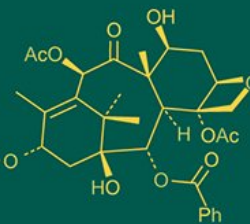
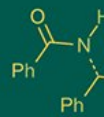


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 205-212
www.biochemjournal.com
Received: 09-03-2026
Accepted: 14-04-2026

Subhalaxmi Mishra
Department of Forest Products
& Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh India

Rajesh Kumar
Department of Forest Products
& Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh India

Komal Khunte
Department of Forest Products
and Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh India

Rashmi
Department of Forest Products
& Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh India

Alok Singh Bargah
Department of Forest Products
& Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh India

Corresponding Author:
Subhalaxmi Mishra
Department of Forest Products
& Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh India

Neem (*azadirachta indica*) based biopesticides: Mechanisms, application and environmental impact: A review

Subhalaxmi Mishra, Rajesh Kumar, Komal Khunte, Rashmi, and Alok Singh Bargah

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sc.8588>

Abstract

Azadirachta indica (Neem) is an important botanical resource for developing eco-friendly biopesticides because of its bioactive compounds such as azadirachtin, nimbin, and salannin. Rising environmental and health concerns associated with synthetic pesticides have increased interest in Neem-based alternatives for sustainable pest management. This review evaluates the pesticidal properties, mechanisms of action, environmental significance, and recent technological advancements related to Neem-based biopesticides, along with their role in Integrated Pest Management (IPM) systems. Relevant information was collected from published research articles, review papers, technical reports, and scientific databases focusing on Neem-derived biopesticides and their agricultural applications. Special emphasis was given to active compounds, extraction methods, nano-formulations, environmental impacts, and compatibility with biological control agents. Findings from laboratory and field studies indicate that Neem-derived compounds possess strong antifeedant, insect growth regulatory, reproductive inhibitory, and metabolic disruptive activities against a wide range of agricultural and storage pests. Neem-based biopesticides also exhibit low toxicity toward non-target organisms and high compatibility with beneficial insects, making them suitable for IPM programs. Their biodegradable nature and low environmental persistence help reduce soil and water contamination. Recent advancements in nano-formulations and improved extraction technologies have enhanced the stability, bioavailability, and field efficacy of Neem products. However, environmental instability and short residual activity remain major limitations affecting long-term field performance. Overall, Neem-based biopesticides have significant potential as environmentally safe and sustainable alternatives to synthetic pesticides, and further improvements in formulation technologies may support their wider adoption in sustainable agriculture.

Keywords: Neem, Biopesticides, Environmental safety, Integrated Pest Management, Sustainable agriculture.

Introduction

The Neem activity and often indiscriminate use of synthetic pesticides in modern agriculture has led to several unintended consequences, including environmental contamination, development of pest resistance, and risks to human and animal health. Persistent pesticide residues in soil and water systems have raised concerns regarding ecological imbalance and long-term sustainability of agricultural practices (Isman, 2020; Sharma *et al.*, 2022) [14, 15, 39]. Seed germination is a complex process that leads to the resumption of active growth in the embryonic axis, rupture of the seed cover and emergence of the young plants. For physiologists and biochemists, germination is complete when the and the cover becomes visible. For seed technologists, foresters, nursery growers, etc (Bhardwaj *et al.*, 2024) [6]. However, germination is a complex process that leads to the resumption of active embryonic growth and continued growth and development until a potentially independent seedling is formed (Bargah *et al.*, 2025) [1]. Agroforestry is a comprehensive term encompassing land-use systems where woody perennials like trees, shrubs, and bamboos are cultivated alongside herbaceous plants such as crops, pasture, and/or livestock. These elements are organized spatially or temporally, facilitating ecological and economic interactions between the tree and non-tree components (Kumar *et al.*, 2023) [24]. The principal constituents of agroforestry

Systems include trees, shrubs, crops, pastures, and livestock. Along with factors like climate, soil, and the surrounding environment (Bargah *et al.*, 2024) ^[2, 4]. Seedlings are small plants with enough potential to grow into mature trees. These seedlings grow naturally, but they can also be propagated by seeding and germinating, which helps them to sprout quicker and boost their chances of survival. The factors must be optimal to produce a health and vigorous seedlings, and among them, the genes and the nursery environment determine to a large degree how a tree can survive (Minj *et al.*, 2024). Plants are propagated and grown to a size that can be planted in a nursery. A quality nursery stock is necessary to create a good plantation. The necessity of forest nurseries in order to properly nurture seedlings before planting them on land that needs to be replanted (Verma *et al.*, 2024) Nurseries provide the means to control moisture, light physical and chemical soil constituents in such a way as to produce healthy and uniform seedlings for planting. Several factors can influence seedling growth in the nursery (Nishad *et al.*, 2025) ^[34]. These challenges have prompted researchers and policymakers to explore safer and more sustainable alternatives for pest management (Kumar *et al.*, 2023) ^[24]. Plant based biopesticides have emerged as a promising solution due to their biodegradability, lower toxicity, and eco-friendly nature (Kumar *et al.*, 2022) ^[22, 23, 25, 26]. Among various botanical sources, Neem (*Azadirachta indica*), belonging to the family Meliaceae, has gained significant attention. Neem contains a diverse array of biologically active compounds, particularly limonoids such as azadirachtin, nimbin and salannin, which exhibit strong insecticidal, antifeedant and growthregulating properties (Campos *et al.*, 2020; Kilani-Morakchi *et al.*, 2021) ^[8, 17]. Historically, Neem has been used in traditional agricultural practices for pest control, especially in tropical and subtropical regions. However, recent scientific investigations have validated its effectiveness and expanded its application in modern crop protection strategies. Advantage of Neembased biopesticides is their multi-target mode of action, which affects insects at various physiological and behavioral levels, thereby reducing the likelihood of resistance development (Mordue & Nisbet, 2021) ^[32]. Neem products exhibit relatively low toxicity toward nontarget organisms, including beneficial insects, birds, and mammals, making them suitable for incorporation into Integrated Pest Management (IPM) systems (Isman &

Grieneisen, 2020) ^[14, 15]. With the increasing demand for sustainable agriculture and reduced chemical inputs, Neembased biopesticides are gaining global importance (Kumar *et al.*, 2022) ^[22, 23, 25, 26]. Their compatibility with organic farming systems and regulatory acceptance further strengthen their role as viable alternatives to synthetic pesticides (Kumar *et al.*, 2022) ^[22, 23, 25, 26].

