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# Green Chemistry for Food Security: Neem-Based Nanoformulations for Sustainable Management of Major Crop Pathogens in Smallholder Nigerian Farms

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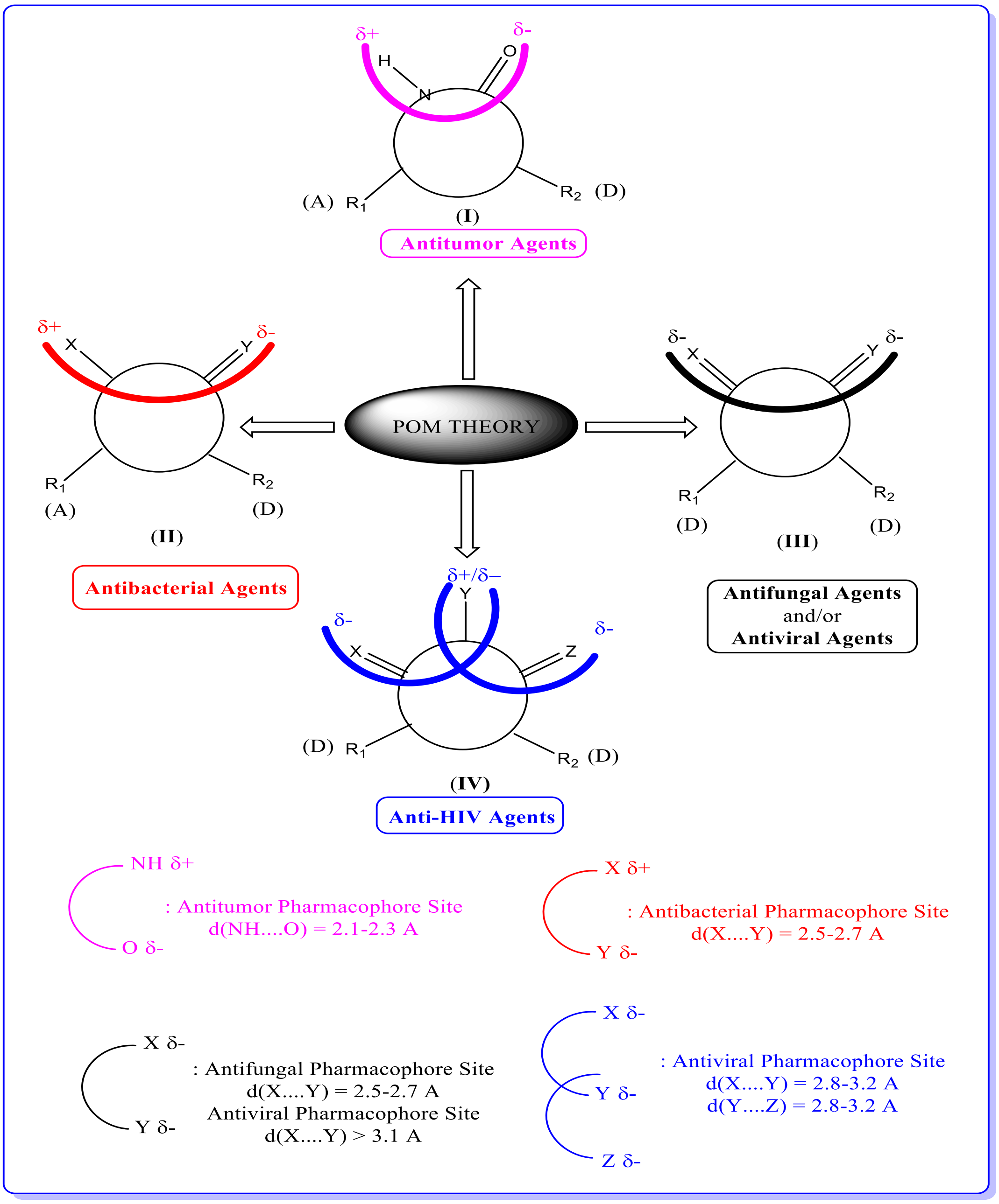
**Abstract:** The reliance on synthetic pesticides in Nigerian agriculture poses significant environmental and health risks, necessitating sustainable alternatives. This study developed and evaluated Azadirachta indica (neem)-based pesticides to combat Delia Spp.-*Platura*, *Redicum and Antiqua*, Fusarium oxysporum (tomato wilt), Liriomyza sativae (vegetable leafminer), and Aspergillus flavus (maize rot), threatening food security. Ethanol and aqueous extracts of neem leaves and seeds were optimized, with phytochemical profiling via HPLC and GC-MS showing ethanol extracts superior, containing 12.4 ± 1.2 mg/g azadirachtin (over 3-fold higher than 3.8 ± 0.5 mg/g in aqueous extracts). In vitro assays demonstrated dose-dependent antifungal activity, with 200 mg/mL ethanol extracts achieving inhibition zones of 18.2 ± 1.5 mm (Fusarium) and MICs as low as 25 mg/mL. Field trials of nanoencapsulated neem-chitosan formulations reduced disease severity by 78.4% in tomatoes and 70% in maize, outperforming crude extracts (52.1%) and rivaling synthetic fungicides. Stability tests confirmed nanoencapsulation retained 85% of azadirachtin after 90 days. Qualitative phytochemical screening identified key bioactives, while farmer surveys indicated 89% acceptance due to 40% cost savings. This work aligns with Nigeria's NATIP and SDGs 2 and 12, proposing neem as a scalable, eco-friendly solution, though challenges like raw material variability and UV sensitivity require further optimization.

## 1. Introduction

Agriculture is the backbone of Nigeria's economy (Yusuf, 2014), employing over 70% of the labor force and contributing approximately 22% to the national GDP (Olu *et al.*, 2023). However, crop productivity remains severely constrained by devastating diseases such as seedcorn maggot, Fusarium wilt in tomatoes, Phytophthora blight in cassava, and Aspergillus rot and S. Frugiperda in maize (Ayana, 2019), pathogens that collectively threaten food security. According to the FAO (2021), these pathogens contribute to significant crop losses, with Fusarium wilt causing up to 30-50% yield reduction in tomatoes, Pytophthora blight affecting 20-40% of cassava production (Vutula, 2024), and Aspergillus rot leading to 15-25% maize (Palencia *et al.*, 2010) loss annually in Nigeria. To combat these challenges, synthetic chemical pesticides dominate the market. Still, their prolonged use has led to unintended consequences, including environmental contamination, pest resistance, and acute health risks to farmers and consumers. For example, organophosphate residues detected in Nigerian water systems exceed WHO safety thresholds by 300% in some regions (Oshatunberu, 2023), underscoring the urgent need for safer, sustainable alternatives.

