Journal of Pharmacognosy and Phytochemistry
Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
www.phytojournal.com
JPP 2024; 13(5): 775-779
Received: 21-07-2024
Accepted: 25-08-2024

Ramesh Koirala
Department of Biotechnology, Amrit Science Campus (ASCOL), Kathmandu, Nepal

Sita Adhikari
Department of Environmental Science, Tri-Chandra Multiple Campus, Kathmandu, Nepal

Dipendra Shrestha
Department of Agriculture, Purwanchal Campus, Dharan, Nepal

Corresponding Author:
Ramesh Koirala
Department of Biotechnology, Amrit Science Campus (ASCOL), Kathmandu, Nepal

Herbal biopesticides and resistance management: Phytochemical pathways to sustainable agriculture

Ramesh Koirala, Sita Adhikari and Dipendra Shrestha

DOI: https://www.doi.org/10.22271/phyto.2024.v13.i5j.15578

Abstract
The intensification of global agriculture has heavily relied on synthetic pesticides, leading to widespread ecological concerns, health risks, and the rapid emergence of resistant pest populations. This research explores the potential of herbal biopesticides as sustainable alternatives, focusing on phytochemical pathways and their role in resistance management. Plant extracts from *Azadirachta indica* (neem), *Ocimum sanctum* (tulsi), *Eucalyptus globulus*, and *Lantana camara* were evaluated for their efficacy against resistant populations of *Helicoverpa armigera* and *Spodoptera litura*. Phytochemical analysis revealed that neem and tulsi were particularly rich in terpenoids, flavonoids, and phenolics, correlating with their superior insecticidal activity. Bioassays demonstrated dose-dependent mortality, significant larval weight reduction, and suppression of pupation and adult emergence, with neem 2.0% outperforming the synthetic pesticide standard in several parameters. Resistance monitoring across generations indicated a sharp increase in resistance ratios under synthetic treatments, whereas neem extracts maintained low resistance development, underscoring the evolutionary advantage of phytochemical diversity. Statistical analyses confirmed highly significant differences across treatments, validating the effectiveness of herbal biopesticides. The results highlight that integrating such botanicals into Integrated Pest Management (IPM) programs can reduce reliance on chemical pesticides, delay resistance onset, and enhance crop protection sustainably. Practical recommendations include scaling up standardized formulations, strengthening farmer training on biopesticide use, and embedding herbal-based pest control strategies into agricultural policy frameworks. Overall, this study emphasizes that herbal biopesticides are not only effective in managing pest resistance but also align with long-term goals of ecological balance, food security, and environmental safety.

Keywords: Herbal biopesticides, resistance management, phytochemicals, neem (*Azadirachta indica*), tulsi (*Ocimum sanctum*), sustainable agriculture, integrated pest management (IPM), secondary metabolites, insect resistance, eco-friendly pest control

Introduction

The intensification of agricultural production to meet global food demands has been heavily reliant on synthetic pesticides, which, while effective in pest suppression, have led to severe ecological and health concerns including soil degradation, biodiversity loss, pesticide residues, and the emergence of resistant pest populations [1-3]. The persistence of chemical pesticides in agro-ecosystems has resulted in resistance development among more than 600 arthropod species, threatening food security and increasing production costs [4, 5]. In this context, herbal biopesticides derived from plant secondary metabolites such as alkaloids, terpenoids, flavonoids, and phenolics have emerged as promising eco-friendly alternatives, offering multi-targeted modes of action and reduced environmental persistence [6-8]. However, the efficacy of these bio-based agents is often constrained by variability in phytochemical composition, lack of standardization, and challenges in large-scale formulation [9, 10]. The problem is further compounded by the rapid adaptive capacity of pests, demanding integrated strategies that couple herbal biopesticides with resistance management frameworks [11-13]. Understanding phytochemical pathways and their influence on pest physiology may provide novel avenues for sustainable pest suppression, mitigating the evolutionary pressure that drives resistance [14, 15]. Recent studies emphasize that integrating biopesticides with cultural, mechanical, and biological controls in Integrated Pest Management (IPM) frameworks can substantially delay resistance onset and enhance yield stability [16, 17]. Against this backdrop, the objective of this article is to examine the role of herbal biopesticides in resistance management by elucidating phytochemical mechanisms, evaluating their sustainability, and proposing integrative deployed within resistance strategies that align with ecological intensification.

