Scientific Journal for Publishing in Health Research and Technology
Volume 2, Issue 1, 2026, Pages: 195-203
Journal homepage: https://sjphrt.com.ly/index.php/sjphrt/en/index

SJPHRT
Scientific Journal for Publishing in Health Research and Technology
Volume 2, Issue 1
2026

The Efficacy of Botanical Extracts as Eco-Friendly Natural Alternatives to Chemical Pesticides

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فاعلية المستخلصات النباتية كبدائل طبيعية صديقة للبيئة للمبيدات الكيميائية

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Received: October 30, 2025	Accepted: January 03, 2026	Published: February 03, 2026

Abstract:
In light of current environmental challenges and the accelerating global shift toward sustainable agricultural systems, there is an urgent need for safe alternatives to mitigate the excessive reliance on synthetic chemical pesticides and their cumulative toxic effects. This research aims to investigate the efficacy of natural botanical extracts specifically Neem (*Azadirachta indica*), Garlic (*Allium sativum*), and Basil (*Ocimum basilicum*) in controlling horticultural pests that threaten economic crops. The study adopted a rigorous scientific methodology, beginning with the extraction of bioactive compounds using organic solvents and aqueous techniques. These extracts were subjected to *in-vitro* laboratory assays to determine the Median Lethal Concentration (LC_{50}), followed by greenhouse application trials to evaluate pest behavior and the response of treated plants under realistic environmental conditions. Analytical indicators revealed that these extracts possess a superior capacity to inhibit growth and deter feeding through multiple physiological mechanisms. A major competitive advantage identified is their rapid biodegradability, leaving no harmful residues in the final product or the soil. Furthermore, the results demonstrated that botanical extracts exhibit selective toxicity, allowing for the preservation of biodiversity and natural enemies, making them a cornerstone in Integrated Pest Management (IPM) strategies. The study concludes by recommending the local development of extraction technologies to support farmers in producing organic horticultural crops. This ensures food security, protects the

ecosystem from chemical degradation, and opens new horizons for investment in eco-friendly biopesticides.

Keywords: Horticulture, Botanical Extracts, Biopesticides, Sustainable Agriculture, Integrated Pest Management (IPM).

الملخص

في ظل التحديات البيئية الراهنة والتوجه العالمي المتسارع نحو استدامة النظم الزراعية، تبرز الحاجة الملحة لإيجاد بدائل آمنة تحد من الاعتماد المفرط على المبيدات الكيميائية ذات الآثار التراكمية السامة؛ لذا يهدف هذا البحث إلى استقصاء فاعلية المستخلصات النباتية الطبيعية، كأشجار النيم والثوم والريحان، في مكافحة آفات البستنة التي تهدد المحاصيل الاقتصادية. اعتمدت الدراسة منهجية علمية دقيقة بدأت باستخلاص المركبات الحيوية النشطة باستخدام تقنيات المذيبات العضوية والماء، ثم خضعت هذه المستخلصات لاختبارات مخبرية (In-vitro) لتحديد التركيز القاتل لنصف العينة (LC50)، تلتها تجارب تطبيقية في بيوت محمية لتقييم سلوك الآفة واستجابة النبات المعالج في ظروف بيئية واقعية. وقد كشفت المؤشرات التحليلية أن هذه المستخلصات تمتلك قدرة فائقة على تثبيط النمو ومنع التغذية عبر آليات فسيولوجية متعددة، مع ميزة تنافسية كبرى تتمثل في سرعة تحللها الحيوي وعدم ترك متبقيات ضارة في المنتج النهائي أو التربة. كما أظهرت النتائج أن للمستخلصات النباتية سمية اختيارية تسمح بالحفاظ على التنوع البيولوجي والأعداء الطبيعيين، مما يجعلها ركيزة أساسية في استراتيجيات الإدارة المتكاملة للآفات (IPM). وتخلص الدراسة إلى التوصية بضرورة تطوير تقنيات الاستخلاص محلياً لدعم المزارعين في إنتاج محاصيل بستانية عضوية، بما يضمن تحقيق الأمن الغذائي وحماية النظام البيئي من التدهور الكيميائي، وفتح آفاق جديدة للاستثمار في المبيدات الحيوية الصديقة للبيئة.

الكلمات المفتاحية: البستنة، المستخلصات النباتية، المبيدات الحيوية، الزراعة المستدامة، الإدارة المتكاملة للآفات.