Active compounds in neem

The pesticidal efficacy of Neem is primarily attributed to a group of highly oxygenated triterpenoids known as limonoids (Kumar *et al.*, 2022) ^[22, 23, 25, 26]. Among these, azadirachtin is recognized as the most potent and extensively studied bioactive compound. In addition to azadirachtin, several other limonoids such as nimbin, salannin, meliantriol and nimbolide contribute significantly to the overall biological activity of Neem extracts (Campos *et al.*, 2020; Kilani-Morakchi *et al.*, 2021) ^[8, 17]. These compounds are distributed in different parts of the Neem tree, including seeds, leaves, bark and oil, although the highest concentration of active constituents is found in the seeds. The complexity and diversity of these phytochemicals are responsible for the broad-spectrum activity of Neem against a wide range of insect pests (Kumar *et al.*, 2018). Azadirachtin, predominantly present in Neem seed kernels, is considered the key active ingredient responsible for insecticidal properties (Kumar *et al.*, 2024) ^[20, 27]. It functions primarily as an insect growth regulator and feeding deterrent by interfering with hormonal systems and disrupting normal physiological processes in insects (Mordue & Nisbet, 2021). Its ability to affect multiple biological pathways makes it highly effective even at low concentrations. Nimbin and salannin exhibit moderate insecticidal and repellent properties, while meliantriol is particularly known for its strong antifeedant activity. The combined action of these compounds results in synergistic effects, enhancing the overall pesticidal efficiency of Neembased formulations (Isman, 2020) ^[14, 15]. The presence of multiple bioactive constituents with different modes of action gives Neem a unique advantage over synthetic pesticides, which typically target a single biochemical pathway (Khandekar *et al.*, 2024) ^[16]. This complexity not only improves efficacy but also reduces the likelihood of resistance development in pest populations (Table:1)

Table 1: List of major active compound in *azadirachta indica*

Bioactive Compound	Major Source in Neem Tree	Main Biological Activity	Mode of Action / Importance	Citation
Azadirachtin	Seed kernels	Insecticidal, antifeedant, insect growth regulator	Interferes with insect hormonal systems, disrupts molting, feeding, and reproduction; highly effective at low concentrations	Campos <i>et al.</i> (2020); Mordue & Nisbet (2021) ^[8, 32]
Nimbin	Seeds, leaves, bark	Moderate insecticidal and repellent activity	Acts as a repellent and contributes to overall pesticidal action	Campos <i>et al.</i> (2020); Isman (2020) ^[8, 14, 15]
Salannin	Seeds and Neem oil	Repellent and antifeedant activity	Deters feeding and reduces insect attraction to crops	Kilani-Morakchi <i>et al.</i> (2021); Isman (2020) ^[14, 15, 17]
Meliantriol	Leaves and seed extracts	Strong antifeedant activity	Prevents feeding behavior in several insect pests	Mordue & Nisbet (2021) ^[32]
Nimbolide	Leaves and bark	Bioactive pesticidal and antimicrobial activity	Enhances broad-spectrum biological activity of Neem extracts	Campos <i>et al.</i> (2020); Kilani-Morakchi <i>et al.</i> (2021) ^[8, 17]

Neem-based biopesticides

Neem-based biopesticides derived from *Azadirachta indica* exhibit a complex and multi-target mode of action, influencing insects at physiological, biochemical, and behavioral levels. Unlike synthetic pesticides that generally act on a single biochemical pathway, Neem-derived compounds such as azadirachtin interfere with several regulatory systems simultaneously (Table 2). This multi-site activity enhances their effectiveness against a broad spectrum of insect pests while reducing the likelihood of resistance development. The different mechanisms through which Neem exerts its pesticidal effects are discussed below. One of the primary actions of Neem compounds is antifeedant activity, where insects lose their appetite after exposure to Neem-treated surfaces (Chandra *et al.*, 2021) ^[9]. Azadirachtin disrupts the sensory receptors responsible for feeding stimulation, causing insects to avoid treated plants and eventually suffer from starvation. Neem also acts as an insect growth regulator by interfering with hormones such as ecdysone and juvenile hormone, which are essential for molting and metamorphosis. As a result, insects experience

abnormal development, incomplete molting, deformities, and death during immature stages. Neem compounds further affect insect reproduction by reducing fecundity, oviposition, egg viability, and hatchability. Reproductive behavior and mating success may also be altered, leading to long-term suppression of pest populations. In addition, Neem exhibits strong repellent and behavioral effects by interfering with host recognition, feeding behavior, and oviposition cues, making treated plants less attractive to pests. At the biochemical level, Neem compounds disrupt digestive enzymes, protein synthesis, nutrient assimilation, and cellular metabolism. Such metabolic interference weakens insects, reduces growth and survival, and increases susceptibility to environmental stress. Because Neem acts through multiple physiological and biochemical pathways rather than a single target site, pests are less likely to develop resistance rapidly. This broad-spectrum and environmentally safe mode of action makes Neem-based biopesticides highly valuable in sustainable agriculture and Integrated Pest Management (IPM) programs.

