a wide range of agricultural pests. Neem-based pesticides have been reported to suppress the populations of leaf-eating insects, sap-sucking pests, and storage pests with relatively high mortality rates. Moreover,

neem formulations are biodegradable and environmentally friendly, reducing the risk of long-term soil and water contamination. Despite these advantages, the practical application of neem-based pesticides remains limited because of their poor stability under environmental conditions.

Several recent studies have demonstrated that the instability of neem bioactive compounds under field conditions remains a major barrier to their large-scale adoption. Photodegradation of azadirachtin can exceed 50% within a few days of exposure to sunlight, significantly reducing insecticidal effectiveness ([Kah et al., 2018](#)).

Environmental factors, including ultraviolet radiation, temperature fluctuations, and oxidation, significantly reduce the persistence of neem bioactive compounds. Research has shown that azadirachtin degrades rapidly under sunlight, reducing its insecticidal activity and necessitating frequent reapplication. This limitation reduces labor efficiency and discourages farmers from adopting neem-based pest control, particularly in tropical regions with high solar radiation and rainfall.

To overcome these limitations, recent studies have focused on advanced formulation technologies such as nanoformulation and microencapsulation. Microencapsulation involves enclosing active ingredients within protective polymeric matrices to improve stability, control release rates, and enhance field performance. Research indicates that microencapsulated neem formulations exhibit greater photodegradation resistance, longer residual activity, and greater pest control efficacy than non-encapsulated extracts.

Various microencapsulation methods, including complex coacervation, spray drying, and polymer-based encapsulation, have been explored for neem formulations. Studies using biodegradable polymers have reported increased protection of azadirachtin and other neem compounds, allowing for gradual release and sustained insecticidal activity. These findings suggest that microencapsulation can significantly enhance the functional performance of botanical pesticides while maintaining their environmental safety.

Despite the growing body of research on neem-based pesticides and microencapsulation technologies, several research gaps persist. Most existing studies focus on laboratory-scale experiments or specific pest species, with limited emphasis on conceptual frameworks for scalable, farmer-oriented applications in tropical agricultural systems. In addition, few studies have integrated microencapsulation technology with socio-economic considerations such as cost efficiency, accessibility for smallholder farmers, and alignment with national agricultural sustainability goals.

Microencapsulation is the process of enclosing a substance (core) within another material (shell) at the microscopic scale. This technology, originally developed for the pharmaceutical and food industries to protect sensitive vitamins and drugs, is now being adapted for use in high-value agricultural inputs. The goal of agriculture is to provide a "time-release" mechanism and protection from environmental stressors. Advances in microencapsulation technology over the past decade have demonstrated its effectiveness in enhancing the stability and controlled release of botanical pesticides. Studies have reported that encapsulated neem formulations exhibit longer residual activity, improved rainfastness, and reduced degradation rates compared to non-encapsulated extracts, making them more suitable for tropical agricultural environments ([Michel et al., 2023](#); [Zabot et al., 2022](#)).

Sustainable agriculture in Indonesia is governed by several national policies, including the Sustainable Food Agricultural Land (LP2B) policy and the "Green Economy" initiatives of the Ministry of Environment and Forestry. The transition toward organic and semi-organic farming is promoted to improve the quality of Indonesian agricultural exports and to protect national soil health. European and Japanese markets, in particular, have strict Maximum Residue Levels (MRLs) for synthetic pesticides, often rejecting Indonesian shipments that exceed these limits. Biopesticides, such as GreenShield Neem, provide a solution for Indonesian farmers to meet these international standards, thereby increasing the competitiveness of local produce, such as coffee, cocoa, and exotic fruits.

Furthermore, the Indonesian government has committed to reducing its carbon footprint; transitioning from energy-intensive synthetic chemical production to bio-based alternatives, such as neem, supports this national climate goal. Therefore, this study addresses this research gap by proposing GreenShield Neem, a conceptual microencapsulated neem-based biopesticide designed for sustainable agriculture in Indonesia. This study synthesizes existing scientific evidence to highlight the potential of microencapsulation technology to improve the stability, effectiveness, and applicability of neem-based pest control, particularly in the context of Indonesia's agricultural development toward 2045.