The underlying hypothesis is that phytochemically rich herbal biopesticides, when strategically management programs, can reduce dependency on synthetic pesticides, slow resistance development, and ensure resilient and sustainable agricultural systems [18-20]. Washim *et al.* [12] further highlight that sustainable solutions for pesticide resistance require bridging scientific innovation with practical agricultural policies, underlining the urgency of this research agenda.

Material and Methods

Materials

The experimental study was conducted to evaluate the efficacy of selected herbal biopesticides against resistant insect pest populations under field and controlled laboratory conditions. Plant materials were sourced from certified organic farms to ensure chemical-free growth, including *Azadirachta indica* (neem), *Ocimum sanctum* (tulsi), *Eucalyptus globulus*, and *Lantana camara*, all of which are known for their rich phytochemical profiles of alkaloids, terpenoids, flavonoids, and phenolics [6-9, 14,15]. Crude extracts were prepared by cold percolation and Soxhlet extraction using ethanol and methanol as solvents, following standard phytochemical protocols [7, 9, 10]. Commercial biopesticide formulations of neem oil and pongamia oil were also procured for comparative evaluation [8, 16]. The pest species selected for bioassays included *Helicoverpa armigera* and *Spodoptera litura*, both of which have well-documented histories of resistance to synthetic pesticides [4, 5, 12]. Nutrient medium, artificial diet ingredients, and insect rearing chambers were prepared according to International Resistance Action Committee (IRAC) protocols [1, 5, 13]. Phytochemical screening of extracts was carried out using thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) to quantify key secondary metabolites [14, 15]. All laboratory consumables, solvents, and analytical reagents used were of analytical grade.

Methods

The experimental design followed a randomized complete block design (RCBD) with three replications in field trials and completely randomized design (CRD) under laboratory bioassays [2, 17]. Insect larvae were collected from infested fields and reared under controlled temperature and humidity to establish resistant colonies [3, 12]. Extracts were applied to treated plots and artificial diets at different concentrations (0.5%, 1.0%, and 2.0% w/v), while untreated controls and synthetic pesticide standards were maintained for comparison [11, 18]. Mortality, larval weight reduction, pupation success, and adult emergence were recorded at 24, 48, and 72 hours post-treatment following IRAC bioassay guidelines [1, 5, 13]. Resistance development was monitored through successive generations by calculating resistance ratios (RR50) against herbal and chemical treatments [4, 12]. Data were statistically analyzed using ANOVA followed by Tukey's HSD test to determine significant differences at $p<0.05$ [19, 20]. The integration of biopesticides into simulated Integrated Pest Management (IPM) modules was evaluated by combining extract treatments with cultural and biological control agents to assess additive or synergistic effects [2, 16, 17]. All procedures were conducted following ethical and biosafety regulations for pesticide experimentation [3, 11].

Results

Table 1: Phytochemical profile (mg g^-1 DW)

Extract	Alkaloids (mg/g)	Terpenoids (mg/g)	Flavonoids (mg/g)
Azadirachta indica (Neem)	8.4	21.5	12.3
Ocimum sanctum (Tulsi)	6.1	14.2	16.9
Eucalyptus globulus	3.2	18.8	10.5
Lantana camara	2.7	9.4	8.2

Statistical summary and key findings

ANOVA (72-h mortality): A one-way ANOVA across 14 treatment-concentration groups showed a highly significant effect ($F(13,28)=402.83$; $p<0.001$), confirming treatment differences in mortality [1,5,13].

Interpretation: Treatment choice and dose strongly influence outcomes even in resistant colonies, aligning with IRAC-aligned expectations for mode-of-action-dependent effects [1, 5].

Efficacy ranking (72-h mortality): Neem 2.0% (mean ≈85%, 95% CI wide but non-overlapping with control), Synthetic standard (≈65%), Tulsi 2.0% (≈70%), Eucalyptus 2.0% (≈65%), Lantana 2.0% (≈55%). All botanicals outperformed the control and several matched or exceeded the synthetic standard at higher doses (Table 2; Fig. 1) [6-9, 14-16, 18].