Table 2: Mechanisms of Action of Neem-Based Biopesticides

Mechanism	Description	Effect on Insects	Citation
Antifeedant Action	Neem compounds (especially azadirachtin) affect insect taste receptors and deter feeding.	Insects stop feeding, leading to starvation and reduced crop damage.	Isman (2006); Mordue & Nisbet (2000) ^[13, 30, 31]
Growth Regulation	Interferes with insect hormones such as ecdysone, disrupting molting and development.	Larval development is inhibited; malformed adults may occur.	Schmutterer (1990); Mordue (Luntz) & Blackwell (1993) ^[37]
Reproductive Inhibition	Affects mating behavior, fecundity, and egg viability.	Reduced fertility and population growth.	Isman (2006); Koul <i>et al.</i> (2008) ^[13, 19]
Oviposition Deterrent	Prevents insects from laying eggs on treated plants.	Decrease in pest infestation in subsequent generations.	Schmutterer (1990) ^[37]
Metabolic Disruption	Alters enzyme activity and physiological processes in insects.	Reduced survival and weakened physiological condition.	Mordue & Nisbet (2000) ^[30, 31]
Repellent Effect	Emits chemical signals that repel insects from treated surfaces.	Prevents pest colonization.	Isman (2006) ^[13]
Sterilization Effect	Causes partial or complete sterility in insects.	Long-term suppression of pest populations.	Schmutterer (1990); Koul <i>et al.</i> (2008) ^[19, 37]
Multi-target Action	Acts on multiple biochemical pathways simultaneously.	Minimizes resistance development compared to synthetic pesticides.	Isman (2006); Mordue & Nisbet (2000) ^[13, 30, 31]

Antifeedant activity

One of the most immediate and prominent effects of Neem compounds derived from *Azadirachta indica* is their antifeedant action. Azadirachtin disrupts the normal functioning of gustatory receptor neurons in insects, particularly those present in the mouthparts and tarsi. This interference alters the insect's perception of food, rendering treated plant surfaces unpalatable. As a result, insects significantly reduce their feeding activity or completely cease feeding, even in the presence of adequate food sources. Prolonged feeding inhibition ultimately leads to starvation and death. This mechanism plays a crucial role in minimizing crop damage at the early stages of infestation, as it prevents insects from consuming plant tissues rather than relying solely on toxic effects (Senthil-Nathan, 2020; Kilani-Morakchi *et al.*, 2021) ^[17, 38]. The antifeedant effect of Neem is considered one of the most important mechanisms responsible for its pesticidal efficiency. Insects depend on chemical and sensory signals to recognize suitable food sources, and Neem compounds interfere with these sensory pathways. After contact with Neem-treated plants, insects experience disruption in taste perception and lose their normal feeding stimulation. Consequently, pests

avoid feeding on treated crops and often move away in search of alternative food sources. This behavioral response reduces the extent of plant injury and protects crops from severe infestation. Neem-induced feeding deterrence is effective against a wide range of chewing and sucking insect pests, including caterpillars, beetles, aphids, grasshoppers, and leafhoppers. Even sublethal concentrations of Neem compounds can significantly reduce food consumption, growth, and survival of insect larvae. Reduced feeding also limits nutrient intake, resulting in weakened physiological condition, slower development, and decreased reproductive capacity. Since Neem acts gradually rather than causing immediate mortality, it exerts lower selection pressure on pest populations, thereby reducing the likelihood of resistance development. Another important advantage of antifeedant activity is its environmental safety. Neem compounds primarily prevent feeding rather than relying entirely on toxic action, making them comparatively safer for beneficial organisms and non-target species. This property enhances their suitability for sustainable agriculture and Integrated Pest Management (IPM) programs aimed at reducing dependence on synthetic pesticides while maintaining ecological balance.

Growth regulation

Neem compounds derived from *Azadirachta indica*, particularly azadirachtin, function as potent insect growth regulators by disrupting the endocrine system. They interfere with the synthesis and release of ecdysone, the hormone responsible for molting and metamorphosis. This hormonal imbalance results in severe developmental abnormalities, including incomplete molting, extended larval stages, and the formation of deformed pupae and adults. In many cases, insects fail to complete their life cycle, leading to mortality or reduced fitness. Additionally, azadirachtin has been reported to affect cellular processes such as microtubule formation, thereby impairing normal development. This growth-regulating effect is especially significant in immature stages, where proper hormonal regulation is essential for successful development (Mordue & Nisbet, 2021; Koul, 2021) ^[18, 32]. Azadirachtin primarily affects the endocrine and neurosecretory systems that regulate insect growth and development. Insects depend on a balanced interaction between ecdysone and juvenile hormone to control molting, metamorphosis, and transformation from larval to adult stages. Neem compounds disturb this hormonal coordination, causing irregular or unsuccessful molting processes. Larvae exposed to Neem often remain trapped within old exoskeletons, fail to shed their cuticle properly, or undergo incomplete metamorphosis (Shukla *et al.*, 2025) ^[41]. Such abnormalities ultimately weaken the insect and increase mortality during developmental stages. The growth-regulating activity of Neem also causes prolonged larval duration and delayed pupation. Since insects are unable to complete development normally, their feeding period may be disrupted, resulting in reduced nutrient accumulation and lower survival rates. Pupae formed after Neem exposure are frequently malformed, undersized, or unable to emerge into healthy adults. Adult insects that survive often exhibit reduced reproductive capacity, impaired mobility, and shortened lifespan, further contributing to population suppression. At the cellular level, azadirachtin interferes with mitosis and protein synthesis by affecting microtubule organization and cellular division. These disruptions impair tissue formation and organ development, leading to deformities in wings, appendages, and reproductive structures. Such physiological disturbances significantly reduce insect fitness and survival. Neem compounds may also affect the nervous system and metabolic pathways associated with growth regulation, further intensifying developmental abnormalities (Netam *et al.*, 2025) ^[33]. Another important advantage of Neem-based growth regulation is its comparatively low toxicity to non-target organisms and beneficial insects. Since Neem primarily disrupts hormonal systems specific to insects, it is considered environmentally safer than many broad-spectrum synthetic insecticides. Furthermore, its multi-target mode of action reduces the likelihood of resistance development. Therefore, the growth-regulating properties of Neem-based biopesticides play a crucial role in sustainable pest management by interrupting insect development, reducing survival, and limiting pest population growth (Mordue & Nisbet, 2021; Koul, 2021) ^[18].