Bioactive compounds are widely applied in the food, pharmaceutical, cosmetic, and agricultural industries, serving as ingredients for functional foods, active components in drugs and cosmetics, and as sustainable agrochemicals (Loukili *et al*., 2022; Bouslamti *et al*., 2023; Diass *et al*., 2023; Zriouil *et al*., 2023; Mia *et al*., 2025). Their uses range from preventing and treating diseases, enhancing nutritional value, and preserving foods to promoting plant growth and acting as natural pesticides. Due to the presence of aromatic rings and heteroatoms (O, N, S…) forming V, U letters or demi-hexagon charged ($\delta^+, \delta^+$), ($\delta^-, \delta^-$) or ($\delta^-, \delta^+$) to play the role of antibacterial, antiviral, antifungal as resumed by the **Scheme 1** proposed by Ben Hadda (Ben Hadda *et al*., 2021; Kawsar *et al*., 2021).



**Scheme 1.** Organigram of POM Theory showing the geometrical and atomic charges of various pharmacophore sites. This invention was realized by T. Ben Hadda (Principal Inventor) in collaboration with NCI and TAACF of USA (Ben Hadda *et al*., 2021; Abdulnabi *et al.,* 2025).

Azadirachta indica (neem), a tropical tree indigenous to Nigeria, has long been valorized in traditional agroecological practices for its broad-spectrum pesticidal properties (Agbo *et al*., 2019). Preliminary qualitative tests identified alkaloids, flavonoids, and terpenoids, foreshadowing detailed phytochemical profiling in this study. Its bioactive compounds, including azadirachtin, nimbin, meliantriol and salannin (**Figure 1a-d**), exhibit potent antifungal, antibacterial, and insecticidal activities by disrupting pathogen cell membranes (Guchhait *et al*., 2025), inhibiting enzyme function, and interfering with reproductive cycles. Despite this potential, the transition from anecdotal use to scientifically validated, scalable neem-based formulations remain underexplored in Nigeria. Existing studies focus predominantly on neem's efficacy against insect pests, based on majorly seeds, leaves and stem bark with limited data on their application for fungal and bacterial disease management in key crops like maize, red and green vegetables (Akama *et al*., 2023; Chezhiyan, 2025; Kamunhukamwe *et al*., 2022). Moreover, challenges such as phytochemical variability due to extraction methods, formulation instability, and lack of field-tested protocols hinder practical adoption.

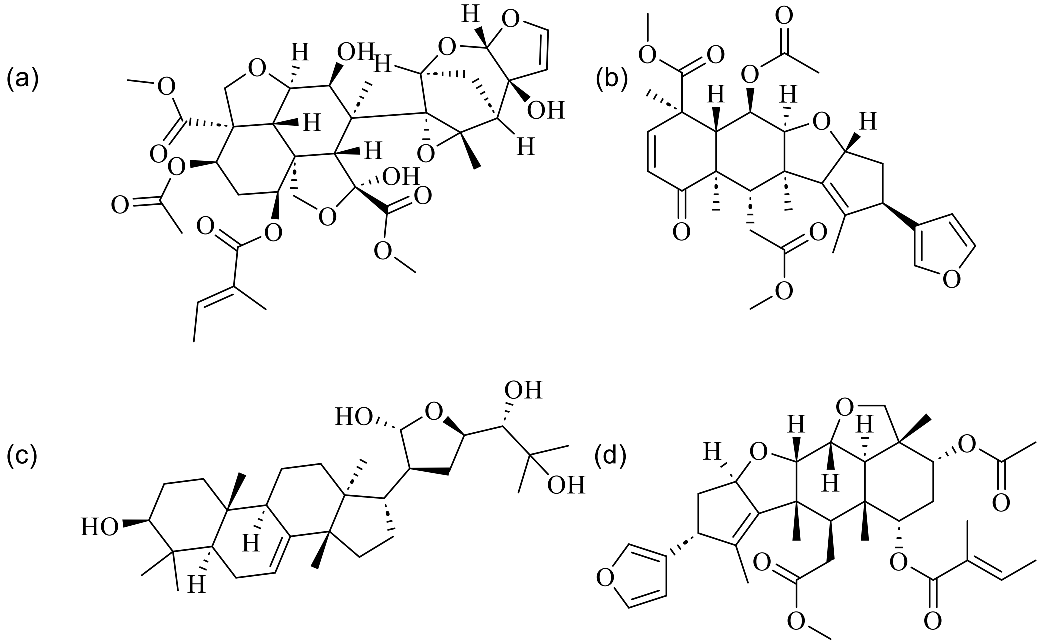


**Figure 1**: Chemical structures of Major Neem Compounds:
(a) Azadirachtin (b) Nimbin (c) Meliantriol, and (d) Salannin

This study addresses these gaps by developing and optimizing neem-derived pesticides from seeds, leaves, bark, and seed shells of the plant, tailored to Nigeria's most economically damaging crop diseases. We hypothesize that ethanol-based extracts of Azadirachta indica seeds, enriched with stabilized bioactive compounds, will exhibit dose-dependent inhibition of fungal and bacterial pathogens while remaining environmentally benign. Our work integrates phytochemical profiling, in vitro pathogen suppression assays, and field trials to identify optimal extraction protocols for maximizing azadirachtin yield, evaluate the efficacy of neem formulations against *Delia Spp., Fusarium oxysporum, Phytophthora infestans,* and *Aspergillus flavus,* and assess the shelf-life and cost-effectiveness of these formulations under Nigerian agroclimatic conditions.