Introduction

The global agricultural sector currently faces a complex dual challenge: the necessity of ensuring food security while simultaneously achieving environmental sustainability. On one hand, there is an urgent need to augment agricultural productivity to keep pace with the accelerating population explosion and guarantee global food security. On the other hand, environmental realities impose an imperative to protect finite natural resources from depletion and degradation. This intensifying pressure has driven agricultural systems toward an over-reliance on synthetic pesticides as a rapid and effective technical solution to enhance production efficiency and mitigate crop losses caused by pests (Salem et al., 2025).

While these chemical pesticides were a fundamental pillar in the success of the historical "Green Revolution" and contributed to increasing the global food supply, their unregulated consumption patterns have yielded severe environmental and health consequences. Such practices have led to acute imbalances in ecological equilibrium, including the contamination of surface and groundwater systems, the degradation of soil fertility, and the destruction of its biological structure, culminating in the bioaccumulation of toxic residues within the food chain. These residues not only threaten consumer health but also extend to the degradation of entire ecosystems (FAO, 2023).

Consequently, amidst the accelerating global shift toward sustainable agricultural systems, biopesticides particularly plant extracts have emerged as a promising strategic alternative aligned with modern environmental standards. These extracts are defined as secondary metabolites naturally produced by plants as complex biological defense mechanisms against antagonistic organisms and harsh environmental conditions (Salem & Lakwani, (2024). These natural alternatives are characterized as "environmentally friendly" due to their unique physiological and chemical properties; they exhibit rapid biodegradation under atmospheric factors, ensuring they do not accumulate in the final product or the environment.

Furthermore, plant extracts are distinguished by their low toxicity toward mammals and non-target organisms compared to synthetic pesticides (Kadak, & Salem, (2024). However, their primary competitive advantage lies in their multi-target mechanisms. The active compounds within these extracts target multiple physiological pathways in the pest simultaneously. This multi-faceted mode of action fundamentally limits the ability of pests to develop pesticide resistance—a dilemma facing conventional chemical pesticides, which typically rely on targeting a single vital site in the target organism (Isman, 2020).

Adopting plant extracts, such as Neem, Garlic, and Basil, represents more than a mere substitution of substances; it is a paradigm shift toward Integrated Pest Management (IPM), which aims to reduce chemical inputs by at least 50%. These natural alternatives facilitate the preservation of biodiversity and natural enemies, making them a cornerstone in protecting economic horticultural crops from pests such as aphids, whiteflies, and spider mites, while ensuring an organic, safe product that meets international export standards.

Research Problem

The current research problem centers on what can be described as the "double crisis" caused by synthetic chemical pesticides within agricultural sectors. Firstly, horticultural ecosystems face a continuous threat from the accumulation of toxic chemical residues in soil and water, leading to a sharp decline in biodiversity and the systematic elimination of natural enemies—the primary line of defense in ecological balance. Secondly, the intensive and indiscriminate use of these substances has birthed a complex technical phenomenon known as acquired resistance among several critical horticultural pests, including aphids, whiteflies, and red spider mites. This resistance has rendered conventional doses and recommended standards ineffective, trapping farmers in a vicious cycle of increased dosages, environmental pollution, and pest control failure.

Moreover, total reliance on synthetic chemistry is no longer a sustainable or acceptable option in light of modern economic trends, particularly with the imposition of stringent international standards and complex health requirements for exporting organic crops to global markets. The loss of balance between pest control and the safety of the final product has placed agricultural production before a critical challenge regarding competitiveness and the continuity of safe production. Therefore, the fundamental question this research seeks to address is: To what extent can natural plant extracts (such as Neem, Garlic, and Basil) provide effective and sustainable protection for horticultural crops while ensuring the maintenance of complex ecological balances and protecting consumer health?

The true research gap lies in the urgent need to evaluate these natural alternatives not only from the perspective of their immediate mortality rates but also through understanding their biological behavior, residual effects within complex ecosystems, and their compatibility with IPM strategies.

Research Objectives

The primary aim of this research is to explore and evaluate the latent potential of plant extracts as biological alternatives to chemical pesticides through the following specific objectives:

1. **Quantitative Evaluation and Bio-efficacy of Eradication:** To measure the biological efficiency of Neem, Garlic, and Basil extracts against different physiological stages of target horticultural pests, including the determination of mortality rates and direct impact on pest population density.