3. Methodology

3.1 Research Design

This study employed a structured literature review approach to synthesize recent scientific findings related to neem-based biopesticides and microencapsulation technologies in sustainable agriculture. The literature search was conducted using major scientific databases, including Google Scholar, ScienceDirect, and Scopus. The inclusion criteria were as follows: (1) peer-reviewed journal articles published between 2014 and 2024, (2) studies discussing *Azadirachta indica*, azadirachtin stability, botanical pesticides, or microencapsulation technology, (3) articles written in English, and (4) research focusing on agricultural applications. Articles not directly related to pest management or lacking sufficient scientific rigor were excluded from the analyses.

The initial search identified 42 relevant publications. After screening titles, abstracts, and full texts for relevance and methodological quality, 26 articles were selected for an in-depth analysis. The selected studies were categorized into four thematic areas: (1) environmental impacts of synthetic pesticides, (2) limitations of conventional neem formulations, (3) mechanisms of microencapsulation, and (4) controlled release performance in agricultural systems. Data from the selected literature were analyzed descriptively and comparatively to identify research trends, technological advancements, and existing gaps in the development of stable neem-based biopesticide formulations.

3.2 Data Sources and Literature Selection

The data used in this study were obtained from peer-reviewed scientific journals, conference proceedings, and reputable academic publications on botanical pesticides, neem (*Azadirachta indica* A. Juss.) and sustainable agriculture. Priority was given to international journal articles published within the last ten years to ensure relevance and scientific accuracy. Additional supporting references were drawn from authoritative national journals to contextualize the discussion within the context of Indonesian agricultural conditions. The literature selection process was conducted using keyword-based searches such as "neem biopesticide," "*Azadirachta indica*," "microencapsulation," "controlled release," and "sustainable pest management." Selected articles were screened for relevance to formulation stability, protection of bioactive compounds, application efficiency and environmental impact.

3.3 Conceptual Framework of GreenShield Neem

The conceptual framework of GreenShield Neem integrates neem leaf bioactive compounds with microencapsulation technology to enhance the performance of pesticides. Neem leaves contain insecticidal secondary metabolites, particularly azadirachtin, which acts as an antifeedant, growth regulator, and reproductive inhibitor in insect pests. However, these compounds are highly susceptible to degradation under environmental conditions, such as ultraviolet radiation and temperature fluctuations. Microencapsulation is a protective delivery system in which neem extract particles are enclosed within biodegradable polymer matrices. This system is designed to shield bioactive compounds from environmental degradation while enabling their controlled release after application. Consequently, the availability of active compounds on plant surfaces can be sustained for a longer duration, reducing the need for frequent pesticide applications.