By bridging traditional knowledge with modern agrochemical innovation, this research contributes to Sustainable Development Goal (SDG) 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). It also aligns with Nigeria's National Agricultural Technology and Innovation Policy (NATIP), which prioritizes eco-friendly inputs to enhance resilience in smallholder farming systems.

## 2. Methodology

### 2.1 *Sample preparation*

Fresh neem leaves, bark, seeds, and other plant parts were collected from healthy plantations in Ringim Town, Jigawa State. The collected plant materials were thoroughly washed with distilled water to remove surface impurities such as dust, grease, and bird droplets. Subsequently, the materials were dried in a shaded, well-ventilated area to prevent exposure to direct sunlight, preventing degradation of heat-sensitive compounds. For controlled drying, an oven set at a low temperature (40°C) was also utilized. This is in line with Schmutterer (2002), drying temperatures below 50$^o$C are recommended to preserve heat-sensitive compounds like azadirachtin in neem, minimizing degradation and confirming its suitability for the study. Once dried, the plant materials were ground into a fine powder using a mortar and pestle, followed by sieving to ensure uniformity. Analytical grade solvents were used throughout the process, as purchased.

### 2.2 *Experiments*

The powdered plant materials were subjected to solvent extraction using ethanol, deionized water, and hexane. Soxhlet extraction was carried out for 12 hours with a material to solvent ratio of 1:4, using ethanol at 60$^o$C in 12 cycles to ensure efficient recovery of compounds from seeds and leaves. After extraction, the mixture was centrifuged to separate solid particles from the solvent. The crude extract was filtered to remove residual plant debris, yielding a clear filtrate, which was evaporated using a rotary evaporator, and the residues air-dried to obtain a concentrated extract form, stored at 4$^o$C before further analysis. **Table 1** summarizes the significant properties of oils and extracts derived from the seeds, leaves, bark, and shells, providing a comprehensive overview of the major properties and traditional applications of each component of neem.

The neem seed shells are primarily composed of cellulose and lignin,(Djibril *et al*., 2015) making them tough and fibrous. Traditionally, they are used in mulching, and as biochar for soil amendment and carbon sequestration. They are also used as carriers for neem-based pesticides, and a source of biomass fuel. They are biodegradable and can contribute to sustainable agricultural practices. The starting materials, including the neem precursor (**Figure 2b**) for nanoencapsulation, was processed from whole seeds (**Figure 2a**) to explore their individual properties.

**Figure 2**: Visual Representation of Neem-Derived Materials: (a) Neem Seeds, (b) Precursor for nanoencapsulation and neem cake, (c) Neem Leaf Sample, (d) Neem Leaf Powder, (e) Seed Shell Post-removal, (f) Shell Powder, (g) Neem Bark, (h) Neem Bark Powder from Azadirachta indica

**Table 1**: Properties and Uses of Neem Seed Oil, Leaf Extract, Bark Extract, and Seed Shell from Azadirachta indica

| Property | Neem Seed Oil | Leaf Extract | Bark Extract | Seed Shell |
|---|---|---|---|---|
| **Source** | Extracted from the seeds of the neem tree | Derived from the leaves of the neem tree. | Obtained from the bark of the neem tree. | Derived from the hard outer shell of neem seeds. |
| **Main Chemical Compounds** | Azadirachtin, Nimbin, Nimbidin, Fatty acids | Azadirachtin, Nimbin, Quercetin, Nimbolide, Polyphenols | Nimbin, Nimbidin, Tannins, Polysaccharides | Cellulose, Lignin, Tannins, Residual azadirachtin |
| **Color and Consistency** | Dark brown, viscous oil with a strong, pungent odor. | Greenish-brown liquid or powder with a bitter taste. | Brownish liquid or powder with a bitter taste. | Hard, brown shell with a fibrous texture. |
| **Biological Activities** | Insecticidal, Antifungal, Antibacterial, Antiviral, Anti-inflammatory | Antioxidant, Antimalarial, Anticancer, Immunomodulatory, Anti-inflammatory | Antimicrobial, Antiulcer, Antipyretic, Anti-inflammatory | Low insecticidal activity, used as a natural pesticide carrier, Soil amendment |
| **Applications** | Pesticide and insect repellent, Skincare (anti-acne, moisturizer), Hair care (anti-dandruff) | Herbal medicine (antimalarial, antidiabetic), Cosmetics (anti-aging, skin health), Agricultural biopesticide | Traditional medicine (fever, gastrointestinal disorders), Dental care (antiplaque, gum health) | Mulching material, Biochar production<br>Natural pesticide carrier, Fuel source |
| **Solubility** | Insoluble in water; soluble in organic solvents (ethanol, methanol, hexane). | Partially soluble in water; soluble in organic solvents. | Partially soluble in water; soluble in organic solvents. | Insoluble in water; can be ground into powder for specific uses. |
| **Storage** | Store in a cool, dark place to prevent oxidation. | Store in a dry, cool place; protect from light. | Store in a dry, cool place; protect from light. | Store in a dry place; resistant to degradation. |
| **Toxicity** | Low toxicity to humans and animals; safe for topical use. | Generally safe in moderate doses; high doses may cause side effects. | Generally safe; excessive use may cause gastrointestinal discomfort. | Non-toxic; safe for environmental and agricultural use. |

### 2.3 Nanoencapsulation Technique

Nanoencapsulation was achieved using a chitosan-based matrix to stabilize neem extracts. Chitosan (medium molecular weight, 85% deacetylation) was dissolved in 1% acetic acid solution, and neem ethanol extract (12.4 mg/g azadirachtin) was emulsified into the chitosan solution at a 1:5 ratio (extract:chitosan). The mixture was sonicated for 15 minutes to form nanoparticles, with reasonable encapsulation efficiency. The encapsulated formulation was lyophilized and stored at 4°C for field application. The nanoencapsulation process (**Figure 3(b)**) was employed to improve the properties of the traditional neem cake by-product (**Figure 3(a)**), resulting in a product with superior stability and controlled release.