Reproductive inhibition

Neem-derived compounds exert significant effects on insect reproduction, contributing to long-term suppression of pest populations. Azadirachtin interferes with ovarian

development and hormonal regulation associated with reproduction, leading to reduced fecundity and impaired egg production. Insects exposed to Neem often exhibit decreased oviposition rates, reduced egg viability, and lower hatchability. In some cases, reproductive behavior itself is altered, limiting successful mating. These effects persist even when insects survive initial exposure, resulting in a gradual decline in population levels over successive generations. Such reproductive inhibition is particularly valuable in sustainable pest management, as it targets the population growth potential rather than only immediate mortality (Rani *et al.*, 2022) ^[36]. The reproductive inhibitory effects of Neem are mainly associated with disruption of the endocrine system in insects. Azadirachtin affects the synthesis and activity of important hormones such as juvenile hormone and ecdysone, which regulate reproduction, growth, and development. Disturbance in these hormonal pathways leads to abnormal ovarian maturation and reduced sperm production, ultimately decreasing reproductive efficiency in both female and male insects (Bhardwaj *et al.*, 2023) ^[7]. Female insects treated with Neem compounds frequently produce fewer eggs, and the eggs laid are often weak, malformed, or incapable of successful embryonic development. Consequently, egg hatchability and larval survival rates decline significantly. Neem compounds also influence insect mating behavior and physiological fitness. Exposure to Neem may reduce feeding activity and nutrient assimilation, limiting the energy available for reproductive processes. In some insect species, altered pheromone communication and mating responses have been observed, reducing successful copulation and further suppressing population growth. These sublethal effects are especially important because insects may survive exposure but fail to reproduce effectively, leading to long-term reduction in pest abundance. Another important advantage of Neem-based reproductive inhibition is the lower risk of resistance development. Since Neem compounds act through multiple biochemical and physiological pathways rather than a single target site, pests are less likely to develop resistance rapidly. This multi-target mode of action enhances the sustainability of Neem-based pest control strategies compared with conventional synthetic pesticides. Furthermore, the reproductive suppression caused by Neem is effective against a broad range of agricultural and storage pests, making it suitable for use in Integrated Pest Management (IPM) programs. Thus, Neem-derived biopesticides provide an environmentally safe and sustainable approach for controlling pest populations through long-term reproductive suppression rather than immediate toxic effects alone (Bargah *et al.*, 2025) ^[1, 3].

Repellent and behavioral effects

Neem also acts as a repellent and behavioral modifier, influencing how insects interact with their host plants. Volatile compounds present in Neem formulations interfere with the sensory cues used by insects for host location, feeding, and oviposition. Consequently, treated plants become less attractive, and insects tend to avoid them. This behavioral modification reduces infestation levels without exerting intense selection pressure, which is often associated with resistance development in conventional pesticides. Unlike fast-acting chemical insecticides, Neem works gradually by altering insect behavior, thereby providing a

more sustainable and ecologically balanced pest control strategy (Isman & Grieneisen, 2020) ^[14, 15]. The repellent activity of Neem is mainly attributed to bioactive compounds such as azadirachtin, salannin, nimbin, and various volatile oils present in Neem seeds and leaves. These compounds disrupt the chemoreception system of insects, preventing them from recognizing suitable host plants. Insects rely heavily on olfactory and gustatory signals for locating food sources and selecting sites for egg laying. Neem compounds interfere with these sensory mechanisms, causing confusion and avoidance behavior (Chandra *et al.*, 2024) ^[10]. Neem-based repellency is effective against a wide range of agricultural and household pests including aphids, whiteflies, beetles, mosquitoes, caterpillars, and storage insects. In many cases, Neem not only deters feeding but also inhibits oviposition by making plant surfaces unsuitable for egg deposition. Female insects exposed to Neem-treated crops frequently lay fewer eggs or avoid treated surfaces entirely, thereby reducing the establishment of future pest generations. Such effects are particularly valuable in sustainable agriculture because they suppress pest populations without causing immediate mortality to beneficial organisms. Behavioral modification induced by Neem also affects insect movement, orientation, and feeding patterns. Insects exposed to Neem compounds may exhibit reduced mobility, disrupted aggregation behavior, and altered responses to environmental stimuli (Tiwari *et al.*, 2024) ^[48]. Feeding deterrence caused by Neem further weakens insect fitness and survival by reducing nutrient intake. Since these effects occur gradually, Neem-based products impose lower selection pressure on pest populations compared to conventional synthetic insecticides, thereby minimizing the risk of resistance development. Another important advantage of Neem's repellent and behavioral effects is its compatibility with Integrated Pest Management (IPM) systems. Neem can be combined with biological control agents and cultural practices without significantly harming beneficial insects, pollinators, or natural predators. Its biodegradable nature and low environmental persistence further support ecological safety. Therefore, the repellent and behavioral modifying properties of Neem contribute significantly to environmentally sustainable pest management by reducing pest infestation, protecting crop productivity, and maintaining ecological balance (Isman & Grieneisen, 2020) ^[14, 15].