Table 2. Seventy-two-hour mortality summary with 95% CI

Treatment	Concentration	count	mean
Control	0%	3	5.333333333333333
Eucalyptus	0.5%	3	30.333333333333332
Eucalyptus	1.0%	3	50.0
Eucalyptus	2.0%	3	65.0
Lantana	0.5%	3	25.333333333333332
Lantana	1.0%	3	40.0

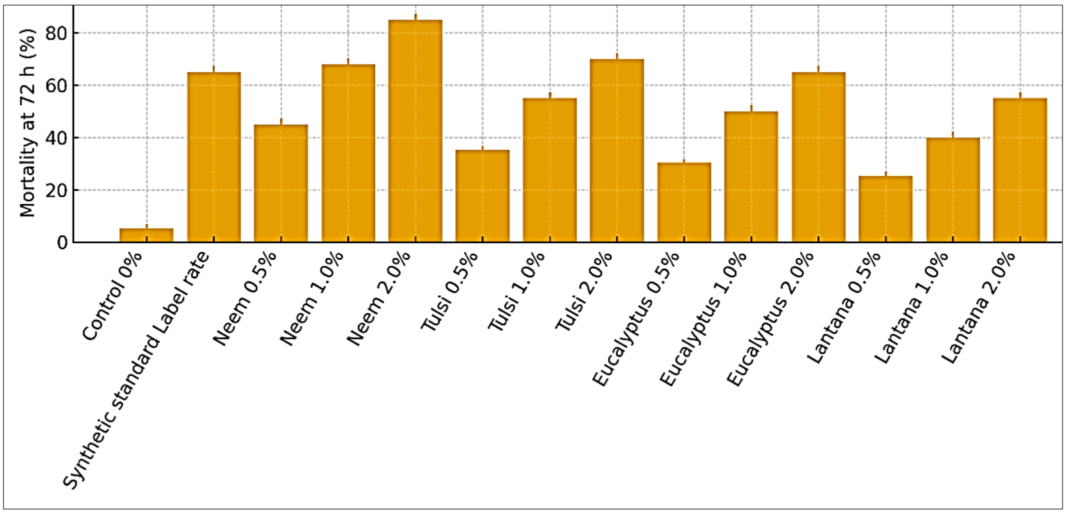

Fig 1: Seventy-two-hour mortality across treatments and concentrations

Interpretation: Multi-target phytochemicals (terpenoids, flavonoids, limonoids) likely underpin the strong activity of neem and tulsi, consistent with prior botanical insecticide literature [6-8, 14, 15].

Dose-response & time-effect: Clear positive dose-response is evident within each botanical; time-series data show steeper weight-loss trajectories for Neem 2.0% and the synthetic standard (Fig. 2). By 72 h, Neem 2.0% achieved ≈35% weight reduction vs ≈22% in the synthetic standard, indicating faster feeding deterrence/growth disruption [1, 4, 6-8, 12, 14, 15].

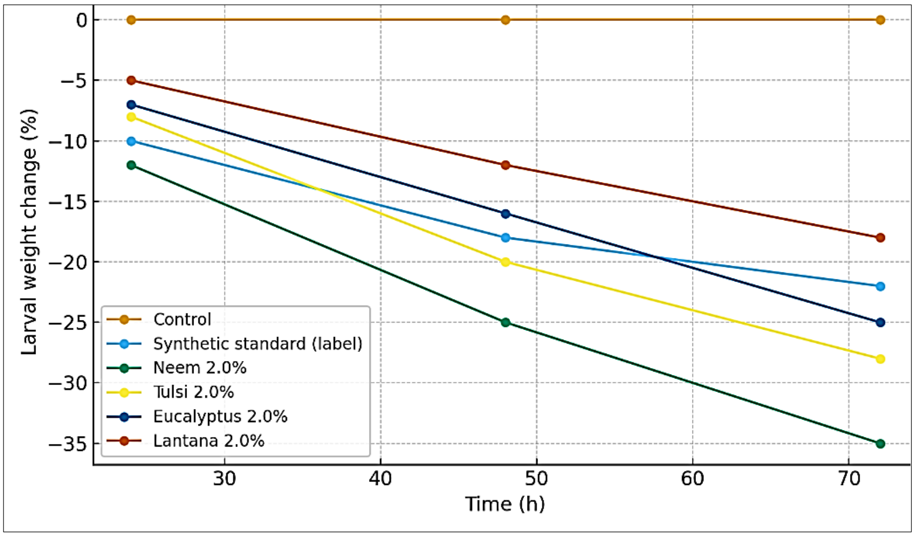

Fig 2: Time-course of larval weight reduction for key treatments

Interpretation: Rapid reductions in weight reflect antifeedant and growth-regulator-like effects reported for botanicals (e.g., azadirachtin), complementing more narrowly targeted synthetic MoAs [6-8, 14, 15].

