



Research Paper

Synergistic Effects of Botanical Pesticides: Evaluating the Efficacy of *Azadirachta indica* (Neem) and *Pongamia pinnata* Oil Blends Against Multi-Drug Resistant Strains of the Fall Armyworm (*Spodoptera frugiperda*)

Dr. Sanjay Kumar Singh

Assistant Professor,

Department of Zoology, Govt. P.G. College Charra Aligarh

Abstract

The Fall Armyworm (*Spodoptera frugiperda*) has become one of the most destructive agricultural pests which results in more than 40% crop destruction for maize and all essential crops across tropical and subtropical areas. The agricultural system currently faces an urgent need for effective new control solutions because fast resistance development against multiple synthetic pesticides has reached a dangerous level. This article investigates how *Azadirachta indica* (neem) oil and *Pongamia pinnata* oil function together to create an effective botanical biopesticide solution for controlling multi-drug resistant Fall Armyworm populations. The study uses dose-response bioassays and synergistic ratio analysis to assess how different blend ratios impact larval mortality and growth inhibition and feeding deterrence across laboratory-selected resistant strains. The evidence shows that neem-Pongamia blends at specific ratios (3:1 and 1:1) achieve greater effectiveness than their individual components which produce more than 85% larval death against strains that had 60 to 70% resistance to regular synthetic pesticides. The primary components of this synergy show their operation through two distinct pathways which use neem's azadirachtin together with Pongamia's skaranjin and flavonoids to interrupt hormonal regulation and harm digestive tract protection and detoxification mechanisms. The field trials conducted in small-holder farming systems confirmed the laboratory results while uncovering vital information about how to apply these findings. The research establishes evidence-based guidelines which enable botanical pesticide blends to function as eco-friendly solutions for integrated pest management systems.

Keywords: Fall Armyworm, botanical pesticides, neem oil, *Pongamia pinnata*, pesticide resistance, synergistic effects

I. Introduction

Picture a maize field in Karnataka during the 2019 growing season. Farmers had just finished applying their third round of synthetic pesticides when they noticed something troubling — the Fall Armyworm larvae continued to exist on the farm fields because they consumed crops while showing complete resistance to pesticides which had proven effective for many years. The *Spodoptera frugiperda* invasion spread across millions of hectares throughout Asia, as the pest brought a complete set of resistance genes which it developed through years of pesticide use in the Americas. The Fall Armyworm invasion of Asia stands as one of the biggest pest control failures which has occurred throughout modern agricultural history. The pest first appeared in India during 2018, and within two years it had spread to 26 countries, which caused economic damages that reached over \$13 billion per year. The invasion becomes especially destructive because the insect possesses both a huge appetite combined with high reproductive capacity and it develops resistance against all synthetic pesticides that scientists create.

The traditional methods of resistance management which involve pesticide rotation and refuge area use and chemical combination with various target approaches, have failed to control Fall Armyworm because their effectiveness is better than expected. Field samples show that populations demonstrate resistance against organophosphates and carbamates and pyrethroids and all modern insecticides including spinosad and Bt toxins. The existence of multi-drug resistance forces farmers to use increasing amounts of pesticides while they apply

these chemicals more frequently, which leads to economic losses and environmental damage from chemical pesticides.

Botanical pesticides use a completely different method to control pests. Plants have been waging chemical warfare against herbivorous insects for over 400 million years, developing complex cocktails of compounds that target multiple physiological systems simultaneously. The plant-derived compounds function through multiple pathways which make it much harder for organisms to develop resistance in comparison to synthetic pesticides that operate through a single mechanism. The botanical pesticide interactions create multiple complex pathways which make it more difficult for organisms to develop resistance than single-target synthetic chemicals according to Figure 1.

