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Integrated Pest Management of Major Pests of *Moringa oleifera* under Climate Change: Sustainable Agriculture Pathways, Biodiversity Conservation and Future Prospects

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Abstract

Moringa oleifera Lam., commonly known as the drumstick tree, is a fast-growing multipurpose crop valued for its nutritional, medicinal, and economic importance in tropical and subtropical regions. Despite its resilience, moringa productivity is severely constrained by several destructive insect pests, including leaf caterpillar (Noorda blitealis), hairy caterpillar (Eupterote mollifera), bud worm (Noorda moringae), pod fly (Gitona distigma), bark caterpillar (Indarbela tetraonis), and long-horn beetle (Batocera rubus). Climate change further intensifies pest incidence by altering pest biology, population dynamics, voltinism, and geographic distribution, leading to frequent outbreaks and reduced effectiveness of conventional control measures. This review synthesizes current knowledge on pest bio-ecology, damage symptoms, and climate–pest interactions, emphasizing integrated pest management (IPM) as a sustainable and climate-resilient strategy. Ecological approaches integrating cultural, mechanical, biological, botanical, and need-based chemical methods are highlighted for minimizing pesticide dependence while conserving biodiversity and ecosystem services. The review underscores future prospects such as climate-smart IPM, habitat manipulation, natural enemy conservation, and farmer-centric strategies to ensure long-term sustainability and resilience of moringa cultivation under changing climatic conditions.

Keywords: *Moringa oleifera, Integrated Pest Management, Climate Change, Sustainable Agriculture, Biological Control, Major Insect Pests, Biodiversity Conservation.*

Introduction-

Moringa oleifera Lam., commonly known as the drumstick or miracle tree, is a fast-growing multipurpose crop widely cultivated in tropical and subtropical regions. It is valued for its high nutritional, medicinal, and economic importance, as its leaves, pods, seeds, and flowers are rich in proteins, vitamins, minerals, and bioactive compounds. Due to its drought tolerance, rapid growth, and adaptability to diverse agro-climatic conditions, moringa is increasingly promoted as a climate-smart crop contributing to food security and rural livelihoods.

Moringa oleifera Lam. adapts well to tropical and subtropical climates, tolerates drought and diverse soil conditions, and produces nutritious leaves, pods, and oil-rich seeds. Because of its high nutritional, medicinal, and industrial value—including uses in traditional medicine, biopesticides, and bioenergy—*M. oleifera* is widely recognized as a "miracle tree" with strong potential for sustainable agriculture and future research (Kumar and Jakhar, 2020). Moringaceae comprises trees or shrubs with compound alternate leaves and zygomorphic flowers arranged in panicles. Fruits are fibrous capsules bearing oil-rich seeds. The bark contains prominent phloem bundles and gum ducts that exude pale-colored gum when injured, while the wood is light and largely parenchymatous. The family is closely related to Caricaceae and occurs mainly in tropical and subtropical regions (Olson, 2010). *Moringa oleifera* Lam. is widely cultivated across tropical and subtropical regions, including Asia, Africa, and the Americas, mainly for its nutritional and medicinal value. Its leaves, pods, seeds, roots, and flowers are used in traditional medicine and human diets. Leaf extracts exhibit strong antioxidant properties, while powdered leaf preparations have shown anti-dyslipidemic and antidiabetic effects, with no reported adverse effects in humans to date (Bashir *et al.*, 2016). The wide range of uses of *Moringa oleifera*—including medicinal, antimicrobial, nutritional, and environmental applications—makes it an important multipurpose crop. Its expanding cultivation across diverse climatic regions increases exposure to varied insect pests and diseases (Mridha and Barakah, 2017). Despite its resilience, moringa productivity is significantly constrained by insect pests that attack the crop at different growth stages. Major pests include the leaf caterpillar (*Noorda blitealis*), hairy caterpillar (*Eupterote mollifera*), bud worm (*Noorda moringae*), pod fly (*Gitona distigma*), bark caterpillar (*Indarbela tetraonis*), and long-horn beetle

(*Batocera rubus*), causing defoliation, bud and pod damage, and stem weakening.