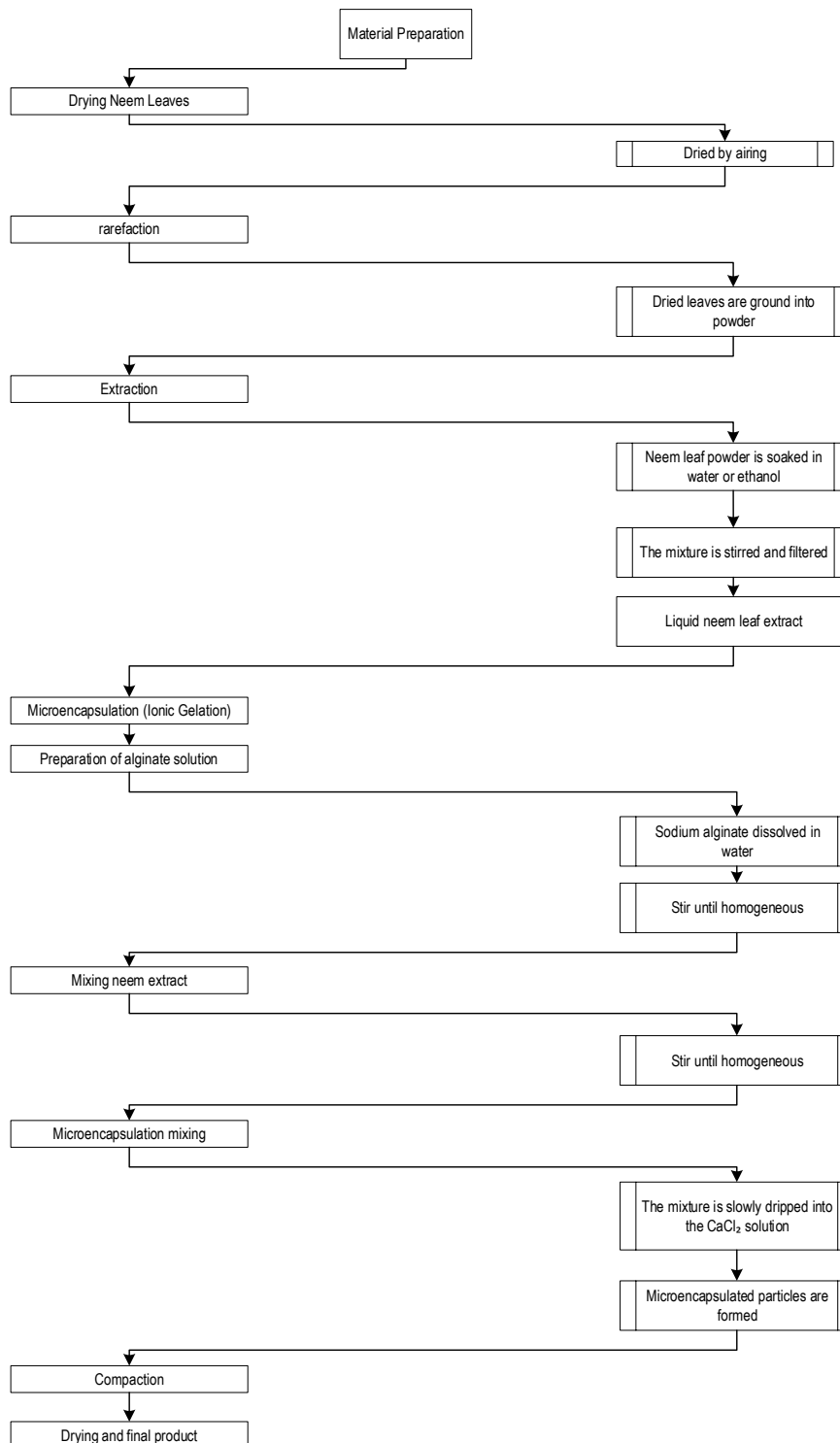


Figure 1. The following is a flow diagram of the Greenshield Neem manufacturing process

3.4 Analytical Approach

The analytical approach of this study involved a qualitative synthesis and comparative analysis of the findings from the selected literature. The key parameters analyzed included the stability of neem bioactive compounds, pest control efficacy, application frequency, and environmental safety. A comparative evaluation was conducted among conventional neem formulations, microencapsulated neem products, and synthetic pesticides using performance indicators reported in previous studies. This synthesis was used to identify the patterns, advantages, and limitations of existing approaches, forming the basis for proposing GreenShield Neem as a viable sustainable pest management technology. The

applicability of the proposed formulation within tropical agricultural systems, particularly those characterized by high rainfall and solar radiation, was also considered.

3.5 Ethical and Sustainability Considerations

As a literature-based conceptual study, this research did not involve human or animal subjects and therefore did not require ethical clearance. Nevertheless, ethical considerations were addressed through responsible citation practices and acknowledgment of the original research sources. Sustainability considerations were emphasized by prioritizing environmentally friendly materials, biodegradable encapsulation matrices, and alignment with the principles of integrated pest management. Through this methodological approach, this study aims to provide a robust conceptual foundation for the future experimental validation and field-scale implementation of GreenShield Neem in sustainable agricultural systems.