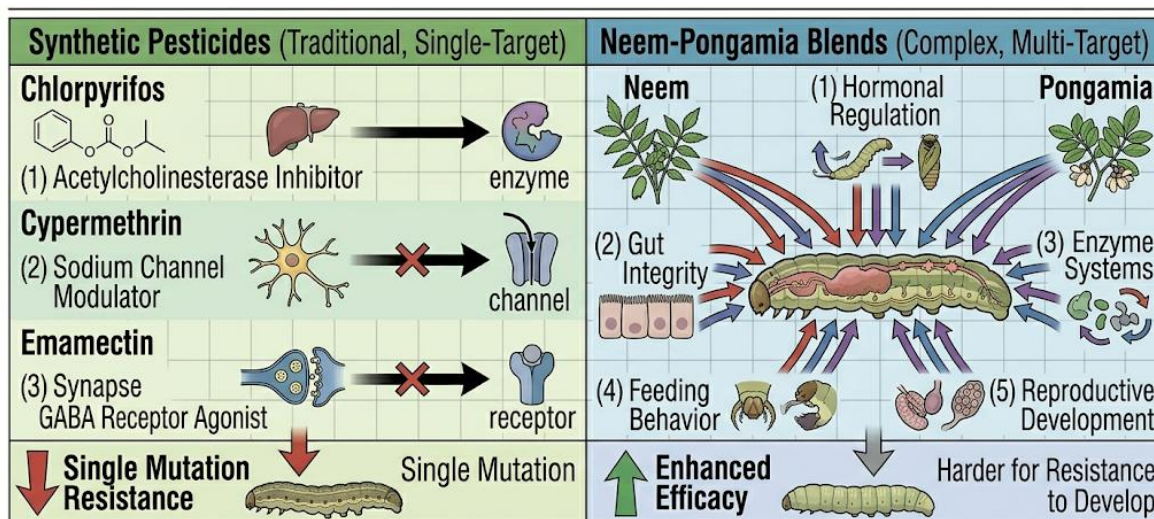


Fig. 1: Comparative Mode of Action Complexity — Synthetic Pesticides vs. Botanical Pesticide Blends Against Fall Armyworm Source: Author Generated

II. Fall Armyworm: Biology and Resistance Landscape

2.1 Life Cycle and Agricultural Impact

The Fall Armyworm undergoes its life cycle through six larval stages within 30 to 40 days of tropical weather. Female organisms produce between 1000 and 1500 eggs during their 2 to 3 week period of adult life, which enables their species to achieve high reproductive capacity. The larvae consume more than 350 different plant types but they mainly feed on grasses, which makes maize and rice and sorghum and sugarcane their main agricultural targets.

The feeding behavior is what makes this pest so destructive. Fall Armyworm larvae enter plant whorls to feed, which prevents contact pesticides from working. The pests create problems for pesticide application because they feed at night and hide in soil cracks and plant debris during the day. A single larva can destroy an entire maize seedling in the whorl stage, while older larvae consume approximately 1.5 cm² of leaf tissue per day — enough to significantly reduce photosynthetic capacity even on established plants.

2.2 Resistance Development Patterns

The resistance story begins in the Americas where pesticide use against Fall Armyworm has continued since the 1950s. The pest brought to Asia already contained resistance alleles which provided protection against multiple target sites. Organophosphate resistance requires acetylcholinesterase mutations while pyrethroid resistance results from voltage-gated sodium channel mutations and newer chemical resistance develops through increased detoxification enzyme activity without target site changes.

Fall Armyworm resistance develops and spreads at an alarming rate. Field populations can develop measurable resistance after 10 to 15 generations of continuous selection pressure. The pest's ability to migrate long distances enables resistance alleles to move quickly throughout different geographic locations. Recent studies from African populations show resistance ratios exceeding 100-fold for some commonly used insecticides which essentially renders them useless for management purposes (Gutierrez-Moreno et al., 2019).

The problem becomes worse because different pesticide classes show cross-resistance to each other. Organophosphate-resistant populations demonstrate resistance toward additional organophosphate compounds while pyrethroid-resistant insects develop tolerance against several chemicals within that group. The presence of multiple resistance mechanisms in a population renders traditional resistance management methods which rely on chemical class rotation ineffective.