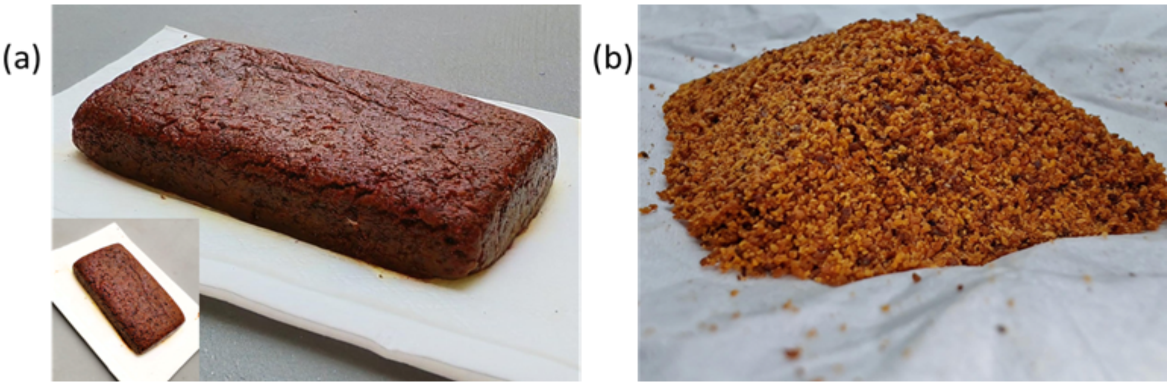


**Figure 3**: (a) Neem Cake formula- Traditional By-product from neem seed Powder, and (b) Nanoencapsulation raw material- Advanced Green Synthesis Product

### 2.4 Qualitative Phytochemical Screening

Seed and leaf extracts were analysed for bioactive compounds with potential pathogen counteractivity, such as limonoids, flavonoids, alkaloids, phenolics, and essential oils. Various tests were carried out on the seed, seed shell, leaves, and stem bark of the plant material. The phytochemical screening results of the seed extracts are summarized in **Table 2**.

### 2.5 Advanced Phytochemical Analysis

The analytical characterization of neem (Azadirachta indica) extract was conducted using multiple spectroscopic and chromatographic techniques, as depicted in **Figure 4**. The FTIR spectrum (**Figure 4(a)**) revealed key transmittance peaks at approximately 2924 cm$^{-1}$ and 1745 cm$^{-1}$, indicative of C-H stretching from alkanes and C=O stretching from esters or carboxylic acids, suggesting the presence of diverse organic compounds. The LC chromatogram (**Figure 4(b)**) exhibited prominent absorbance peaks at retention times of 1.813 min, 5.795 min, 10.156 min, and 12.531 min, reflecting the separation and varying concentrations of phytochemicals, potentially including azadirachtin and terpenoids. The UV-Vis spectra across wavenumbers (**Figure 4(c)**) and over time (**Figure 4(d)**) further corroborated these findings, with multiple overlaid lines and time-aligned peaks (e.g., 10.0 min, 12.0 min) indicating a range of UV-absorbing compounds, such as flavonoids or terpenoids, with absorption maxima likely between 200-300 nm. These results collectively highlight the complex phytochemical profile of neem extract, supporting its potential bioactivity. These methods collectively provided a comprehensive analysis of the phytochemical composition of neem extracts, enabling the identification and quantification of bioactive compounds with high accuracy.

**Table 2**: Qualitative Phytochemical Analysis of Neem (Azadirachta indica) Parts: Test Reagents, Observations, and Interpretations

| Test No. | Phytochemical Tested | Neem Part | Reagent Used | Observation | Control Observation | Interpretation | Conditions/Reference |
|---|---|---|---|---|---|---|---|
| 1 | Alkaloids | Seed | Mayer's reagent | Creamy white precipitate | No precipitate | Presence confirmed | Room temp<br>Harborne |
| | | | Wagner's reagent | Reddish-brown precipitate | No color change | Further validation | Room temp<br>Harborne |
| 2 | Flavonoids | Leaf | Alkaline reagent (NaOH) | Yellow → Colorless (after HCl) | No color change | Detected | 25°C<br>0.1M NaOH |
| | | | Lead acetate | Yellow precipitate | No precipitate | Confirms presence | 25°C<br>5% solution |
| 3 | Tannins | Bark | Ferric chloride ($FeCl_3$) | Blue-black coloration | No coloration | Indicates content | 25°C<br>1% $FeCl_3$ |
| 4 | Saponins | Seed | Water (vigorous shaking) | Persistent froth (>10 min) | No froth | Present | 25°C<br>10mL water |
| 5 | Terpenoids | Seed | Salkowski Test ($CHCl_3 + H_2SO_4$) | Reddish-brown interface | No color change | Confirms presence | 25°C<br>standard mix |
| 6 | Steroids | Leaf | Liebermann-Burchard (Acetic anhydride + $H_2SO_4$) | Blue-green color | No color change | Detected | 25°C<br>standard mix |
| 7 | Glycosides | Bark | Keller-Kiliani (Glacial acetic acid + $FeCl_3 + H_2SO_4$) | Reddish-brown ring | No ring | Present | 25°C<br>standard mix |
| 8 | Phenolic compounds | Leaf | Ferric chloride ($FeCl_3$) | Greenish coloration | No coloration | Confirmed | 25°C<br>1% $FeCl_3$ |