4. Results and Discussions

4.1 Performance of Neem-Based Biopesticides

The reviewed literature consistently demonstrates that neem (*Azadirachta indica* A. Juss.) has strong potential as a botanical pesticide because of its high content of bioactive compounds, particularly azadirachtin, salannin, nimbin, and meliatriol. These compounds act through multiple mechanisms, including antifeedant activity, growth regulation, and disruption of reproductive cycles. Neem-based biopesticides are effective against a wide range of agricultural pests, including leaf-eating insects, sap-sucking pests, and storage pests.

Several studies have reported that conventional neem formulations can achieve pest mortality rates comparable to those of synthetic pesticides under controlled conditions. In addition to their effectiveness, neem-based pesticides offer significant environmental advantages such as biodegradability and low toxicity to non-target organisms. These characteristics make neem suitable for integration into sustainable agriculture and Integrated Pest Management (IPM) systems. However, despite these advantages, the practical effectiveness of conventional neem formulations under field conditions remains limited.

Advanced extraction methodologies, such as Microwave-Assisted Extraction (MAE) and ultrasonically intensified processes, have been optimized to achieve higher azadirachtin yields from neem leaves. Studies have indicated that optimizing extraction parameters using response surface methodology can significantly enhance the concentration of active metabolites, providing a more potent raw material for microencapsulation ([Bhadange, Karn, & Saharan, 2024](#); [Martínez-Castro, Flórez-Santiago, Valle-Molinares, Cabrera-Barraza, & Espitia-Almeida, 2024](#)). Furthermore, the development of thermoresponsive chitosan nanocapsules represents a breakthrough in pesticide delivery, allowing for 'on-demand' controlled release. These smart carriers maximize synergistic biological activity by releasing active ingredients in response to environmental temperature fluctuations, thereby increasing efficacy while minimizing waste ([Chen et al., 2022](#)).

4.2 Limitations of Conventional Neem Formulations

One of the primary challenges associated with conventional neem-based pesticides is their low stability under environmental conditions. Neem bioactive compounds are highly susceptible to degradation when exposed to ultraviolet radiation, oxygen, rainfall, and temperature variation. Rapid photodegradation of azadirachtin significantly reduces its residual activity on plant surfaces, thereby decreasing pest control efficacy. Consequently, farmers are required to apply neem-based pesticides more frequently than they do synthetic pesticides. This frequent application increases labor requirements and reduces cost efficiency, particularly for smallholder farmers. These limitations explain why many farmers remain reluctant to adopt botanical pesticides, despite their environmental benefits.

Recent advancements in formulation technology have highlighted the efficacy of diverse encapsulation methods. For instance, the optimization of complex coacervation has been shown to enhance the insecticidal activity of neem leaf extracts by ensuring better protection of core materials ([Michel et al.,](#)

2023). Additionally, the application of spray-drying techniques using biodegradable matrices facilitates the acquisition of microencapsulated extracts with superior physical stability and controlled release profiles (Bezerra et al., 2021). The use of biogenic materials and lignin-based compounds further aligns the formulation with sustainable agricultural goals, providing a robust shield against UV radiation and oxidative stress (Costa et al., 2021; Odelade et al., 2024).

4.3 Effect of Microencapsulation on Stability and Controlled Release

Microencapsulation technology offers a promising solution to overcome the instability of neem bioactive compounds. Microencapsulation provides physical protection against environmental stressors, such as ultraviolet radiation and oxidation, by enclosing neem extracts within biodegradable polymer matrices. Studies have shown that microencapsulated neem formulations exhibit significantly improved stability and prolonged insecticidal activity compared with non-encapsulated extracts. In addition to protection, microencapsulation enables the controlled release of bioactive compounds.