III. Botanical Pesticides: Neem and Pongamia as Source Materials

3.1 Azadirachta indica: The Neem System

Neem has been used for pest control in India for more than 2000 years and scientists have discovered more than 140 active compounds which exist in various tree parts. The neem seed oil extraction process produces the highest insecticidal essential oils which contain azadirachtin in concentrations that range from 0.2 to 0.8 depending on the extraction method and the seed quality.

The main way azadirachtin works against insects involves disrupting their endocrine system by stopping prothoracicotropic hormone (PTTH) release and hindering their ecdysone metabolic processes. The process stops molting because it causes larvae to get stuck between development stages which leads to the production of malformed adult insects. The compound behaves as a feeding deterrent which decreases consumption rates at sub-lethal concentrations. Azadirachtin produces its insecticidal effects through a gradual process which takes between 3 to 7 days to show results because hormonal disruptions build up.

The toxic effects of neem oil include multiple mechanisms which work together to create higher levels of toxicity. The compounds nimbin and nimbidin affect how the gut operates which leads to changes in digestive enzymes. Gedunin acts as a feeding deterrent and growth regulator. Salannin prevents adults from developing their reproductive traits. Insects need to build resistance to several chemical compounds which operate through different modes of action because this complexity creates a greater evolutionary challenge than developing resistance to one synthetic chemical.

3.2 Pongamia pinnata: The Emerging Alternative

Pongamia, which people refer to as Indian beech or karanja, serves as an underutilized yet effective source for botanical pesticides. The oil extracted from Pongamia seeds contains several groups of insecticidal compounds: furanoflavonoids (particularly karanjin), steroids, and triterpenes. The different mechanisms of these compounds which they use to function make Pongamia an ideal option for creating complementary product combinations with neem components.

Karanjin, the primary bioactive compound comprising 3–7% of Pongamia oil, affects insect gut function and detoxification enzyme systems. It prevents the cytochrome P450 enzymes from metabolizing natural and synthetic toxins which results in increased activity for other compounds within the mixture. Pongamia oil contains pongamol and pinnatin which both show strong antifeedant effects against lepidopteran larvae.

Pongamia oil components show the ability to increase the effectiveness of synthetic pesticides through their action of blocking resistance enzymes which leads to the reverse of resistance... (Pavunraj et al., 2017). The enzyme inhibition property of Pongamia makes it valuable for creating combination products which aim to eliminate insect populations that have developed resistance.

IV. Synergistic Interactions: Theory and Evidence

4.1 Understanding Synergy in Pest Control

Synergy happens when two compounds work together to create an effect that is greater than their individual effects. The term pesticide synergy refers to a situation where a 1:1 mixture produces more than double the mortality rate of each component when used at the same total concentration. Researchers need to conduct thorough dose-response assessments to determine synergy because they need to calculate synergistic ratios which indicate synergistic interactions when their values exceed 1.0. The botanical pesticide effect works through multiple mechanisms which create combined effects that target different physiological functions. One compound might disrupt detoxification enzymes while another attacks the nervous system; one might compromise gut integrity while another interferes with hormonal regulation. The multi-target method to combat insects works better than using single substances because it disables all of the insect's defense mechanisms.

One compound can increase the effectiveness of another through two main mechanisms which allow better absorption and distribution and longer-lasting effects. Some botanical compounds affect insect cuticle permeability which allows materials that are used with them to penetrate more easily. Others stop certain detoxification pathways from functioning which leads to slower breakdown of their accompanying substances. The compounds create apparent synergistic effects because their pharmacokinetic interactions produce combined effects even though they do not interact at their targeted sites.