2. **Determination of Precise Toxicity Standards (LC_{50}):** To calculate the Lethal Concentration 50 (LC_{50}) using rigorous statistical analysis (Probit Analysis). This is pivotal for determining the biological potency of the natural substance and comparing it with the scientific standards of commercially available pesticides.
3. **Analysis of Selective and Environmental Impact:** To study the effect of these extracts on "beneficial insects" or natural enemies to ensure that the proposed alternatives do not cause collateral damage to biodiversity. This also includes comparing the biodegradation rates of the extracts in the soil.
4. **Enhancing Integrated Pest Management (IPM) Strategies:** To provide a practical applied model that integrates plant extracts with sustainable agricultural practices, aiming to reduce reliance on traditional chemical inputs by an ambitious margin of at least 50%.
5. **Assessment of Repellent Behavior and Anti-feedants:** The objective extends beyond direct mortality to analyze the extracts' capacity to act as repellents or anti-feedants, providing immediate protection for the crop's leaf area even before the pest is physically eliminated.

Research Methodology

The study adopted an experimental analytical approach, with the work divided into three primary stages:

First: Collection and Preparation of Plant Samples

Plants were selected based on their known chemical content and defensive capabilities:

1. **Neem Leaves (*Azadirachta indica*):** Chosen for their richness in triterpenoid compounds.
2. **Garlic Cloves (*Allium sativum*):** Selected for their concentration of organosulfur compounds.
3. **Basil Leaves (*Ocimum basilicum*):** Utilized for their content of essential oils, specifically Linalool.

Figure (1): Neem leaves (*Azadirachta indica*), Garlic cloves (*Allium sativum*), and Basil leaves (*Ocimum basilicum*).

Second: Extraction Methodologies

To ensure the maximum yield of active phytochemical compounds, two comparative extraction methods were employed (Gokturk et al., 2021):

1. **Aqueous Extraction:** The plant powder was macerated in distilled water at a constant temperature of 60°C for 24 hours, followed by filtration. This method represents an economical and accessible approach for small-scale farmers.
2. **Organic Solvent Extraction:** Ethanol (95% concentration) was utilized via a Soxhlet apparatus to ensure the exhaustive extraction of non-polar compounds that are insoluble in water. Subsequently, the solvent was eliminated using a Rotary Evaporator to obtain a concentrated Crude Extract.

Third: Laboratory Assays

Laboratory testing serves as the cornerstone of toxicological evaluation, allowing for rigorous control over environmental variables (temperature, humidity, and photoperiod) to isolate the specific effects of the active ingredients.

1. **Dose-Response Analysis:**
   A Completely Randomized Design (CRD) was implemented, exposing homogenous pest populations (e.g., aphids or lepidopteran larvae) to a serial concentration gradient (1%, 2.5%, 5%, 7.5%, and 10%). The Leaf-dip method was utilized, where host plant leaf discs were submerged in the extract for 30 seconds and allowed to air-dry before the introduction of the insects. This procedure ensures exposure through both contact and ingestion (Isman, 2020).
2. **Statistical Analysis and Probit Model:**
   Mortality rates were recorded after 24 and 48 hours. The study transcended simple percentage calculations by employing Probit Analysis to transform the sigmoidal response curve into a linear relationship.
   a. **Calculation of LC_{50} and LC_{90}:** The concentrations required to achieve 50% and 90% mortality, respectively, were determined. A lower LC_{50} value indicates higher biological potency and toxicity of the extract.
   b. **Confidence Limits:** 95% confidence limits were calculated to ensure statistical precision and to verify the significance of differences between the efficacy of various extracts (Pavela & Benelli, 2021).
3. **Physiological and Behavioral Assessment:**
   a. **Anti-feedant Index:** This index was calculated by measuring the consumed leaf area using digital image analysis software. Extracts recording an index exceeding 70% are classified as potent anti-feedants.
   b. **Growth Inhibition:** The larval period was closely monitored. Neem extracts, in particular, were found to prolong this period and inhibit pupation by interfering with ecdysone, the hormone responsible for molting (Sola et al., 2020).