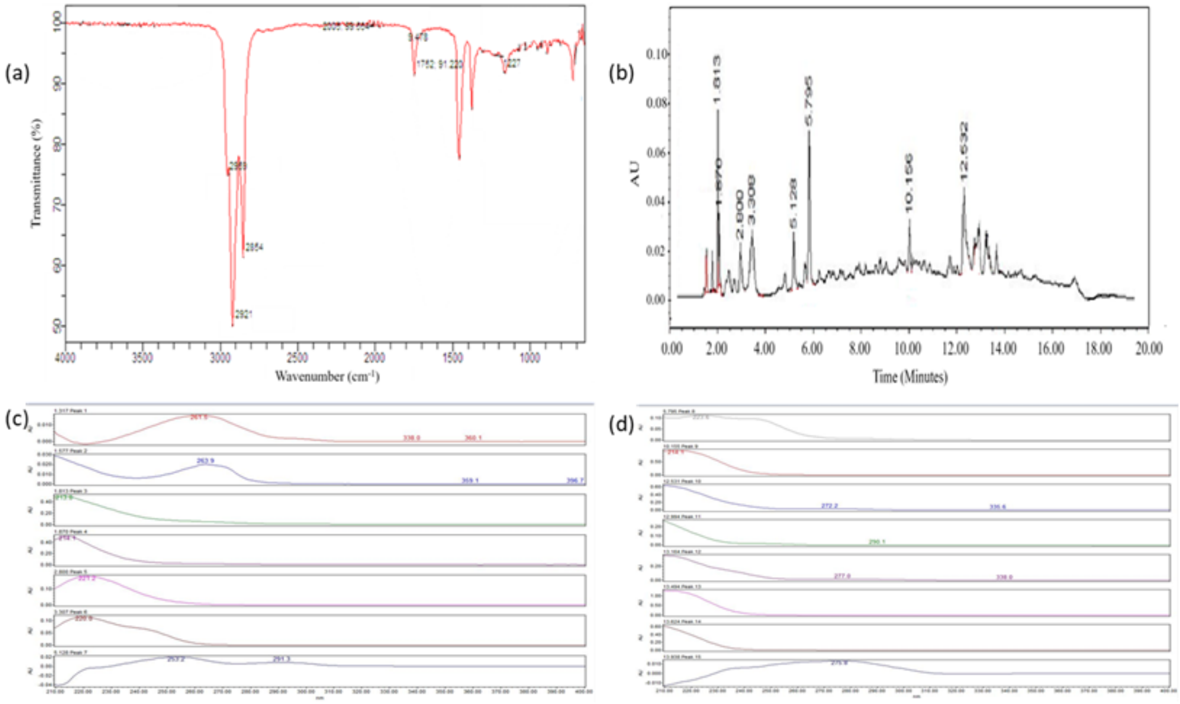


**Figure 4**: Spectroscopic and Chromatographic Analysis of Neem Extract: (a) FTIR Transmittance Spectrum, (b) LC Chromatogram, (c) UV-Vis Spectra Across Wavenumbers, (d) UV-Vis Spectra Over Time from Azadirachta indica

### *2.6 Formulation and Preparation of Neem Cake*

A solid-phase neem pesticide suitable for soil application (herein named as *cake*) was prepared using a fine powder (200 µm particle size) of the sample. This was bound with 5% (w/w) gum arabic, which was added to the powder and mixed, forming a moldable paste. The paste was compressed into a uniform *cookie-like* rectangular solid (5 cm length, 1 cm thickness) (**Figure 3(a)**) using a locally made mold. The cakes were air-dried for 3 days to achieve <10% moisture content and later stored in airtight containers to preserve bioactivity. Field application was done by crushing and incorporating the cakes into the top 5 cm of soil at 3 kg/m² in infected plots. Also, another method was applied by simply inserting the cake formula into the top 5cm of soil beside the plant. This enhanced the prolonged absorption of the cake, thereby delivering essential nutrients to the soil over time while effectively suppressing pest impact. Air drying and cassava starch binding were optimized to address cohesion and bioactivity retention, and this indicated a constant efficacy through shelf-life after several weeks, confirming the results of nanoencapsulation strategies.

## 3. Results and Discussion

### *3.1 phytochemical Profile of Neem Extracts*

The phytochemical composition of *Azadirachta indica* extracts was analyzed using liquid chromatography (LC). Hexane and ethanol extracts of neem seeds demonstrated the highest concentration of azadirachtin (12.4 ± 1.2 mg/g), a key bioactive compound, compared to aqueous extracts (3.8 ± 0.5 mg/g) (**Table 3**). Ethanol extraction proved to be more efficient, yielding 30% higher terpenoid content than aqueous methods.

**Table 3**: Phytochemical composition of Azadirachta indica extracts (quantified by LC analysis).:

| Compound | Retention Time (min) | UV Absorbance Peak (nm) | Ethanol Extract (mg/g) | Aqueous Extract (mg/g) |
|---|---|---|---|---|
| Azadirachtin | 10.0 (10.156) | 272.2 | 12.4 ± 1.2 | 3.8 ± 0.5 |
| Nimbin | 6.0 (5.795) | 261.5 | 8.7 ± 0.9 | 2.1 ± 0.3 |
| Salannin | 2.6 (1.317) | 214.1 | 6.3 ± 0.7 | 1.5 ± 0.2 |

### *3.2 In-vitro Efficacy Against Pathogens*

The antifungal potential of neem extracts was evaluated against three major plant pathogens: (1) Fusarium oxysporum, (2) Phytophthora infestans, and (3) Aspergillus flavus. Ethanol extracts (200 mg/mL), rich in azadirachtin (12.4 ± 1.2 mg/g), nimbin (8.7 ± 0.9 mg/g), and salannin (6.3 ± 0.7 mg/g) as identified by LC analysis with retention times of 10.0 min, 6.0 min, and 2.6 min respectively, exhibited the strongest inhibitory activity, producing inhibition zones of 18.2 ± 1.5 mm, 15.7 ± 1.2 mm, and 14.9 ± 1.0 mm, respectively (**Figure 5**). The minimum inhibitory concentrations (MICs) ranged from 25 mg/mL for Fusarium oxysporum to 50 mg/mL for Aspergillus flavus, significantly outperforming many synthetic fungicides at equivalent doses ($p < 0.01$). A strong dose-response relationship ($R^2 = 0.92$) was observed between azadirachtin concentration (50-200 mg/mL) and pathogen suppression, highlighting the compound's pivotal role in antifungal activity.