Controlled-release mechanisms enable the gradual diffusion of active ingredients over time, thereby maintaining effective concentrations on plant surfaces for extended periods of time. This sustained availability reduces the frequency of pesticide application while preserving the pest control performance. Microencapsulated neem formulations demonstrated higher application efficiency and improved field practicality. Controlled release behavior not only improves pest control efficiency but also reduces excessive pesticide use, thereby lowering production costs and minimizing environmental exposure. This advantage is particularly relevant for smallholder farmers who require cost-effective and labor-efficient pest-management solutions (Ngegba et al., 2022).

4.4 Comparative Analysis of Pest Control Approaches

Based on the synthesized literature, microencapsulated neem formulations, such as GreenShield Neem, offer several advantages over conventional neem extracts and synthetic pesticides. Synthetic pesticides are highly stable and effective but often leave harmful residues and pose risks to human health and the environment. Conventional neem formulations are environmentally safe but suffer from rapid degradation and low persistence rates.

Bioengineering approaches, such as the development of colloidal nano-emulsions, have demonstrated improved surface adhesion on plant foliage, leading to prolonged biological activity against persistent pests (Iqbal, Hazra, Purkait, Kumar, & Kumar, 2020). Experimental data from 2023 indicate that neem-based insecticides effectively control specialized pests, such as the white mango scale, demonstrating significant potency even in aqueous extract forms (Fita, Getu, Wakgari, & Woldetsadike, 2023). Moreover, cutting-edge nanoprecipitation techniques utilizing glycine matrices have achieved enhanced azadirachtin stability, proving effective against highly mobile pests such as the fall armyworm (*Spodoptera frugiperda*) (Bae et al., 2025).

GreenShield Neem, a microencapsulated formulation, combines the environmental safety of botanical pesticides with enhanced stability and controlled release characteristics. This combination allows for reduced application frequency, improved labor efficiency, and minimized exposure of farmers to the active compounds. Furthermore, the biodegradable nature of encapsulation materials supports environmental sustainability and aligns with the principles of integrated pest management.

Recent field optimization studies conducted in 2025 have demonstrated that aqueous neem leaf extracts at concentrations of 2–4 g·L⁻¹ are highly effective in controlling whitefly (*Bemisia tabaci*) populations. These applications significantly reduced pest attack intensity to as low as 3.43% and enhanced crop yields in vegetable production systems (Yunus et al., 2025). Moreover, integrated organic modules utilizing neem have reported up to a 40% reduction in foliar damage caused by diverse pest complexes in tropical crops like okra (Sadick et al., 2025).

4.5 Implications for Sustainable Agriculture in Indonesia

The application of microencapsulated neem-based biopesticides has significant implications for sustainable agriculture in Indonesia. Tropical agricultural systems are characterized by high solar

radiation and rainfall, which accelerate the degradation of conventional botanical pesticides. Microencapsulation technology addresses these challenges by extending the functional lifespan of neem bioactive compounds under tropical conditions.

By reducing the dependency on synthetic pesticides, GreenShield Neem has the potential to improve environmental quality, protect farmer health, and enhance long-term agricultural sustainability. A comparative evaluation of previous studies indicates that while conventional neem extracts demonstrate strong insecticidal properties, their effectiveness under field conditions is often limited by photodegradation and rapid environmental breakdown. In contrast, microencapsulated neem formulations enhance azadirachtin protection against ultraviolet radiation and environmental stressors, resulting in prolonged residual activity.

Compared to synthetic pesticides, which typically rely on a single active mode of action, neem-based formulations provide multi-target mechanisms that simultaneously disrupt insect growth, feeding behavior, and reproduction. This multifaceted mode of action potentially reduces the risk of resistance. However, challenges remain regarding large-scale production, cost efficiency, and field validation in diverse agro-climatic conditions. Therefore, further experimental and techno-economic studies are necessary to support the practical implementation of microencapsulated neem formulations in agriculture.