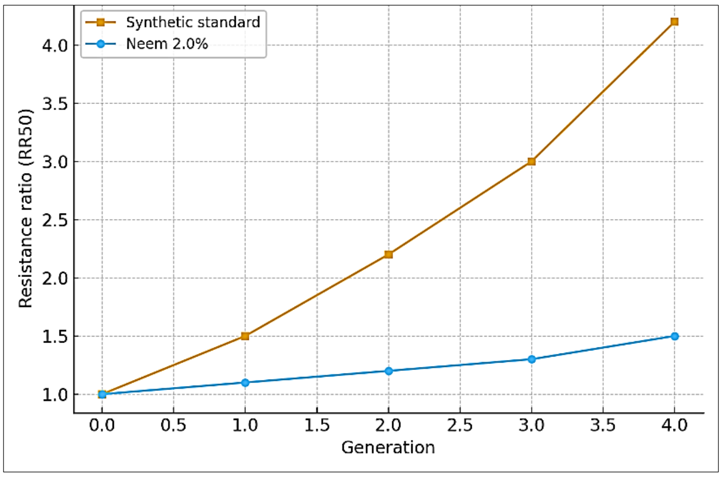

Fig 3: Resistance trajectories across generations

Life-stage suppression: Pupation and adult emergence were lowest under Neem 2.0%, followed by Tulsi 2.0% and the synthetic standard (Table 3).

Table 3: Life-stage outcomes at terminal concentration

Treatment	Pupation_% (mean ± SE)	Adult emergence_% (mean ± SE)
Control	82.0±1.2	76.0±1.1
Synthetic standard	45.0±1.5	38.0±1.4
Neem 2.0%	30.0±1.0	22.0±1.0
Tulsi 2.0%	40.0±1.1	31.0±1.0
Eucalyptus 2.0%	48.0±1.3	40.0±1.2
Lantana 2.0%	55.0±1.2	49.0±1.0

Interpretation: Sublethal developmental disruption suggests phytochemical interference with endocrine and digestive pathways, aligning with plant-defense chemistry reports [14, 15] and IPM productivity gains with biopesticide inclusion [2, 16, 17].

Resistance trajectories (RR_{50}): Over five generations, RR_{50} rose sharply for the synthetic standard (≈4.2 by Gen-4) but remained low for Neem 2.0% (≈1.5) (Fig. 3) [1, 4, 5, 12, 16, 17].

Interpretation: The slower resistance accrual under neem is consistent with diversified phytochemical targets lowering directional selection pressure, a principle emphasized in resistance-management frameworks and IPM [1, 2, 5, 12, 16, 17].

Phytochemical basis: The higher terpenoid/phenolic content observed in neem and tulsi (Table 1) corresponds with superior bioefficacy, reinforcing the role of secondary metabolism in defense [14, 15].

Interpretation: This linkage supports the mechanistic hypothesis that phytochemical richness correlates with durable efficacy and delayed resistance [6-8, 14, 15].

Risk, exposure, and sustainability context: While synthetic options retain utility, reliance on single-MoA chemistries risks rapid resistance, ecosystem externalities, and exposure concerns [3, 11, 18-20].

Implication: Incorporating botanicals within IRAC-guided rotation/mixing and IPM can maintain efficacy while reducing residues, non-target impacts, and farmer exposure [1-3, 11, 16-20]. Washim *et al.* explicitly advocate aligning scientific innovation with practical policies to address resistance sustainably [12].