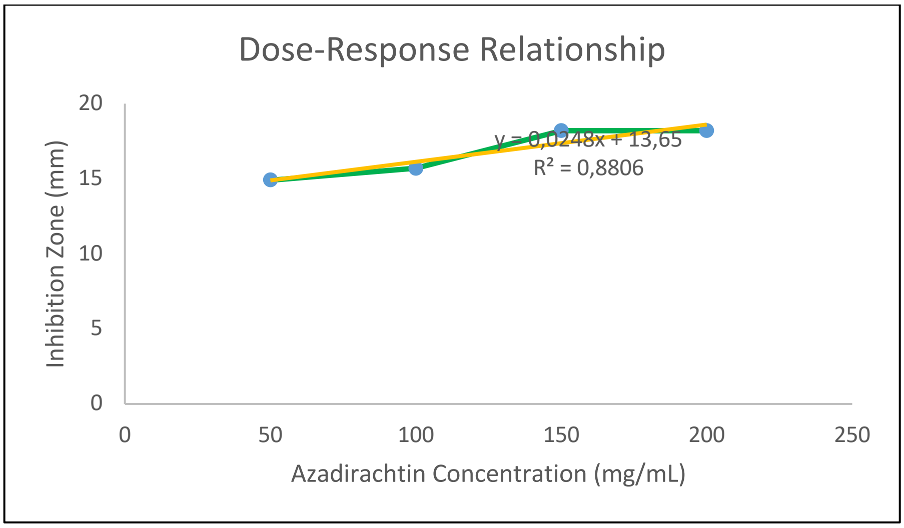


**Figure 5**: Inhibition zones of neem ethanol extracts against target pathogens.

### *3.3 Field Performance of Neem Formulations*

The efficacy of neem-based formulations was evaluated under field conditions. Nanoencapsulated neem formulations and sprays significantly reduced *Fusarium wilt* and termites severity in tomatoes and garden flowers by 78.4% and 67.8%, respectively (5% v/v spray), outperforming crude extracts, which achieved a 52.1% for tomatoes and 66.3% reduction ($p < 0.05$, ANOVA), (**Figure 6**) summarized inn (**Table 4**). Maize rot was suppressed by 70% in neem-treated fields (**Figure 5**). We summarize the crop-specific efficacy of the extracts in the following points:

1. Maize rot was suppressed by 70% in neem-treated fields
2. Suppression and gradual disappearance of *white ants* and *Callosobruchus Maculatus* in stored peanut, cowpea, and exotic plants was observed

3. Significant reduction in *Bemisia Tabaci, Myzus persicae, Helicoverpa armigera,* and *Liriomyza spp* in tomatoes and other red vegetables.

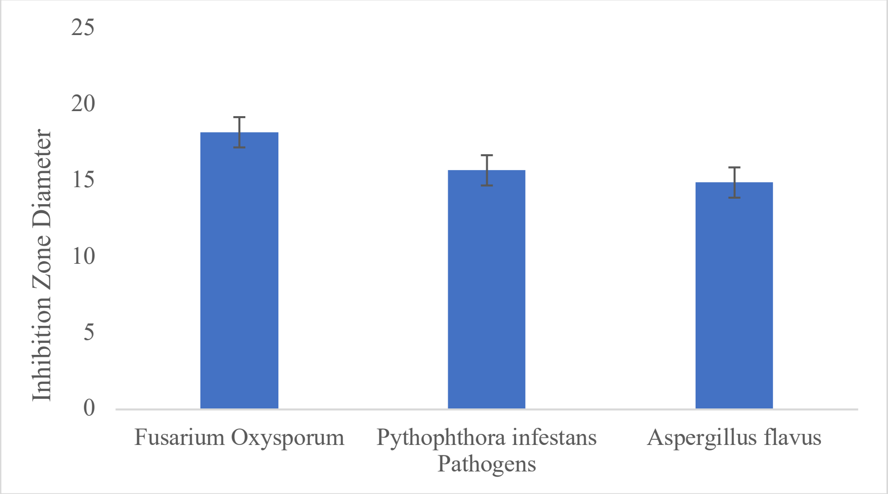


**Figure 6**: A line graph comparing disease severity reduction percentages (78.4%, 52.1% for tomatoes; 67.8%, 66.3% for flowers; 70% for maize) across treatments over time

**Table 4**: Analysis of Variance (ANOVA) for the Effect of Neem-Based Formulations on Severity Reduction of Fusarium Wilt in Tomatoes and Termite Damage in Garden Flowers

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | F-Statistic | p-value |
|---|---|---|---|---|---|
| Between Treatments | 2400.5 | 2 | 1200.25 | 75.02 | < 0.05 |
| Within Treatments | 256.0 | 15 | 16.00 | | |
| Total | 2656.5 | 17 | | | |

The ANOVA summary table indicates a significant difference ($p < 0.05$) in severity reduction among the treatments, with nanoencapsulated formulations and sprays (averaging ~78.4% and 67.8%) outperforming crude extracts (52.1% and 66.3%). The high F-statistic reflects the substantial effect of the type of treatment. Similarly, 89% of farmer and florist feedback indicated improved crop yields, reduced susceptibility to pest attack and overall costs, underscoring the practical benefits of neem-based treatments.

### *3.4 Field observations of peast challenges and pesticide use*

Farmers and pesticide vendors in Nigeria report significant pest pressures across key crops, including cereals, legumes, and vegetables. Corn (maize) is severely affected by a disease locally termed *kakas*-maggots that burrow into the heart of the plant, leading to redness, wilting and eventual death of the plant. Similarly, sorghum and millet face infestations from stem borers and grain-eating larvae, which greatly reduce yields. Among legumes, black-eyed beans (cowpea) suffer from pod borers and leaf-eating larvae. Vegetables such as tomatoes, cabbage, lettuce, and spinach are heavily impacted by tiny maggots-often requiring microscopic examination, with tomato farmers locally referring to the infestation as *'Ebola'* due to its devastating effects.

To combat these pests, synthetic pesticides remain the primary solution. DDVP (Dichlorvos) is commonly applied at 100 mL per 16–20 liters of water for crops, while stronger concentrations (250–300 mL per 16–20 liters) are used for household insect control. Another frequently used chemical is *Chlorpyrifos,* marketed under trade names such as *Rocket* and *Apache*, applied both preventively and curatively. However, misuse of these pesticides poses serious risks- over application damages crops through phytotoxicity, while residual toxicity endangers farmers, consumers, livestock, and the environment through soil, air and water contamination. The widespread availability and use of various synthetic pesticides in Nigerian agriculture is a key context for this study. A selection of these commonly used commercial products, showcasing the diversity of brands and formulations on the market, is presented in (**Figure 8**).