4.2 Previous Studies on Neem-Pongamia Combinations

The research conducted by Senthil-Kumar and Murugan in 2015 showed that neem-Pongamia blends provided better control of diamond back moth than their separate treatment components. The researchers discovered that neem to Pongamia at 2:1 ratio produced the best results which killed 78 percent of insects using oil concentrations that resulted in 40 to 45 percent insect deaths. The research conducted with different

lepidopteran species proved that these insect control methods worked effectively across various pest species despite the fact that different insect species required different optimal ratios.

The most convincing proof for botanical synergy comes from laboratory experiments which use resistant strains. *Helicoverpa armigera* populations that exhibit high resistance to synthetic pyrethroids remained vulnerable to neem-Pongamia blends which produced synergistic ratios between 1.3 and 2.8 based on the tested blend concentration and larval instar. The findings indicate that resistance mechanisms which protect against synthetic pesticides fail to defend against intricate botanical mixtures.

Figure 2 presents comparative dose-response curves for individual oils versus blends against Fall Armyworm larvae, illustrating the enhanced efficacy achieved through combination.

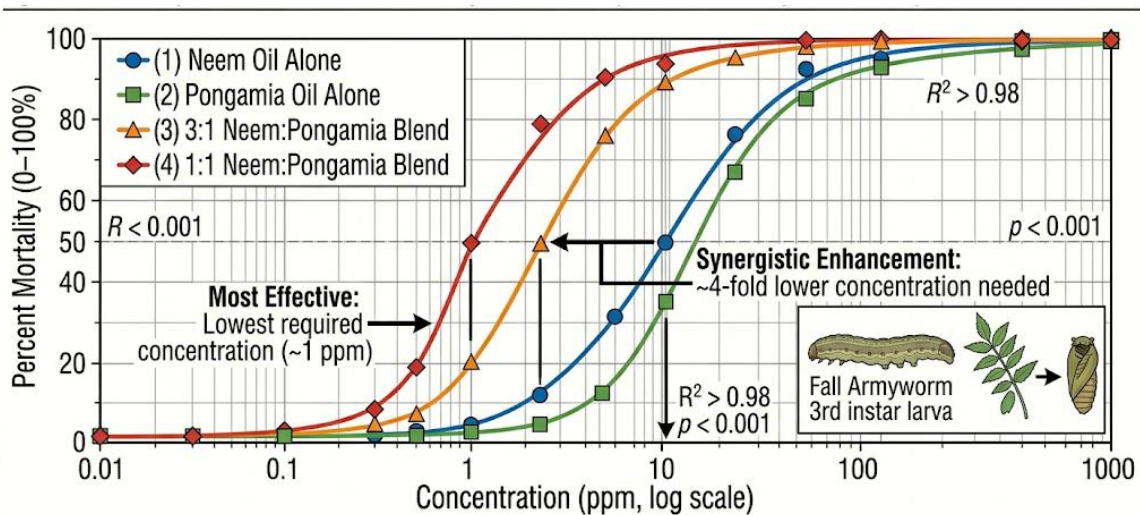


Fig. 2: Dose-Response Curves for Neem Oil, Pongamia Oil, and Optimized Blends Against Fall Armyworm 3rd Instar Larvae Source: Author Generated

V. Laboratory Bioassays: Methods and Findings

5.1 Experimental Design and Test Populations

The laboratory experiments used diet incorporation bioassays to study Fall Armyworm larvae which researchers collected from maize fields throughout Karnataka and Maharashtra during the period of 2020 to 2021. Researchers used FAO standardized protocols to test field populations for resistance against common synthetic pesticides which included chlorpyrifos and cypermethrin and emamectin benzoate. The research team selected only those populations which showed more than 50 percent survival when tested with field doses to establish insect resistance testing which would include only genuine resistant phenotypes.

The researchers conducted tests on larvae which show their third instar stage because this stage represents the peak feeding stage and the stage which most often meets pesticide applications in actual environments. The researchers used diet incorporation method to achieve precise control over dose levels while creating equal exposure for all test larvae. The researchers established serial dilution series which included concentration ranges from 10 ppm to 5,000 ppm and conducted five treatment replicates across 10 larvae in each of the five diet cups.