Climate change, characterized by rising temperatures and erratic rainfall, alters pest biology, population dynamics, and outbreak frequency, often intensifying crop losses. Conventional pesticide-based control is increasingly unsustainable due to resistance development and ecological risks. Therefore, integrated pest management (IPM), combining cultural, biological, mechanical, and need-based chemical approaches, offers a sustainable and climate-resilient strategy for protecting moringa while conserving biodiversity and ensuring long-term productivity.

Objectives-

The primary objectives of this review are:

1. To describe major insect pests of *Moringa oleifera* under changing climatic conditions.
2. To assess climate change effects on pest incidence and dynamics in moringa.
3. To evaluate IPM strategies for sustainable pest control in moringa cultivation.
4. To examine the role of biodiversity and natural enemies in moringa IPM systems.
5. To identify future needs for climate-resilient and eco-friendly pest management in moringa.

Data and Methodology-

This review is based exclusively on secondary data obtained from peer-reviewed research articles, review papers, books, technical reports, extension bulletins, and institutional publications related to *Moringa oleifera*, insect pest management, and climate change. A systematic literature search was carried out using scientific databases and platforms such as Google Scholar, ScienceDirect, Scopus, PubMed, AGRIS, CAB Abstracts, and agricultural institutional repositories.

Relevant studies published between 1980 and 2025 were identified using targeted keywords related to moringa insect pests, integrated pest management, climate change impacts, and the six major pests (*Noorda blitealis*, *Eupterote mollifera*, *Noorda moringae*, *Gitona distigma*, *Indarbela tetraonis*, and *Batocera rubus*). The selected literature was screened to extract information on pest biology, damage symptoms, seasonal and geographical distribution, climate–pest interactions, and IPM strategies, including field-validated AESA-based recommendations.

The extracted information was critically evaluated and qualitatively synthesized using a narrative and thematic approach to develop an integrated overview of climate-resilient, biodiversity-based IPM practices for sustainable moringa cultivation. No primary experimental data or quantitative meta-analysis was undertaken in this review.

Climate Change: Sustainable Agriculture, Biodiversity Conservation and IPM -

Climate change is significantly altering agricultural ecosystems by increasing temperature variability, irregular rainfall, and extreme weather events, which enhance insect pest pressure and reduce crop resilience. These changes threaten sustainable agricultural production and disturb ecological balance.

Sustainable agriculture focuses on maintaining productivity while conserving natural resources and minimizing environmental degradation. Biodiversity conservation plays a key role in this approach by supporting natural enemies, pollinators, and ecosystem services that regulate pest populations naturally.

Global climate change alters temperature and rainfall patterns, significantly influencing agro-ecosystems. Insects respond through changes in physiology, distribution, and population dynamics, often resulting in higher pest abundance, frequent outbreaks, multiple generations, and the emergence of resistant biotypes. Climate stress also reduces the effectiveness of natural enemies, increasing risks to crop productivity and food security (Yadav *et al.*, 2019). Integrated Pest Management (IPM) is an eco-friendly and science-based approach that integrates cultural, biological, mechanical, and need-based chemical methods for pest control. By emphasizing prevention, pest monitoring, and economic threshold-based decisions, IPM reduces pesticide use, supports biodiversity, and maintains crop productivity. Advances in biopesticides, digital tools, and precision agriculture have enhanced IPM effectiveness, though wider adoption requires improved farmer awareness, extension support, and policy incentives (Ahirwar and Ahirwar, 2025). Rapid population growth in India is increasing pressure on food security amid limited land and degrading natural resources. Sustainable productivity gains are therefore essential without harming the environment or human health. Integrated Pest Management (IPM), supported by bioengineering, information, and environmental technologies, offers an effective pathway for sustainable agricultural production (Mohamed, 2023). Integrated Pest Management (IPM) promotes sustainable agriculture by reducing chemical pesticide dependence while enhancing crop productivity and ecosystem health. Recent advances highlight the growing role of biological and genetic control, conservation of natural enemies, novel biopesticides, and targeted pesticide delivery systems that improve pest control efficiency with minimal environmental impact (Zhou *et al.*, 2024).