Enzyme and Metabolic Disruption

At the biochemical level, Neem compounds disrupt key metabolic processes within insects. Azadirachtin affects the activity of digestive enzymes such as proteases, amylases, and lipases, resulting in inefficient digestion and poor nutrient assimilation. It also interferes with protein synthesis and cellular metabolism, leading to reduced energy production and slower growth rates. Prolonged exposure causes physiological stress, weakening the insect and increasing its susceptibility to environmental factors. This metabolic disruption contributes significantly to reduced survival and overall fitness of insect populations (Senthil-Nathan, 2020) ^[38]. Neem-derived compounds obtained from *Azadirachta indica* interfere with several essential biochemical pathways responsible for maintaining normal physiological functions in insects. Digestive enzymes play a critical role in breaking down carbohydrates, proteins, and

lipids into absorbable nutrients required for growth, development, and reproduction. When insects consume Neem-treated plant material, the activity of these enzymes declines significantly, reducing the efficiency of food digestion. Consequently, insects experience nutritional deficiency, reduced body weight, and impaired development even when food is available in sufficient quantity. Azadirachtin also disrupts protein synthesis by affecting ribosomal activity and enzyme production within insect tissues. This impairment limits the formation of structural proteins and metabolic enzymes necessary for cellular growth and repair. In addition, Neem compounds influence mitochondrial activity and energy metabolism, reducing ATP production and causing metabolic imbalance. As energy availability decreases, insects become less active, feed less efficiently, and exhibit slower growth rates. Larvae exposed to Neem frequently remain undersized, weak, or unable to complete normal development. The metabolic stress induced by Neem compounds further affects detoxification mechanisms and immune responses in insects. Prolonged exposure weakens physiological resistance, making insects more vulnerable to pathogens, predators, and unfavorable environmental conditions. In many cases, insects exposed to sublethal doses of Neem survive temporarily but suffer severe reductions in fitness, reproductive capacity, and lifespan. Such chronic physiological stress contributes to gradual population decline over successive generations. Another important feature of Neem-induced metabolic disruption is its multi-target mode of action. Unlike synthetic pesticides that often act on a single biochemical site, Neem compounds simultaneously affect digestion, respiration, enzyme activity, hormonal balance, and nutrient utilization (Singh *et al.*, 2022) ^[42]. This broad-spectrum interference reduces the likelihood of resistance development and enhances long-term pest control efficiency. Furthermore, metabolic disruption caused by Neem is generally selective toward target pests and exhibits relatively low toxicity to beneficial organisms and non-target species. Therefore, Neem-based biopesticides provide an environmentally safe and sustainable approach for pest management by weakening insect physiology, reducing survival, and impairing overall population fitness (Senthil-Nathan, 2020) ^[38].

Applications of neem-based biopesticides

Neem-based biopesticides derived from *Azadirachta indica* have gained widespread acceptance due to their versatility and effectiveness across different domains of pest management. Their broad-spectrum activity, coupled with environmental safety, allows their application not only in crop protection but also in storage systems and public health. Bioactive compounds such as azadirachtin, nimbin, and salannin exhibit insecticidal, antifeedant, repellent, growth regulatory, and reproductive inhibitory properties against a wide range of insect pests. Unlike conventional synthetic pesticides, Neem products are biodegradable, less toxic to non-target organisms, and compatible with Integrated Pest Management (IPM) programs, making them highly suitable for sustainable agriculture and ecological conservation (Mohale *et al.*, 2025). In agriculture, Neem-based formulations are extensively used for controlling chewing, sucking, and boring insect pests affecting cereals, pulses, vegetables, fruits, oilseeds, and plantation crops. Neem extracts, Neem oil, and Neem seed kernel

formulations effectively manage pests such as aphids, whiteflies, caterpillars, beetles, leafhoppers, and stem borers while minimizing harmful environmental impacts (Daroo *et al.*, 2022). Their compatibility with biological control agents further enhances their usefulness in integrated pest management systems. Neem biopesticides are also widely utilized in storage pest management for protecting stored grains, seeds, and food products against insects such as weevils, beetles, and moths. Neem products act as repellents and feeding deterrents, reducing grain damage and maintaining seed quality during storage. Since Neem residues are biodegradable and relatively safe, they provide a safer alternative to synthetic fumigants and storage chemicals (Tekam *et al.*, 2025) ^[47]. In public health and vector management, Neem formulations have shown effectiveness against mosquitoes and other disease vectors. Neem oil and extracts exhibit larvicidal, repellent, and growth-disrupting effects against mosquito species responsible for diseases such as malaria, dengue, and filariasis (Verma *et al.*, 2025) ^[50]. Their lower toxicity to humans and animals makes them suitable for environmentally safer vector control programs. Apart from insect control, Neem-based products are also used in organic farming, horticulture, forestry, and nursery management to promote sustainable plant protection. Continuous research and advancements in formulation technologies, particularly Nano-formulations and improved extraction methods, are further expanding the scope and efficiency of Neem-based

biopesticides (Vaishnav *et al.*, 2025) ^[49]. Therefore, Neem products represent an important component of environmentally sustainable pest management strategies across agricultural, storage, and public health sectors (Table3).