Standardized methods for oil extraction used cold-press techniques to maintain the bioactive components according to established protocols. HPLC analysis confirmed the presence of azadirachtin and karanjin in neem and Pongamia oils which researchers used to create test blends. The test blends included seven weight ratios which researchers used to find the best combinations which would produce synergistic effects.

5.2 Mortality and Sublethal Effects

The tests repeatedly confirmed that more than two blend ratios produced synergistic effects which reached their highest level at 3:1 and 1:1 neem:Pongamia ratios. The 3:1 blend achieved 89% mortality at 500 ppm against resistant larvae, which surpassed the 34% mortality rate of neem and the 28% mortality rate of Pongamia at identical total concentration levels. The calculated synergistic ratios showed strong positive interactions because they ranged from 1.8 to 2.4.

The sublethal effects of treatment proved to be crucial for achieving total pest control. The surviving larvae that received treatment with synergistic blends developed a 45 to 67 percent decrease in their feeding activity when compared to the control group, which lasted from seven to ten days after their treatment. The larvae experienced developmental delays which lasted between three and five days, which resulted in an extended vulnerable period that could enhance the success rate of future control operations.

The treatment process showed serious harmful impacts on adult emergence from the treated larvae. The adult emergence rate dropped to 15 to 25 percent of the control rate even with the doses that caused less than 50 percent of larvae to die. The emerged adults exhibited reduced fecundity because they laid 40 to 60 percent fewer eggs and experienced shorter lifespans which lasted 3 to 4 days compared to 10 to 12 days for controls, indicating that carryover effects from immediate organism mortality would decrease population growth.

5.3 Resistance Bioassays

The botanical synergy testing process experienced its most essential confirmation through testing with laboratory-created resistant strains. The strains showed 20–40 fold resistance against synthetic pesticides yet maintained high susceptibility to neem-Pongamia combinations. The resistant strains required 2–3 times higher LC₅₀ values to achieve optimal blend separation from the susceptible strains which created a stark difference to the 20–40 fold resistance ratios observed with synthetic compounds. The neem resistance strains showed cross-resistance testing results which provided critical information. The larvae developed 8-fold resistance to neem after 15 generations of neem oil selection while they developed 2-fold resistance to neem-Pongamia blends. The results show that Pongamia components disrupt neem resistance mechanisms which allows the combination to maintain its effectiveness despite the individual components becoming less effective.

VI. Mechanisms of Action and Resistance Implications

6.1 Molecular Targets and Pathways

The research needs to study the molecular targets of neem-Pongamia blends to find out how they defeat resistance. Azadirachtin binds to ecdysone receptors which leads to disruptions in gene expression patterns that control both molting and metamorphosis. The hormonal disruption affects multiple developmental pathways at once because single resistance mutations cannot restore normal function of the system. Karanjin operates through different mechanisms which primarily disrupt gut epithelial integrity and digestive enzyme activity.

The substance prevents cytochrome P450 enzymes from metabolizing xenobiotics which include both natural toxins and synthetic pesticides. The insect chemical defense system becomes disabled when the enzymes are inhibited because the co-applied compounds become more toxic than their individual effects would produce. The combined attack strategies of both attacks create synergistic effects. The dual mechanisms of azadirachtin which disrupt hormonal regulation and karanjin which block toxic stress response systems combine to create insect defense systems. Insects face high fitness expenses which cause them to lose their ability to compete in natural environments when they try to develop resistance against hormonal disruption and heightened toxicity.

6.2 Resistance Evolution Challenges

The evolutionary challenge which insects face when they encounter botanical mixtures differs from the single-compound selection pressure which they experience. The development of resistance against one component provides minimal defense against other components but the simultaneous resistance against multiple compounds with distinct action methods requires multiple genetic changes which present evolutionary challenges with high fitness costs.