Integrated Pest Management (IPM) is a sustainable approach that combines biological, cultural, and need-based chemical methods for long-term pest control. It relies on pest monitoring and uses pesticides only when economically necessary, reducing risks to human health and the environment (Singh and Sharma, 2004). The excessive use of pesticides has raised serious concerns about environmental safety and human health. Integrated Pest Management (IPM) provides an eco-friendly and sustainable alternative by combining biological control, cultural practices, habitat management, and resistant varieties. It reduces dependence on chemical pesticides, minimizes environmental damage, and improves crop yield and sustainability in agro-ecosystems (Shivam *et al.*, 2024). Biodiversity refers to the complete variety of life, including genetic, species, and ecosystem diversity. It supports climate regulation and enhances ecosystem resilience, helping ecosystems continue providing essential services under climate stress. However, recent climate change driven by human activities has negatively impacted biological resources (Prakash and Shrivastava, 2019). Biodiversity includes the variety of plants, animals, microorganisms, their genes, and ecosystems, encompassing genetic, species, and ecosystem diversity. It supports environmental balance by regulating climate, biogeochemical cycles, pollution control, and providing economic and aesthetic benefits. However, human activities, pollution, faulty policies, and climate change pose serious threats to biodiversity, making its conservation essential for present and future generations through measures like protected areas, botanical gardens, and seed banks (Singhariya, 2023). Healthy ecosystems and biodiversity are essential for life, but climate change is rapidly altering habitats. Rising temperatures and changing rainfall patterns force species to adapt or migrate, often leading to biodiversity loss. Human-induced global warming from greenhouse gas emissions is accelerating these changes, posing serious threats to ecosystems worldwide (Dey, 2020). Climate change, driven mainly by human activities, has intensified in recent decades and poses serious threats to biodiversity. Many species have become extinct or are at risk due to habitat loss and forced migration into unsuitable areas. Climate change refers to long-term shifts in average weather conditions such as temperature and rainfall, leading to widespread impacts on plants, animals, and human life (Ara and Devi, 2021). Climate change affects agriculture and ecosystems, while well-managed ecosystems help reduce its impacts. Therefore, sustainable agriculture plays an important role in biodiversity conservation and climate change mitigation (Harnowo *et al.*, 2021). Moringa is a fast-growing, drought-tolerant plant of Asian origin, widely cultivated worldwide for its nutritional, medicinal, environmental, and industrial value (Outani *et al.*, 2023). Despite major gains in agricultural production, food security remains threatened by pests and post-harvest losses. Crop pests significantly reduce yields and limit productivity. Integrated Pest Management (IPM) offers a sustainable solution by combining biological, cultural, genetic, and minimal chemical methods to keep pest populations below economic thresholds while reducing environmental and health risks (Istatu *et al.*, 2025).

Integrated Pest Management (IPM) promotes ecological balance by conserving natural enemies, reducing chemical inputs, and improving soil and plant health through organic amendments. Biodiversity-friendly practices such as habitat diversification, flowering borders, agroforestry, and reduced tillage enhance natural pest regulation and ecosystem resilience under climate stress. By supporting beneficial insects, soil microorganisms, and pollinators, IPM strengthens ecosystem services and ensures sustainable, climate-resilient moringa production.

Integrated Pest Management (IPM) acts as a climate-resilient strategy by integrating cultural, biological, mechanical, and need-based chemical methods. IPM emphasizes pest monitoring, economic threshold-based decision-making, and conservation of beneficial organisms. By reducing chemical dependence and strengthening ecosystem stability, IPM supports sustainable agriculture and biodiversity conservation under changing climatic conditions.

Results and Discussion-

Major Insect Pests of *Moringa oleifera*:

Moringa oleifera is affected by several crop-specific insect pests that cause defoliation, tissue damage, and yield loss.

Moringa (*Moringa oleifera* Lam.) is a widely consumed vegetable in Southeast Asia and West Africa, where it is severely affected by the leaf caterpillar *Noorda blitealis*, a major year-round pest causing serious damage (Outani *et al.*, 2023). Limited information exists on insect pests of Moringa oleifera at different growth stages. Integrated Pest Management provides a safe and effective control strategy, which is crucial since moringa is often consumed raw, and chemical pesticides pose health risks (Saha *et al.*, 2014). *Moringa oleifera* (Lam.), a member of the family Moringaceae, is native to India and widely cultivated in tropical and subtropical regions for its highly nutritious and medicinal edible parts. The crop is mainly damaged by defoliators, borers, and sucking insects, with key pests including *Eupterote mollifera*, *Noorda blitealis*, *Noorda moringae*, *Gitona distigma*, *Myllocerus* spp., and *Aphis craccivora* (Selvi *et al.*, 2017).