Agricultural pest control

Neem formulations such as Neem oil, Neem seed kernel extract (NSKE) and commercially standardized azadirachtin-based products are widely used in agricultural systems for controlling a variety of insect pests. These include sap-sucking pests like aphids and whiteflies, as well as chewing insects such as caterpillars and beetles (Shukla *et al.*, 2025) ^[41]. The effectiveness of Neem lies in its ability to disrupt feeding, growth and reproduction simultaneously, which reduces pest pressure over time rather than causing immediate knockdown. Field level studies have demonstrated that Neem-based treatments can achieve a significant reduction in pest populations, often ranging between 60 and 80 percent under different cropping conditions (Mandwa *et al.*, 2024). In crops such as cotton, rice, vegetables and pulses, Neem formulations have been successfully integrated as an alternative to synthetic pesticides, particularly in organic and low-input farming systems (Sharma *et al.*, 2022; Isman, 2020) ^[14, 15, 39]. In addition to pest suppression, Neem also contributes to reduced pesticide residues in harvested produce, thereby improving food safety (Table: 4)

Table 4: Agricultural Pest Control Using Neem-Based Biopesticides

Aspect	Description	Details / Examples	Citation
Neem Formulations	Various Neem-based products used in agriculture.	Neem oil, Neem seed kernel extract (NSKE), azadirachtin-based formulations.	Murray B. Isman (2020) ^[14, 15]
Target Pests	Effective against a wide range of insect pests.	Aphids, whiteflies (sap-sucking); caterpillars, beetles (chewing insects).	Sharma <i>et al.</i> (2022); Murray B. Isman (2020) ^[39]
Mode of Action	Multi-target impact on insect physiology and behavior.	Disrupts feeding, growth, and reproduction simultaneously.	Murray B. Isman (2020) ^[14, 15]
Pest Reduction Efficiency	Demonstrated effectiveness under field conditions.	Reduces pest populations by 60–80% in various crops.	Sharma <i>et al.</i> (2022) ^[39]
Crop Applications	Widely applied across different cropping systems.	Cotton, rice, vegetables, pulses.	Sharma <i>et al.</i> (2022) ^[39]
Role in Sustainable Farming	Suitable for eco-friendly and organic agriculture.	Used as an alternative to synthetic pesticides in low-input systems.	Murray B. Isman (2020) ^[14, 15]
Food Safety Benefits	Reduces harmful chemical residues in produce.	Enhances safety and quality of harvested crops.	Sharma <i>et al.</i> (2022) ^[39]

Integrated pest management (ipm)

One of the most important advantages of Neem-based biopesticides derived from *Azadirachta indica* is their compatibility with Integrated Pest Management (IPM) strategies (Singh *et al.*, 2024) ^[44]. Unlike many conventional synthetic pesticides, Neem products exhibit selective toxicity, meaning they are relatively safe for beneficial organisms such as predators, parasitoids, pollinators, and other natural enemies of crop pests. This selective nature enables Neem formulations to be used alongside biological control agents without significantly disturbing ecological balance or reducing beneficial insect populations (Singh *et al.*, 2025) ^[43]. Consequently, Neem-based products are increasingly recognized as valuable components of sustainable pest management systems. Neem compounds primarily act through behavioral and physiological disruption rather than immediate acute toxicity. Bioactive constituents such as azadirachtin interfere with feeding behavior, growth regulation, molting, reproduction, and

metabolic activities of insects. Because of this gradual mode of action, Neem products impose comparatively lower risks to non-target organisms than broad-spectrum chemical insecticides. Beneficial insects that contribute to natural pest suppression are therefore less affected, allowing ecological interactions within agroecosystems to remain stable and functional (Soni *et al.*, 2025) ^[46]. This conservation of natural enemies enhances the long-term effectiveness of pest management programs by supporting biological control processes naturally present in the environment. Another major advantage of Neem in IPM systems is its compatibility with multiple pest control approaches. Neem-based formulations can be integrated successfully with biological control agents such as predatory beetles, parasitoid wasps, entomopathogenic fungi, bacteria, and nematodes. In addition, Neem products complement cultural practices including crop rotation, sanitation, trap cropping, resistant crop varieties, and habitat management. Such integration reduces dependence on synthetic pesticides

while maintaining effective pest suppression below economic threshold levels. Neem products are also biodegradable and exhibit minimal environmental persistence, reducing the accumulation of toxic residues in soil, water, and agricultural produce. Their relatively low mammalian toxicity further enhances their suitability for environmentally safe crop protection. Since Neem compounds act through multiple physiological and biochemical pathways, the likelihood of rapid resistance development in pest populations is considerably reduced compared with single-target synthetic pesticides. This characteristic strengthens the sustainability and long-term reliability of IPM programs. Several studies have confirmed that Neem-based formulations can be effectively combined with biological, cultural, and mechanical control methods to improve pest management efficiency while minimizing environmental risks (Isman & Grieneisen, 2020; Kilani-Morakchi *et al.*, 2021) [14, 15, 17]. Therefore, Neem-based biopesticides represent an important tool in modern IPM systems by promoting ecological balance, conserving beneficial organisms, and supporting sustainable agricultural production.

Conclusion

Neem-based biopesticides derived from *Azadirachta indica* provide an eco-friendly and sustainable alternative to synthetic pesticides. Bioactive compounds such as azadirachtin, nimbin, and salannin exhibit multiple mechanisms of action including antifeedant activity, growth disruption, reproductive inhibition, and metabolic interference, which enhance pest control and reduce resistance development. Neem products are biodegradable, less toxic to non-target organisms, and highly compatible with Integrated Pest Management (IPM) systems, making them important for sustainable agriculture and ecological balance. However, limitations such as environmental instability, inconsistent field performance, and repeated application requirements still restrict their wider adoption. Recent advancements in nano-formulations and improved extraction technologies are improving their stability and effectiveness. Continued research and farmer awareness can further strengthen the role of Neem biopesticides in sustainable pest management.