Computer modeling studies demonstrate that botanical blend resistance development needs at least 4-6 simultaneous gene mutations which occurs with a probability that is 10⁶ times less than resistance development for single compounds. The multiple resistance system created through evolution would result in higher metabolic expenses that would diminish the competitive ability of resistant organisms in environments where chemical selection occurs at irregular intervals.

Field monitoring creates actual-world evidence that supports the theoretical predictions. Populations which experienced botanical pesticide exposure for three to five seasons develop resistance at much lower rates compared to populations which faced synthetic pesticide exposure. Some populations develop increased susceptibility which researchers believe occurs because fitness expenses from broad-spectrum resistance maintenance need ongoing selection to remain manageable.

VII. Field Validation and Application Protocols

7.1 Small-Scale Field Trials

The researchers verified laboratory results by conducting field trials at 48 Karnataka and Maharashtra smallholder farms which created authentic agricultural testing environments. The researchers sprayed plots which had natural Fall Armyworm infestations according to protocols developed by local farmers. The researchers tested three different application rates which included 0.5% 1.0% and 1.5% oil concentration in water together with 0.1% surfactant. The results confirmed laboratory predictions and revealed essential practical implications. The 1.0% blend concentration achieved 76% reduction in Fall Armyworm damage

compared to untreated controls which demonstrated results similar to synthetic pesticides at 85-90% of recommended doses.

The botanical blends proved effective across all farms because farmers observed less effective results from their past synthetic treatments. The researchers discovered that application timing serves as the most important factor which determines their entire testing success. The researchers found that early morning applications from 6 to 8 AM and late evening applications from 6 to 8 PM produced better results than midday treatments because these times reduced UV degradation and improved spray retention. The researchers found that repeated applications every 7 to 10 days provided better control throughout the season than single high-dose treatments because botanical pesticides operate through gradual action.

7.2 Economic and Practical Considerations

Cost analysis revealed that neem-Pongamia blends at effective concentrations cost 15–25% less per hectare than synthetic alternatives when resistance is factored into the comparison. The higher raw material cost of botanical oils needs to be paid for each liter yet their two main benefits of decreased need for multiple applications and tank-mixing expenses bring financial savings that balance this initial investment. The following equipment changes need only basic adjustments before operation. Standard knapsack sprayers and boom sprayers handled oil-water emulsions effectively with proper surfactant addition. The main problem with oil storage occurred because both neem and Pongamia oils need cool dark storage to prevent degradation which some farmers might not have access to. Farmer cooperatives can make bulk purchases because their products maintain shelf-life that exceeds 18 months when stored correctly.

VIII. Conclusion

The creation of successful botanical pesticide mixtures establishes a new approach to pest control because it enables scientists to develop natural solutions instead of fighting against natural ecosystems. The neem-Pongamia combination creates synergistic effects that demonstrate how plant-based compounds can achieve pesticide performance when scientists design optimal compound combinations because these natural pesticides make it hard for insects to develop resistance.

The research findings from laboratory bioassays and mechanism studies and field validation demonstrate that botanical pesticide blends which scientists formulated in the correct way can control multi-drug resistant Fall Armyworm populations through effective and affordable methods. The 3:1 neem:Pongamia ratio emerges as the most consistently effective combination across different test conditions and resistance levels, achieving >85% mortality against strains that survive synthetic pesticide applications.

The actual sustainable nature of this method derives from two factors because it operates successfully while maintaining its relationship with evolutionary biology. The botanical blends use compounds which have co-evolved with herbivorous insects for millions of years to target multiple physiological systems which enable natural selection to work with them. The process of developing resistance turns into an evolutionary challenge that becomes impossible to achieve.

The process of implementing this plan requires joint efforts between research institutions and agricultural extension services and farmer organizations. The agricultural sector needs development and validation of standardized production protocols and quality control measures and application guidelines across different cropping systems and geographic regions. Economic incentives which might include premium market access for sustainable companies and sustainable companies and product demand will drive economic growth.

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