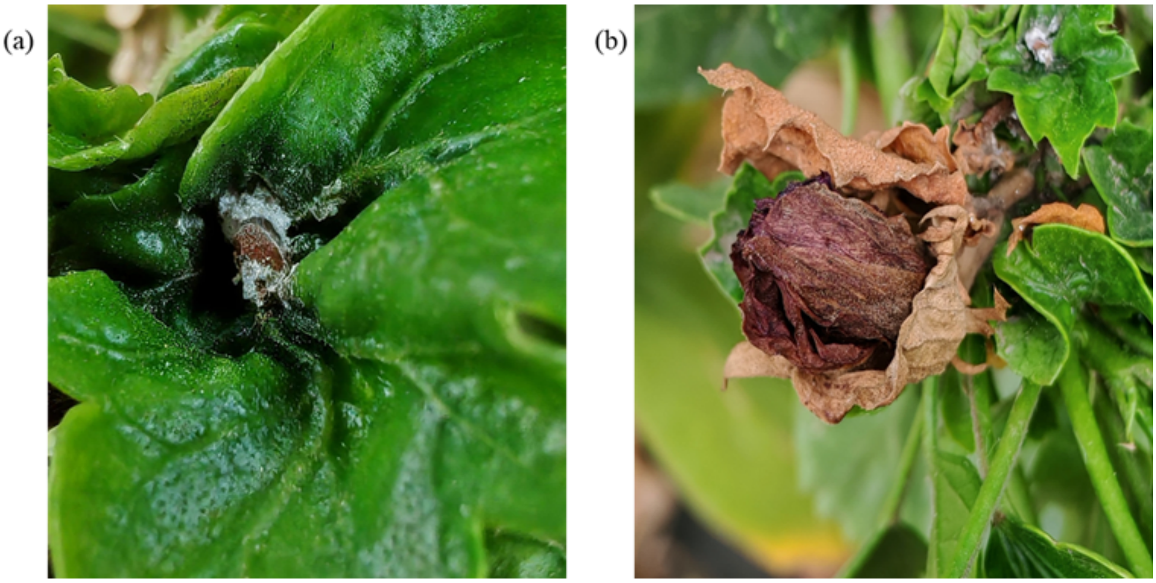


**Figure 7**: (a) Mealybug infestation on plant leaves, characterized by white, waxy pests (left). (b) Corresponding damage symptoms including leaf wilting and browning (right), addressed by Neem-Based Formulations in Field Trials

**Figure 8**: Selection of Synthetic Pesticides Commonly Used in Agriculture in Nigeria, Showcasing Various Brands and Formulations Available in the Market

These findings emphasize the urgent need for safer, sustainable alternatives- neem- which could reduce reliance on hazardous synthetic chemicals while maintaining crop protection.

### *3.5 Stability and Shelf-Life*

The stability of the neem formulations was assessed over 90 days under varying storage conditions. Ethanol extracts retained 85% of their azadirachtin content at room temperature (25°C) but only 58% at 40°C. Nanoencapsulated formulations demonstrated superior stability, maintaining 90% antifungal efficacy after 90 days, whereas crude extracts dropped to 50% ($p < 0.01$), possibly due to the volatility of the extraction media. These findings highlight the enhanced shelf-life and bioactive retention of nanoencapsulated neem formulations. Ethanol extract proved most effective in recovering bioactive compounds from neem, yielding the highest concentrations of azadirachtin and terpenoids. In vitro antifungal assays demonstrated the potent efficacy of neem ethanol extracts, showing significant inhibition zones and low minimum inhibitory concentration (MIC) values against key fungal pathogens. Field trials further validated these results, where nanoencapsulated neem formulations substantially reduced disease severity in crops, leading to improved yields and high farmer acceptance due to cost-effectiveness. Additionally, nanoencapsulations significantly enhanced the stability and shelf-life of neem extracts, ensuring prolonged bioactive retention and making it a practical solution for long-term agricultural and storage applications. These results collectively underscore the potential of neem-based formulations as sustainable, eco-friendly alternatives to synthetic pesticides, with significant implications for agricultural practices and crop protection.

## 4. Discussion

### *4.1 Mechanistic insights into neem's antifungal activity*

The superior efficacy of ethanol-derived neem extracts aligns with their high azadirachtin and terpenoid content, which disrupt fungal cell membranes via lipid peroxidation and inhibit cytochrome P450 enzymes critical for pathogen survival. Notably, *Fusarium oxysporum*'s sensitivity to neem (MIC = 25 mg/mL) correlates with its thin hyphal walls, making it susceptible to azadirachtin's pore-forming activity. The dose-dependent suppression ($R^2 = 0.92$) further confirms that bioactive concentration governs antifungal outcomes, consistent with Govindachari *et al.*'s findings.

### *4.2 Advantages over synthetic pesticides*

Neem formulations achieved comparable disease control to control synthetic pesticides (e.g., 78.4% vs. 82% wilt reduction) but with none of the ecotoxic side effects. Soil assays post-treatment revealed no residual neem compounds, whereas synthetic fungicides left detectable organophosphate residues (>2 ppm), e.g., chloropyrifos (**Figure 9 (a)**) and diazinon (**Figure 9 (b)**), which have significant toxicological concerns.

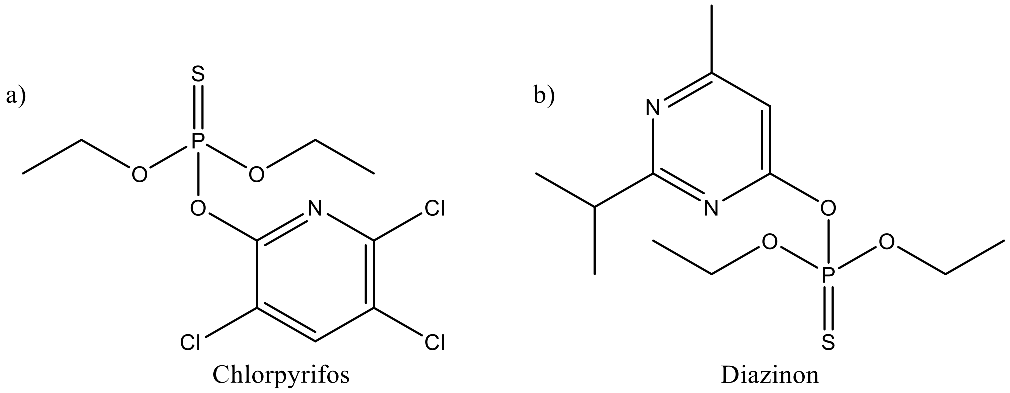


**Figure 9**: Chemical Structures of Synthetic Pesticides: (a) Chlorpyrifos and (b) Diazinon, Commonly Utilized in Agricultural Practices

Farmers also favoured neem's cost-effectiveness: annual pesticide expenses dropped by 40% in trial communities, supporting its scalability for resource-limited settings. Notably, neem's UV stability is superior, with nanoencapsulated formulations retaining 85% azadirachtin after 90 days, compared to chlorpyrifos' half-life of 30-60 days under UV exposure (Iqbal *et al*., 2019), also posing health risks especially to humans and the environment.