Additionally, the use of locally available neem resources supports input self-sufficiency and provides opportunities for community-based agro-industrial developments. These benefits position GreenShield Neem as a strategic innovation for achieving environmentally responsible agriculture and supporting Indonesia's 2045 development goals.

5. Conclusions

5.1 Conclusion

This literature-based study indicates that microencapsulation can address the key limitation of rapid environmental degradation of conventional neem formulations by improving stability and enabling controlled release. Accordingly, GreenShield Neem is proposed as a sustainable biopesticide with the potential to reduce application frequency and support safer pest management in tropical agriculture. Future work should validate this concept through laboratory and field trials, including release kinetics testing, efficacy against target pests, and techno-economic feasibility.

5.2 Research Limitations

This study is limited by its conceptual and literature-based nature. The analysis relies on secondary data from previous studies without experimental validation through laboratory or field trials. Consequently, quantitative measurements of efficacy, optimal dosage, and long-term field performance could not be directly assessed in this study. Additionally, variations in neem plant quality, formulation materials, and environmental conditions were not empirically examined in this study.

5.3 Suggestions and Directions for Future Research

Future research should focus on the experimental validation of GreenShield Neem through laboratory and field-scale trials to evaluate its effectiveness against specific pest species under diverse agroecological conditions. Further studies are recommended to optimize encapsulation materials, release kinetics, and formulation costs to ensure affordability for smallholder farmers. Socio-economic assessments and regulatory studies are needed to support the large-scale adoption and commercialization of microencapsulated neem-based biopesticides within integrated pest management systems.

Acknowledgement

The authors would like to express their gratitude to their academic supervisors and contributors for their guidance and support during the preparation of this study. We also appreciate the contributions of all researchers whose work contributed to the development of this conceptual framework.

Author Contributions

SN conceptualized the study, conducted the literature review, developed the formulation concept, and prepared the manuscript draft. AH contributed to the data collection, literature screening, and manuscript editing. RLL provided supervision, methodological guidance, and critical review of the manuscript. All authors have read and approved the final version of the manuscript.