References

1. Bargah AS, Sharma D, Kumar R, Nag R, Pradhan R. Enhancing germination of forest tree seeds in Chhattisgarh through PGR-based treatments: A review. *J Adv Biol Biotechnol.* 2025; 28(7):851–863.
2. Bargah AS, Toppo P, Singh L, Tuteja SS, Mankur MK, Painkra DS, *et al.* Effect of nutrient management on growth performance of geranium (*Pelargonium graveolens*) under karanj (*Pongamia pinnata*) based agroforestry system in Chhattisgarh plain. *Int J Res Agron.* 2024; 7(1S):25–29. <https://doi.org/10.33545/2618060X.2024.v7.i1Sa.220>
3. Bargah AS, Vishwakarma SP, Yadav S, Verma S, Netam P, Tondan M, *et al.* A comprehensive review on lac cultivation: Biology, management and future prospects. *Int J Adv Biochem Res.* 2025; 9(12S):1204–1212. <https://doi.org/10.33545/26174693.2025.v9.i12So.6690>
4. Bargah AS, Kumar R, Khandekar H, Vaishnav AK. A status of different non-wood forest products in Chhattisgarh, India. *Int J Plant Soil Sci.* 2024; 36(11):23–40.
5. Benelli G, Pavea R, Canale A, Mehlhorn H. Botanical insecticides in mosquito control: Role and applications. *Environ Sci Pollut Res Int.* 2020; 27:32764–32780. <https://doi.org/10.1007/s11356-020-08795-y>
6. Bhardwaj AK, Chandra KK, Kumar R. Inoculants of arbuscular mycorrhizal fungi influence growth and biomass of *Terminalia Arjuna* under amendment and unamended Entisol. *Mycobiology.* 2024; 52(3):183–190.
7. Bhardwaj AK, Chandra KK, Kumar R. Mycorrhizal inoculation under water stress conditions and its influence on host–microbe symbiosis of *Terminalia arjuna* species. *Bull Natl Res Cent.* 2023; 47:89. <https://doi.org/10.1186/s42269-023-01089-7>
8. Campos EVR, Proença PLF, Oliveira JL, Pereira AES, Ribeiro LNM, Fernandes FO, *et al.* Neem oil and crop protection: From now to the future. *Front Plant Sci.* 2020; 11:610. <https://doi.org/10.3389/fpls.2020.00610>
9. Chandra KK, Kumar R, Baretha G. Vandalism: A review for potential solutions. In: *Tree Benefits in Urban Environment and Incidences of Tree.* Hoboken (NJ): Wiley; 2021.
10. Chandra KK, Kumar R, Dixit B, Nayak PP, Bhardwaj AK, Pandey SK. Analyzing the contribution of *Moringa oleifera* to CO₂ stock and other advantages for urban residents. *Int J Plant Soil Sci.* 2024; 36(10):305–317.
11. Darro H, Swamy SL, Kumar R, Bhardwaj AK. Comparison of physico-chemical properties of soils under different forest types in dry tropical forest ecosystem in Achanakmar-Amarkantak Biosphere Reserve, India. *Eco Environ Conserv.* 2022; 28:S163–S169.
12. Dhakad AK, Pandey VV, Beg S, Rawat JM, Singh A. Biological, medicinal and agricultural applications of Neem (*Azadirachta indica*): A review. *J Pharmacogn Phytochem.* 2018; 7(1):2457–2465.
13. Isman MB. Botanical insecticides, deterrents, and repellents in modern agriculture: An increasingly regulated world. *Annu Rev Entomol.* 2006; 51:45–66.
14. Isman MB. Botanical insecticides in the twenty-first century—fulfilling their promise. *Annu Rev Entomol.* 2020; 65:233–249. <https://doi.org/10.1146/annurev-ento-011019-025010>
15. Isman MB, Grieneisen ML. Botanical insecticide research: Many publications, limited useful data. *Pest Manag Sci.* 2020; 76(2):561–567. <https://doi.org/10.1002/ps.5646>
16. Khandekar H, Kumar R, Vaishnav AK, Bargah AS. Non-timber forest products-based initiatives for sustainable rural livelihood in Chhattisgarh, India. *J Non-Timber for Prod.* 2024; 31(3):242–249.
17. Kilani-Morakchi S, Aribi N, Soltani N. Azadirachtin-based insecticides: Overview, risk assessment and future directions. *Front Agron.* 2021; 3:676208. <https://doi.org/10.3389/fagro.2021.676208>
18. Koul O. Multifunctional insecticidal properties of Neem and its derivatives. *J Biopestic.* 2021; 14(2):89–102.
19. Koul O, Walia S, Dhaliwal GS. Essential oils as green pesticides: Potential and constraints. *Biopestic Int.* 2008; 4(1):63–84.
20. Kumar R, Bhardwaj AK, Chandra KK, Dixit B, Singh AK. Diverse role of mycorrhiza in plant growth and