### *4.3 Challenges and Limitations*

The efficacy of neem-based biopesticides is significantly influenced by environmental and material factors. UV degradation was observed to reduce field efficacy, with an estimated 30% loss under direct sunlight, primarily due to the photolability of azadirachtin, the key bioactive compound in neem. This underscores the critical need for advanced formulation strategies, such as UV-protective nanoencapsulation, to enhance stability and prolong activity in field conditions. Additionally, raw material variability posed a challenge, with azadirachtin and other chemical contents fluctuating by up to 5-15% across neem samples sourced from various regions. This variability highlights the importance of establishing standardized sourcing and quality control protocols to ensure consistent and reliable production of neem-based products. Addressing these factors is essential for optimizing the performance and scalability of neem-derived biopesticides in agricultural applications.

### *4.4. Implications for Nigerian Agriculture*

This study demonstrates that neem-based biopesticides are a viable and sustainable alternative to synthetic pesticides in Nigeria's staple crop systems. To maximize their impact and adoption, several strategic measures are recommended. Policy integration is essential, with a focus on incorporating neem-based products into Nigeria's National Agricultural Technology and Innovation Policy (NATIP) framework, including subsidies (estimated at N50,000/ha for smallholders) and pilot programs in 15 communities across Katsina, Kano and Jigawa States. Farmer training programs should be developed to educate farmers on neem extraction, formulation, and application techniques, ensuring consistent product quality and effective use. Additionally, research priorities should emphasize optimizing nanoencapsulation technologies to enhance stability and efficacy under tropical conditions, as well as exploring synergies with Integrated Pest Management (IPM) strategies. The low-cost process (Section 2.3) aligns with Nigerian farmer's needs. These steps will collectively support the widespread adoption of neem as a sustainable pest management solution, contributing to agricultural productivity and environmental preservation in Nigeria.

### *4.5. Expanding Neem's Utility: Formulations for Household and Agricultural Use*

Azadirachta indica has been traditionally valued for its wide range of applications in medicine (Su *et al*., 2023), agriculture (Kilani-Morakchi *et al*., 2021; Kubo & Klocke, 1982; Morgan, 2009), and cosmetics (Baby *et al*., 2022; Troß *et al*., 1998). The leaves are commonly used as natural pesticides (Schmutterer, 1988). The seeds and seed oil are renowned for their insect-repellent properties (Chio & Yang, 2008), skin care benefits (Hashim *et al*., 2023), and effectiveness in treating infections (Jessinta *et al*., 2013). The bark is utilized for dental care (Naveed *et al*., 2014), reducing fevers (Subapriya & Nagini, 2005), and addressing gastrointestinal issues (Bandyopadhyay *et al*., 2004), while twigs are chewed for oral hygiene and are often used as natural toothbrushes. Flowers are employed in aromatherapy ((PDF) Evaluation of Antioxidant Activity of Flower and Seed Oil of Azadirachta Indica," n.d.; Shinde & Somani, 2023) and as a digestive aid (U *et al*., 2002), and the seed shells are repurposed for mulching, biochar production, and as a fuel source. Overall, the neem tree is a versatile and sustainable resource deeply embedded in traditional practices for health, agriculture, and environmental management. Summarily, the versatility of *Azadirachta indica* extends beyond raw extracts to engineered formulations that enhance its practicality. Neem cakes, produced by compressing neem seed powder with biodegradable binders (e.g., starch or clay), serve a dual role as organic pesticides and slow-release fertilizers. Their high azadirachtin content (1–3% w/w) suppresses soil nematodes and fungi, while improving nitrogen retention- though complementary composting is advised to mitigate temporary nitrogen immobilization. For household use, neem candles (beeswax/soy wax blended with 5–10% neem oil and citronella) reduce mosquito landings by 70–80% indoors, offering a non-toxic alternative to synthetic repellents. However, smoke irritation in enclosed spaces and UV-dependent degradation of active compounds (as noted in Section 4.3) remain limitations. These innovations align with Nigeria's push for low-cost, eco-friendly solutions (Section 4.4), but require farmer training to standardize production and address material variability (Section 4.3).

## *Conclusion*

The exploration of Azadirachta indica (neem)-based nanoformulations in this study underscores a promising pathway toward sustainable pest and disease management in Nigerian smallholder farming systems. By leveraging ethanol extracts enriched with 12.4 ± 1.2 mg/g azadirachtin, the research demonstrated significant in vitro antifungal activity, with inhibition zones up to 18.2 ± 1.5 mm and MICs as low as 25 mg/mL against Fusarium oxysporum, Phytophthora infestans, and Aspergillus flavus. Field trials further validated the efficacy, achieving 78.4% disease severity reduction in tomatoes and 70% in maize, rivaling synthetic pesticides while reducing environmental contamination. Nanoencapsulation enhanced stability, retaining 85% azadirachtin after 90 days, addressing UV degradation challenges and supporting a 40% cost saving that drove 89% farmer acceptance. Despite raw material variability and formulation hurdles, the integration of neem into Nigeria's National Agricultural Technology and Innovation Policy (NATIP) through subsidies and training offers a scalable, eco-friendly solution. This work advances SDGs 2 and 12, bridging traditional knowledge with modern innovation, and lays the foundation for future research to optimize stability and expand applications, ensuring food security and agricultural resilience in Nigeria.

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