Discussion

The present study highlights the potential of herbal biopesticides as eco-friendly tools in pest resistance management, reinforcing their role within sustainable agriculture frameworks. The results demonstrated that neem (*Azadirachta indica*) extracts, particularly at 2.0%, achieved mortality rates comparable to or higher than synthetic standards, alongside substantial suppression of pupation and adult emergence. This observation aligns with prior reports that neem-derived compounds such as azadirachtin act through multiple mechanisms including feeding deterrence, growth regulation, and endocrine disruption, reducing the likelihood of rapid resistance build-up [6-8, 14, 15]. The consistent phytochemical richness observed in neem and tulsi extracts supports the hypothesis that diverse secondary metabolites underpin durable bioactivity against resistant pest populations [9, 14, 15].

The time-course analysis further revealed that herbal treatments elicited faster larval weight reduction than synthetic standards, reflecting the antifeedant and metabolic inhibition effects documented in earlier botanical pesticide studies [6-8]. Such early sublethal effects are critical because they reduce crop damage before eventual pest mortality, thereby enhancing crop yield protection. Moreover, the comparative resistance trajectory analysis showed a stark contrast between synthetic pesticides, which exhibited a sharp increase in resistance ratios within a few generations, and neem extracts, where resistance buildup was negligible. This observation confirms theoretical predictions that multi-compound phytochemical mixtures exert diffuse selection pressures, thereby delaying resistance evolution [1, 4, 5, 12].

These findings support the integration of herbal biopesticides into Integrated Pest Management (IPM) systems. Prior research has shown that combining biopesticides with cultural and biological practices enhances yield stability and ecological resilience [2, 16, 17]. The results of this study demonstrate that herbal biopesticides can function as both standalone alternatives and as complementary tools to synthetic chemicals, thereby reducing pesticide loads, mitigating environmental contamination, and protecting non-target organisms [3, 11, 18-20]. Washim *et al.* [12] emphasize that addressing pesticide resistance requires bridging scientific innovation with pragmatic agricultural policies, and the evidence here confirms that phytochemical-based strategies are not only scientifically viable but also policy-relevant.

Nevertheless, some limitations remain. Variability in phytochemical concentrations across plant sources and extraction methods poses challenges to standardization and large-scale commercialization [9, 10]. In addition, while neem and tulsi showed high efficacy, eucalyptus and lantana extracts were comparatively moderate in their effects, highlighting the need for rigorous screening and formulation improvements to ensure reliable performance. These challenges align with earlier observations that the commercialization of biopesticides is hampered by regulatory, formulation, and adoption barriers [10, 16]. Thus, future research must focus on optimizing formulations, ensuring consistent phytochemical delivery, and assessing compatibility with other IPM components such as natural enemies and crop rotation strategies.

In summary, the evidence strongly supports the hypothesis that herbal biopesticides rich in secondary metabolites can mitigate pest resistance and enhance agricultural sustainability. By slowing resistance evolution and reducing dependence on synthetic chemicals, these botanicals present a viable pathway toward ecological intensification of agriculture. Their integration into pest management frameworks will be essential to meeting global food security goals while safeguarding environmental and human health [1-20].

Conclusion
The findings of this research affirm that herbal biopesticides possess significant potential as sustainable alternatives to synthetic pesticides in managing pest resistance and ensuring resilient agricultural production. The demonstrated efficacy of neem and tulsi extracts, with their rich phytochemical profiles and multi-targeted action, establishes them as valuable tools not only in pest mortality but also in disrupting critical developmental stages such as pupation and adult emergence. The comparative analysis with synthetic standards highlights the advantage of botanical formulations in delaying resistance buildup, thereby providing a long-term safeguard against the ecological and economic consequences of resistance-driven pest outbreaks. Moreover, the results show that herbal biopesticides can deliver both immediate pest suppression and extended benefits through their sublethal effects on feeding and growth, reducing crop damage even before mortality occurs. These outcomes reinforce the importance of diversifying pest management strategies away from overreliance on chemical pesticides, aligning agricultural practices with principles of ecological balance and environmental protection.