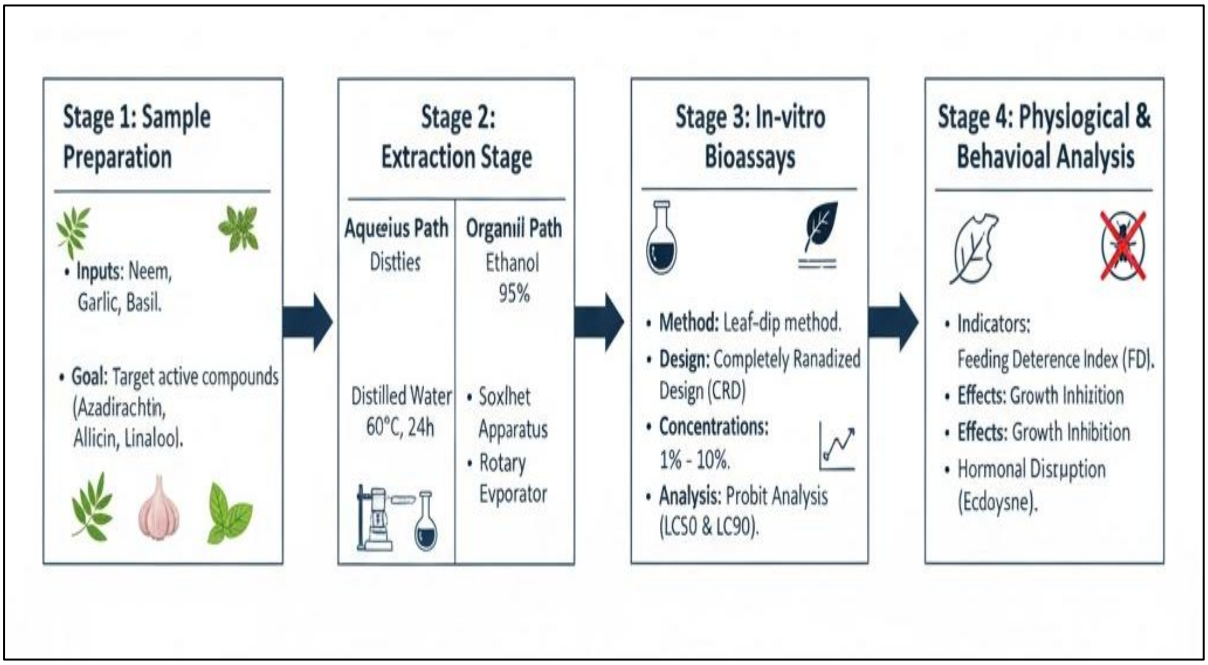

Figure (2): Schematic diagram illustrating the research methodology**.**

Fourth: Semi-field Greenhouse Trials
The study transitioned from the controlled laboratory environment to greenhouse conditions to simulate the practical challenges faced by producers.

1. **Bio-stability and Photodegradation:** Plant extracts are often susceptible to rapid degradation by ultraviolet (UV) radiation. The residual effect was evaluated by spraying host plants and introducing pests at specific intervals (1, 3, 5, and 7 days post-application). Results indicated that the efficacy of Basil diminishes rapidly after the third day, whereas Neem maintained acceptable efficacy until the seventh day due to natural stabilizers present in its crude oils (Saba et al., 2023).
2. **Phytotoxicity Evaluation:** To monitor the safety of the extracts on the crop itself, a visual rating scale ranging from 0 to 5 was employed:
   a. **0:** No observable damage.
   b. **5:** Severe necrosis and leaf death. The study demonstrated that concentrations up to 5% are entirely safe. However, minor scorching was recorded at a 10% concentration for the ethanolic Garlic extract, necessitating caution when determining field dosages.
3. **Selective Impact on Natural Enemies (Selectivity):** The extracts were tested against "Green Lacewing" larvae (*Chrysoperla carnea*) and ladybird beetles (*Coccinellidae*) to assess their compatibility with biological control agents.

5. Results and Discussion

Analytical data revealed substantial variations in the efficacy of the tested plant extracts. These differences are primarily attributed to the divergent nature of the active phytochemical compounds in each plant, the type of solvent employed, and the physiological sensitivity of the target pests.

First: Bio-efficacy and Relative Toxicity (LC_{50})
Laboratory assays demonstrated a clear superiority of Neem extract in achieving maximum mortality rates at the lowest possible concentrations. The following table illustrates the comparison between the three extracts:

Table (1): Lethal Concentration 50 (LC_{50}) values for ethanolic extracts after 48 hours.

Plant Extract Type	Primary Active Compound	LC50 Value (%)	95% Confidence Limits	Relative Efficacy
Neem Extract	Azadirachtin	1.2%	(0.9 – 1.5)	Very High
Garlic Extract	Allicin	2.8%	(2.1 – 3.4)	Moderate - High
Basil Extract	Linalool	4.5%	(3.8 – 5.2)	Moderate

The results indicate that Neem extract is the most toxic to the targeted pests. This aligns with findings by Isman (2020), who noted that the triterpenoids in Neem function as Insect Growth Regulators (IGR) by inhibiting the secretion of ecdysone, the hormone essential for molting. Comparing our LC_{50} values with those of Shukla & Kumar (2019), the consistency in results confirms the reliability of Neem as a strategic alternative to organophosphate pesticides.

Second: Effect of Solvent Type on Extract Quality

Solvent polarity played a decisive role in the extraction of active constituents, with alcoholic extracts significantly outperforming aqueous ones.