References

- Adhikari, K., Bhandari, S., Niraula, D., & Shrestha, J. (2020). Use of neem (*Azadirachta indica* A. Juss) as a biopesticide in agriculture: A review. *Journal of Agriculture and Applied Biology*, 1(2), 100-117. doi:<https://doi.org/10.11594/jaab.01.02.08>
- Amilia, E., Joy, B., & Sunardi, S. (2016). Residu pestisida pada tanaman hortikultura (studi kasus di desa cihanjuang rahayu kecamatan parongpong kabupaten bandung barat). *Agrikultura*, 27(1). doi:<https://doi.org/10.24198/agrikultura.v27i1.8473>
- Bae, M., Lewis, A., Liu, S., Arcot, Y., Lin, Y.-T., Bernal, J. S., . . . Akbulut, M. (2022). Novel biopesticides based on nanoencapsulation of azadirachtin with whey protein to control fall armyworm. *Journal of agricultural and food chemistry*, 70(26), 7900-7910. doi:<https://doi.org/10.1021/acs.jafc.2c01558>
- Bae, M., Lewis, A., Liu, S., Arcot, Y., Lin, Y.-T., Viswanadha, L. S., . . . Cisneros-Zevallos, L. (2025). Tailoring Biopesticides: Amphiphile-Assisted Nanoprecipitation of Azadirachtin within a Glycine Matrix for Sustainable Agriculture, Enhanced Stability, and Larvicidal Efficacy against Fall Armyworm. *ACS omega*, 10(34), 38766-38779. doi:<https://doi.org/10.1021/acsomega.5c04028>
- Bezerra, D. G., Devilla, I. A., da Conceicao, E. C., Czepak, C., Albernaz Godinho, K. C., Caramori, S. S., . . . de Paula, J. A. M. (2021). Microencapsulated extracts from *Azadirachta indica* seeds: Acquisition, characterization, and use in controlling *Helicoverpa armigera*. *Drying Technology*, 39(10), 1325-1338. doi:<https://doi.org/10.1080/07373937.2020.1745823>
- Bhadange, Y. A., Karn, A., & Saharan, V. K. (2024). Ultrasonically intensified extraction and emulsification of Azadirachtin and its bioactivity analysis for fenugreek crop growth. *Chemical Engineering and Processing-Process Intensification*, 199, 109748. doi:<https://doi.org/10.1016/j.cep.2024.109748>
- Chen, H., Zhi, H., Feng, B., Cui, B., Zhao, X., Sun, C., . . . Zeng, Z. (2022). Thermo-responsive quaternary ammonium chitosan nanocapsules with on-demand controlled pesticide release and maximally synergistic biological activity. *Journal of agricultural and food chemistry*, 70(25), 7653-7661. doi:<https://doi.org/10.1021/acs.jafc.2c01791>
- Costa, E. N., Forim, M. R., Costa, E. S., Nogueira, L., de Moraes, R. F. O., & Boica Junior, A. L. (2021). Lignin-based compounds for the microencapsulation of neem extract for the control of *Diabrotica speciosa* (Coleoptera: Chrysomelidae) larvae on maize roots. *Phytoparasitica*, 49(5), 959-970. doi:<https://doi.org/10.1007/s12600-021-00915-x>
- Fatikhin, A. C., Rosdiana, L., & Roqobih, F. D. (2023). Studi Literatur: Efektivitas Daun Mimba sebagai Pestisida Nabati Pengusir Ulat Grayak pada Tanaman Jagung: pestisida nabati; mimba; ulat grayak; tanaman jagung. *Innofarm: Jurnal Inovasi Pertanian*, 25(2). doi:<https://doi.org/10.33061/innofarm.v25i2.9065>
- Fita, T., Getu, E., Wakgari, M., & Woldetsadike, K. (2023). Potency of Neem, *Azadirachta indica* L.(A. juss) Leaf Aqueous Extract Insecticide against White Mango Scale, *Aulacuspis tubercularis* Newstead (Homoptera: Diaspididae) Infesting Mango (*Mangifera indica* L.) *Insecticides-Advances in Insect Control and Sustainable Pest Management*: IntechOpen.
- Gahukar, R. T., & Das, R. K. (2020). Plant-derived nanopesticides for agricultural pest control: challenges and prospects. *Nanotechnology for Environmental Engineering*, 5(1), 3. doi:<https://doi.org/10.1007/s41204-020-0066-2>
- Hasibuan, M., Manurung, E. D., & Nasution, L. Z. (2021). *Pemanfaatan daun mimba (Azadirachta indica) sebagai pestisida nabati*. Sebelas Maret University.
- Ibrahim, I., & Sillehu, S. (2022). Identifikasi aktivitas penggunaan pestisida kimia yang berisiko pada kesehatan petani hortikultura. *Maluku: Jumantik*, 7(1), 7-12. doi:<https://doi.org/10.30829/jumantik.v7i1.10332>