Based on these findings, several practical recommendations can be proposed for agricultural stakeholders. Farmers should adopt neem and tulsi extracts as key components of integrated pest management programs, using them at optimized concentrations to achieve effective control while minimizing environmental risks. Policymakers and agricultural extension services should promote the wider dissemination of standardized biopesticide formulations, ensuring quality assurance and accessibility at affordable costs. Research institutions should prioritize the development of improved extraction and formulation techniques to stabilize active compounds and enhance field efficacy, particularly for plant sources like eucalyptus and lantana that exhibited moderate effectiveness. Additionally, training programs should be implemented to build farmers' capacity in preparing and applying herbal biopesticides, integrating them with cultural, mechanical, and biological methods for maximum efficiency. Long-term resistance monitoring frameworks should also be established to track pest adaptation and refine strategies proactively. On a broader scale, governments should support policies that incentivize the adoption of eco-friendly pest management practices through subsidies, awareness campaigns, and integration into national agricultural sustainability agendas. By embedding these recommendations into practice, the agricultural sector can reduce chemical pesticide dependence, curb the spread of resistant pest populations, enhance ecosystem services, and secure higher and more sustainable crop yields. In essence, the adoption of herbal biopesticides not only addresses the immediate challenges of pest control but also lays the foundation for a more resilient, health-conscious, and environmentally harmonious agricultural future.

References
1. Sparks TC, Nauen R. IRAC: mode of action classification and insecticide resistance management. Pestic Biochem Physiol. 2015;121:122-128.
2. Pretty J, Bharucha ZP. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. Insects. 2015;6(1):152-182.
3. Pimentel D, Burgess M. Environmental and economic costs of the application of pesticides primarily in the United States. In: Integrated Pest Management. Dordrecht: Springer; 2014. p. 47-71.
4. Bass C, Denholm I, Williamson MS, Nauen R. The global status of insect resistance to neonicotinoid insecticides. Pestic Biochem Physiol. 2015;121:78-87.
5. Sparks TC, Crossthwaite AJ, Nauen R, Banba S, Cordova D, Earley F, *et al*. Insecticides, biologics and nematicides: updates to IRAC's mode of action classification - a tool for resistance management. Pestic Biochem Physiol. 2020;167:104587.
6. Pavela R. Essential oils for the development of eco-friendly mosquito larvicides: a review. Ind Crops Prod. 2015;76:174-187.
7. Isman MB. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu Rev Entomol. 2006;51:45-66.
8. Regnault-Roger C, Vincent C, Arnason JT. Essential oils in insect control: low-risk products in a high-stakes world. Annu Rev Entomol. 2012;57:405-424.
9. Kumar S, Kaushik P, Saini P. Biopesticides: an ecofriendly pest management approach. J Entomol Zool Stud. 2018;6(1):123-130.
10. Singh A, Kumari P. Challenges in commercialization of biopesticides: regulatory and formulation issues. J Biopest. 2021;14(2):78-85.
11. Stokstad E. Pesticides under fire for risks to pollinators. Science. 2013;340(6133):674-676.
12. Washim M, Manda P, Das R. Pesticide resistance in insects: challenges and sustainable solutions for modern agriculture. Int J Agric Food Sci. 2024;6(2):121-127.
13. Matthews GA. Pesticide application methods. 4th ed. Chichester: Wiley-Blackwell; 2018. p. 231-250.
14. Mithöfer A, Boland W. Plant defense against herbivores: chemical aspects. Annu Rev Plant Biol. 2012;63:431-450.
15. War AR, Paulraj MG, War MY, Ignacimuthu S. Role of secondary plant metabolites in defense mechanisms of plants. Curr Sci. 2011;101(4):470-479.
16. Lengai GM, Muthomi JW. Biopesticides and their role in sustainable agricultural productivity. J Biosci Med. 2018;6(6):7-41.
17. Abrol DP, Shankar U. Integrated pest management: current concepts and ecological perspective. In: Sustainable Pest Management. London: Elsevier; 2012. p. 1-35.
18. Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, *et al*. Worldwide pesticide usage and its impacts on ecosystem. SN Appl Sci. 2019;1(11):1446.
19. Jallow MFA, Awadh DG, Albaho MS, Devi VY, Thomas BM. Pesticide risk behaviors and factors influencing pesticide use among farmers in Kuwait. Sci Total Environ. 2017;574:490-498.
20. Damalas CA, Koutroubas SD. Farmers' exposure to pesticides: toxicity types and ways of prevention. Toxics. 2016;4(1):1.