The six most economically important major insect pests include leaf caterpillar (*Noorda blitealis*), hairy caterpillar (*Eupterote mollifera*), bud worm (*Noorda moringae*), pod fly (*Gitona distigma*), bark caterpillar (*Indarbela tetraonis*), and long-horn beetles (*Batocera rubus*). Pest incidence and severity vary with crop stage, season, and weather conditions, particularly temperature and rainfall. AESA-based Integrated Pest Management emphasizes regular field monitoring, conservation of natural enemies, and minimal chemical use. Climate change further increases pest pressure, making ecological and biodiversity-based management strategies essential for sustainable moringa production.

1. **Leaf Caterpillar, *Norda blitealis* Walker (Crambidae: Lepidoptera)—**
   The leaf caterpillar *Noorda blitealis* (Lepidoptera: Crambidae) is one of the most destructive defoliators of Moringa oleifera. Its larvae feed aggressively on leaf lamina, skeletonizing foliage and drastically reducing photosynthetic area, especially in young plantations. Infestations peak during warm and humid conditions, with climate warming likely to extend its activity and increase damage.
2. **Hairy Caterpillar, *Eupterote mollifera* Walker (Eupterotidae: Lepidoptera)—**
   The hairy caterpillar Eupterote mollifera is a serious defoliator of Moringa oleifera, with gregarious larvae causing rapid and sometimes complete defoliation, especially in young trees. Warm temperatures, humidity, and climatic stress favor frequent outbreaks, while the larvae's irritating hairs hinder manual control.
3. **Bud Worm, *Noorda moringae* Tams (Crambidae: Lepidoptera)—**
   The Bud worm (*Noorda moringae*) damages flower buds and young pods of *Moringa oleifera* by boring internally, causing premature bud drop and poor pod set. Losses increase during warm, dry conditions and extended summers linked to climate change. The pest is most active at the flowering stage.

4. **Pod Fly, *Gitona distigma* Meigen (Drosophilidae: Diptera)—**
   The Pod fly (*Gitona distigma*) damages developing moringa pods as larvae feed inside, causing gummy exudation, pod deformation, and premature drop, leading to heavy yield loss. Warm conditions favor rapid multiplication, while control relies on sanitation, neem-based treatments, and IPM practices.
5. **Bark Caterpillar, *Indarbela tetraonis* Moore (Indarbelidae: Lepidoptera)—**
   The bark caterpillar (*Indarbela tetraonis*) bores into bark and stems, forming concealed galleries that disrupt sap flow, weaken branches, and cause dieback, especially under drought stress.
6. **Long-Horn Beetles, *Batocera rubus* (Cerambycidae: Coleoptera)—**
   The longhorn beetle (*Batocera rubus*) is a stem borer whose larvae tunnel deep into woody trunks and branches, weakening the structure, disrupting sap flow, and sometimes causing plant death, especially in stressed trees.

Overall, pest severity is strongly influenced by climate factors such as rising temperatures, prolonged dry spells, and irregular rainfall, which accelerate pest multiplication and weaken plant defenses. This underscores the need for climate-responsive integrated pest management strategies based on timely monitoring and ecological approaches.

Impacts of Climate Change on Pest Dynamics-

Climate change significantly affects insect pest biology and population dynamics. Increasing temperatures speed up insect development, enhance reproduction, and allow multiple generations within a single season, leading to faster pest population growth. In moringa-growing areas, warmer conditions improve the survival of defoliators and sap-sucking insects, resulting in more frequent pest outbreaks.

Changes in rainfall and humidity also influence pest incidence. Irregular rainfall and drought stress weaken moringa plants and disturb natural enemy populations, often giving pests an advantage over predators and parasitoids. Elevated atmospheric CO_2 can alter plant nutrition and defensive traits, indirectly affecting pest feeding behavior and the severity of crop damage.

Rising temperatures further support the spread of insect pests into new regions, increasing pest pressure in emerging moringa cultivation zones. Practices such as monocropping, excessive fertilizer use, and unregulated pesticide application worsen these impacts by reducing biodiversity and natural pest control. Overall, climate and environmental changes intensify pest problems in moringa, emphasizing the importance of climate-resilient and ecosystem-based pest management strategies.