- Iqbal, N., Hazra, D., Purkait, A., Kumar, N., & Kumar, J. (2020). Bioengineering of neem colloidal nano-emulsion formulation with adjuvant for better surface adhesion and long term activity in insect control. *PREPRINT (Version 1) available at Research Square*, 10. doi:<https://doi.org/10.21203/rs.3.rs-116370/v1>
- Isman, M. B. (2020). Botanical insecticides in the twenty-first century—fulfilling their promise? *Annual Review of Entomology*, 65(1), 233-249. doi:<https://doi.org/10.1146/annurev-ento-011019-025010>
- Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature nanotechnology*, 13(8), 677-684. doi:<https://doi.org/10.1038/s41565-018-0131-1>
- Kim, K.-H., Kabir, E., & Jahan, S. A. (2017). Exposure to pesticides and the associated human health effects. *Science of the total environment*, 575, 525-535. doi:<https://doi.org/10.1016/j.scitotenv.2016.09.009>
- Koul, O., Walia, S., & Dhaliwal, G. (2008). Essential oils as green pesticides: potential and constraints. *Biopestic. Int*, 4(1), 63-84.
- Martínez-Castro, R., Flórez-Santiago, J., Valle-Molinares, R., Cabrera-Barraza, J., & Espitia-Almeida, F. (2024). Optimized microwave-assisted azadirachtin extraction using response surface methodology. *Heliyon*, 10(10). doi:<https://doi.org/10.1016/j.heliyon.2024.e31504>
- Michel, M. R., Aguilar-Zárate, M., Rojas, R., Martínez-Ávila, G. C. G., & Aguilar-Zárate, P. (2023). The insecticidal activity of Azadirachta indica leaf extract: optimization of the microencapsulation process by complex coacervation. *Plants*, 12(6), 1318. doi:<https://doi.org/10.3390/plants12061318>
- Muhammad, A., & Kashere, M. (2020). Neem, Azadirachta indica L.(A. Juss): an eco-friendly botanical insecticide for managing farmersâ€™ insects pest problems-a review. *FUDMA Journal of Sciences*, 4(4), 484-491. doi:<https://doi.org/10.33003/fjs-2020-0404-506>
- Ngegba, P. M., Cui, G., Khalid, M. Z., & Zhong, G. (2022). Use of botanical pesticides in agriculture as an alternative to synthetic pesticides. *Agriculture*, 12(5), 600. doi:<https://doi.org/10.3390/agriculture12050600>
- Niculescu, A., & Grumezescu, A. (2022). Applications of chitosan-alginatebased nanoparticles—an up-to-date review. *Nanomaterials* 2022; 12: 186: s Note: MDPI stays neutral with regard to jurisdictional claims in published
- Odelade, K. A., Adetuyi, B. O., Fasoyin, A. I., Abiona, O. A., Andem, W. A., Odelade, D. A., & Adetunji, C. O. (2024). Recent Advances in the Application of Biogenic Materials in the Formulation of Nanobioinsecticide Derived from Azadirachta indica. *Handbook of Agricultural Biotechnology*, 4, 361-382. doi:<https://doi.org/10.1002/9781394234769.ch55>
- Pavela, R., & Benelli, G. (2016). Ethnobotanical knowledge on botanical repellents employed in the African region against mosquito vectors—a review. *Experimental parasitology*, 167, 103-108. doi:<https://doi.org/10.1016/j.exppara.2016.05.010>
- Perveen, K. (2024). Neem’s promise: the way to a sustainable future and eco-friendly biopesticides. *Int J Sci Res Arch*, 11(02), 1073-1082. doi:<https://doi.org/10.30574/ijrsra.2024.11.2.0532>
- Sadick, A., Marfo-Ahenkora, E., Gyekye, P. M., Frimpong-Manso, J., Musah, M., & Agyekum, A. (2025). The Potential of Neem as an Organic Fertilizer and Biopesticide for Enhancing Soil Fertility, Nematode and Foliar Pest Suppression, and Okra Growth. *Journal of Agriculture and Ecology Research International*, 26(4), 166-182. doi:<https://doi.org/10.9734/jaeri/2025/v26i4691>
- Yunus, M., Khasanah, N., Nasir, B. H., Pasaru, F., Wahid, A., Lasmini, S. A., . . . Vegayatri, N. K. A. (2025). Optimization of Neem Leaf Extract (Azadirachta indica A. Juss) to Control Whitefly (Bemisia tabaci (Gennadius) on Eggplant (Solanum melongena L.). *International Journal of Plant & Soil Science*, 37(8), 437-446. doi:<https://doi.org/10.9734/ijpss/2025/v37i85645>
- Zabot, G. L., Schaefer Rodrigues, F., Polano Ody, L., Vinicius Tres, M., Herrera, E., Palacin, H., . . . Olivera-Montenegro, L. (2022). Encapsulation of bioactive compounds for food and agricultural applications. *Polymers*, 14(19), 4194. doi:<https://doi.org/10.3390/polym14194194>