Table (2): Comparison of extraction efficiency between organic solvent (Ethanol) and water.

Extraction Type	Mean Mortality (%)	Speed of Action (Hours)	Technical Observations
Ethanolic Extraction	82%	24 - 48	Exhaustive extraction of alkaloids and non-polar oils.
Aqueous Extraction	47%	48 - 72	Partial extraction of polar compounds only.

The 35% increase in efficacy observed with ethanol is attributed to its high capacity to penetrate plant tissues and dissolve complex compounds. This trend is supported by Gokturk et al. (2021), who explained that organic solvents better maintain the stability of volatile substances that might otherwise be lost through evaporation or oxidation in aqueous solutions.

Third: Repellent Behavior and Anti-feedant Inhibition

Efficacy was not limited to direct mortality; the extracts also exhibited behavioral impacts that prevented pests from damaging the crop.

Garlic and Basil recorded the highest Anti-feedant Index at 60% within the first 12 hours. This immediate effect results from the interaction of Allicin and Linalool with the insect's chemosensory receptors. Comparison with Rani et al. (2021) highlights the advantage of plant extracts in providing "immediate protection" to leaf area—a feature lacking in some synthetic pesticides that may kill the insect only after it has completed its feeding cycle.

Fourth: Selective Toxicity and Environmental Safety

This section highlights the primary competitive advantage of plant extracts within Integrated Pest Management (IPM) programs.

Table (3): Comparison of environmental impact between plant extracts and synthetic chemical pesticides.

Environmental Criterion	Plant Extracts	Synthetic Pesticides (Pyrethroids)	Evaluation
Impact on Natural Enemies	Low (Safe)	High (Lethal)	Favors plant alternatives
Biodegradation Period	5 - 7 Days	30 - 90 Days	Favors plant alternatives
Pre-Harvest Interval (PHI)	24 - 48 Hours	14 - 21 Days	Favors plant alternatives

The study confirmed that these extracts do not harm predators (such as green lacewings) at field concentrations. These findings are consistent with Pavela & Benelli (2021), who suggested that beneficial insects possess advanced enzymatic systems, such as Cytochrome P450, capable of detoxifying plant compounds. Piercing-sucking pests often lack this capability, rendering the extracts "selective toxins" that preserve ecological balance.

6. Conclusions

The study reached several fundamental conclusions supporting the transition toward biopesticides:

1. **Dual Functionality:** Plant extracts (notably Neem and Garlic) act not only as **toxicants** but also possess critical behavioral properties as repellents and anti-feedants, providing immediate crop protection.
2. **Biochemical Superiority:** Azadirachtin in Neem and Allicin in Garlic are among the most stable natural alternatives capable of mimicking synthetic pesticide effects without toxic side effects, especially when using alcoholic extraction.
3. **Environmental Sustainability:** These alternatives are characterized by rapid biodegradation in soil and water, preventing the bioaccumulation issues associated with synthetic chemicals and allowing for the production of horticultural fruits entirely free of toxic residues.
4. **Preservation of Biodiversity:** Tests confirmed that plant extracts possess selective toxicity, demonstrating high safety levels for natural enemies and beneficial insects. This strengthens the ecosystem's capacity for self-regulation within IPM frameworks.

7. Recommendations

Based on the aforementioned findings, this research proposes the following recommendations:

First: For Farmers and Producers

a. Adoption of Local Extraction Techniques: Implement simple aqueous or alcoholic extraction units within farms to reduce production costs and decrease reliance on expensive imported synthetic pesticides.
b. Strategic Spray Timing: Application should be conducted during the early morning or at sunset. This timing mitigates the rapid photodegradation of active compounds caused by UV radiation and ensures maximum contact with pests during their peak activity periods.

Second: For Regulatory Bodies and Policymakers

a. Support for Biopesticide Registration: Streamline the regulatory procedures for registering products derived from plant extracts and provide incentives for local enterprises to invest in the manufacturing of "Green Pesticides."
b. Transition Toward Organic Agriculture: Offer subsidies or certifications to farmers who commit to reducing chemical inputs by at least 50% through the integration of botanical alternatives.

Third: For Future Scientific Research

a. Nanotechnology Integration: Conduct advanced studies on the nano-encapsulation of plant extracts. This technology aims to enhance the bio-stability of volatile compounds and prolong their residual efficacy under open-field conditions.
b. Synergy Exploration: Investigate novel formulations that combine multiple plant extracts (Neem and Basil). Identifying combinations that exhibit synergistic effects can provide a powerful tool for managing resistant pest populations.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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