- development: A review. *Solovyov Stud ISPU*. 2024; 72(2):37–61.
21. Kumar R, Bhardwaj AK, Chandra KK, Shukla AK, Singh AK. Twenty-first years of global research on fly ash: A review. *Indian Forester*. 2025; 151(9):840–846.
 22. Kumar R, Bhardwaj AK, Chandra KK. Mycorrhizae: An historical journey of plant association. *Chhattisgarh J Sci Technol*. 2022; 19(4):437–447.
 23. Kumar R, Bhardwaj AK, Chandra KK. A review on agroforestry practices for improving socioeconomic and environmental status. *Indian Forester*. 2022; 148(5):474–478.
 24. Kumar R, Bhardwaj AK, Chandra KK. Effects of arbuscular mycorrhizal fungi on germination of *Terminalia Arjuna* under nursery conditions. *Forestist*. 2023; 74:142–146.
 25. Kumar R, Darro H, Bhardwaj AK, Chandra KK. Forest fire and its influence on environmental conditions: A review. *Bull Environ Pharmacol Life Sci*. 2022; 10(12):258–267.
 26. Kumar R, Ramchandra, Bhardwaj AK, Chandra KK. Impacts of nitrogen levels on leaf length of onion under poplar-based agroforestry system. *Indian Forester*. 2022; 148(12):1241–1244.
 27. Mandwa AK, Bhardwaj AK, Kumar R, Chandra KK, Kumari C, Pandey SK. Impact of urban xenobiotics on mycorrhizal associations in urban plants. *Nat Environ Pollut Technol*. 2024; 23(4):1–15.
 28. Minj N, Toppo P, Tuteja SS, Singh L, Mankur MK, Bargah AS, Verma S. Effect of different potting media on seed germination and growth of *Cordia macleodii* in nursery. (Incomplete details).
 29. Mordue AJ, Blackwell A. Azadirachtin: An update. *J Insect Physiol*. 1993; 39(11):903–924.
 30. Mordue AJ, Nisbet AJ. Azadirachtin from the Neem tree *Azadirachta indica*: Its action against insects. *An Soc Entomol Bras*. 2000; 29(4):615–632.
 31. Mordue AJ, Nisbet AJ. Azadirachtin from the Neem tree: Its action against insects. *Annu Rev Entomol*. 2000; 45:321–340.
 32. Mordue AJ, Nisbet AJ. Azadirachtin from the Neem tree: Its action against insects. *J Insect Physiol*. 2021; 133:104275.
<https://doi.org/10.1016/j.jinsphys.2021.104275>
 33. Netam G, Kumar R, Singh B, Sahu C, Soni P, *et al*. Minor forest produce livelihoods and gendered challenges in Keshkal Forest Division, Chhattisgarh: A review. *Adv Res*. 2025; 26(4):522–532.
 34. Nishad HK, Sharma D, Bargah AS, Rajwade AK. Influence of pre-sowed biochemical, chemical and organic treatments on germination and growth of *Tamarindus indica* L. *Plant Cell Biotechnol Mol Biol*. 2025; 26(9–10):24–36.
<https://doi.org/10.56557/pcbmb/2025/v26i9-109629>
 35. Pavela R. Essential oils and botanical insecticides: Current trends and future perspectives. *Ind Crops Prod*. 2021; 164:113390.
<https://doi.org/10.1016/j.indcrop.2021.113390>
 36. Rani PU, Madhumitha G, Rajasekaran C. Toxicological and physiological effects of Neem-based compounds on insects. *Environ Toxicol*. 2022; 37(2):345–356.
<https://doi.org/10.1002/tox.23345>
 37. Schmutterer H. Properties and potential of natural pesticides from the Neem tree. *Annu Rev Entomol*. 1990; 35:271–297.
 38. Senthil-Nathan S. Physiological and biochemical effects of botanical insecticides on insect pests. *Ecotoxicol Environ Saf*. 2020; 187:109805.
<https://doi.org/10.1016/j.ecoenv.2019.109805>
 39. Sharma P, Mohan L, Srivastava CN. Phytopesticides: A sustainable approach for pest control. *Crop Prot*. 2022; 157:105995.
<https://doi.org/10.1016/j.cropro.2022.105995>
 40. Shukla AK, Chandra KK, Kumar R, Bhardwaj AK. Riverine agroforestry systems: Tree diversity and species structure along Lilagar River catchment, Chhattisgarh, India. *Green Technol Sustain*. 2025; 3(3):100211
 41. Shukla AK, Chandra KK, Kumar R, Bhardwaj AK. Riverine agroforestry for high carbon sequestration and ecosystem rejuvenation: Lilagar River case. *Sustain Environ*. 2025; 11(1):2522504
 42. Singh AK, Chandra KK, Kumar R, Bhardwaj AK. Phytochemical analysis and medicinal properties of *Soymida febrifuga*: A review. *Adv Bioresearch*. 2022; 13(6):37–43.
 43. Singh B, Kumar R, Bargah AS, *et al*. Seasonal dynamics and utilization of non-timber forest products in Chhattisgarh, India: A review. *J Biol Nat*. 2025; 17(2):449–459.
 44. Singh S, Dixit B, Prajapati L, Chandrakar S, Tamrakar A. Species structure and regeneration patterns in tropical Sal forest. *Environ Conserv J*. 2024; 25(3):824–835.
 45. Singh B, Sharma DK, Kumar R, Gupta A. Advances in botanical pesticides for sustainable agriculture. *Agronomy*. 2023; 13(6):1456.
<https://doi.org/10.3390/agronomy13061456>
 46. Soni P, Kumar R, Singh B, *et al*. Certification pathways for non-wood forest products: Opportunities and challenges. *J Sci Res Rep*. 2025; 31(7):103–111.
 47. Tekam KK, Kumar R, Bargah AS, *et al*. Linking forests to livelihoods: Tendu leaves and tribal income in Chhattisgarh, India. *Arch Curr Res Int*. 2025; 25(8):112–122.
 48. Tiwari RKS, Chandra KK, Kumar R, Bhardwaj AK, Pandey SK, Dixit B. Microbial biopesticides: An ecofriendly plant protection measure. *Environ Ecol*. 2024; 42(4):1590–1598.
 49. Vaishnav AK, Kumar R, Khandekar H, Bargah AS. Sericulture: A dynamic contribution to Indian agriculture. *Int J Agric Sci*. 2025; 17(1):13317–13321.
 50. Verma S, Kumar R, Singh B, *et al*. Wood waste utilization in forest industry: Innovations for sustainable management. *Arch Curr Res Int*. 2025; 25(7):889–898.
 51. Wylie MR, Merrell DS, Camacho FT. Antimicrobial and pesticidal potential of Neem (*Azadirachta indica*). *Plants*. 2022; 11(11):1432.
<https://doi.org/10.3390/plants11111432>
 52. Yadav D, Kumar S, Singh B. Role of Neem in sustainable agriculture and soil health. *Sustainability*. 2023; 15(10):7890. <https://doi.org/10.3390/su15107890>