Integrated Pest Management Strategies-

Integrated Pest Management (IPM) offers a sustainable and climate-resilient approach for controlling insect pests of *Moringa oleifera*. It combines compatible management practices to maintain pest populations below economic threshold levels while reducing risks to human health and the environment.

- **Cultural Control:**
  Cultural practices are the backbone of IPM in moringa cultivation. Use of healthy planting material, optimum spacing, balanced fertilization, timely pruning, and proper field sanitation limits pest establishment and survival. Removal and destruction of infested shoots, pods, and bark reduce pest carryover. Adjusting sowing or pruning schedules and avoiding continuous monocropping further suppress pest incidence. Intercropping and conservation of on-farm biodiversity improve crop resilience against pest outbreaks.
- **Biological Control:**
  Biological control plays a key role in sustainable moringa pest management. Conservation of natural enemies such as ladybird beetles, lacewings (*Chrysoperla* spp.), parasitoids (*Trichogramma* spp.), and predatory bugs ensures natural regulation of pests. Entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*) and microbial agents like *Bacillus thuringiensis* effectively control caterpillar pests with minimal impact on non-target organisms.
- **Mechanical and Physical Control:**
  Mechanical measures are useful for early pest suppression and monitoring. Manual removal of egg masses, gregarious larvae, and webbed plant parts lowers pest populations. Plugging borer holes prevents further damage. Light traps and colored sticky traps help in monitoring and reducing adult populations of moths and sap-feeding pests.
- **Botanical and Biopesticides:**
  Botanical pesticides offer environmentally safe alternatives to chemical insecticides. Neem-based products containing azadirachtin act as antifeedants, repellents, and growth regulators against sucking and chewing pests. Extracts from moringa plants have also shown potential for use in low-input and organic IPM programs.
- **Chemical Control:**
  Chemical control should be used only when pest levels exceed economic thresholds. Selective and low-toxicity insecticides are preferred to protect beneficial organisms and minimize residues. Need-based application and rotation of insecticide groups are important to prevent resistance development, especially under climate-induced pest fluctuations.

Future Prospects of IPM in *Moringa oleifera*-

Climate change is likely to intensify pest pressure in *Moringa oleifera* by influencing pest development, survival, and outbreak patterns. These changes demand climate-resilient Integrated Pest Management (IPM) strategies that emphasize timely and informed decision-making. Pest forecasting models, climate-based surveillance, and early warning systems can help farmers anticipate infestations and apply control measures at the right time.

Future IPM approaches in moringa should prioritize ecological and biological control methods. Increased use of natural enemies, microbial biopesticides, and botanical pesticides can effectively suppress pests while minimizing environmental risks. The adoption of resistant moringa varieties and habitat management practices such as mixed cropping and conservation of beneficial organisms will further strengthen natural pest regulation and biodiversity conservation.

Adaptive management and farmer participation will be key to successful IPM implementation under changing climatic conditions. Regular field scouting and Agro-Ecosystem Analysis (AESA) enable early detection of pest changes and support balanced pest management decisions. Integrating traditional farmer knowledge with digital tools, training programs, and participatory IPM will enhance field-level adoption and ensure sustainable, low-chemical moringa pest management. Future research should focus on climate-smart pest forecasting models, development of pest-resistant moringa cultivars, and integration of precision agriculture tools (e.g., remote sensing, decision support systems) into IPM frameworks.

Conclusion-

Climate change has increased insect pest pressure on *Moringa oleifera* by altering pest biology and crop–pest interactions, threatening sustainable production. Major pests such as leaf caterpillar (*Noorda blitealis*), hairy caterpillar (*Eupterote mollifera*), bud worm (*Noorda moringae*), pod fly (*Gitona distigma*), bark caterpillar (*Indarbela tetraonis*), and long-horn beetles (*Batocera rubus*) show greater adaptability under changing climatic conditions. Integrated Pest Management (IPM), combining cultural, mechanical, biological, and botanical approaches with limited chemical use, provides an effective and environmentally safe solution. Future efforts should focus on climate-based pest forecasting, conservation biological control, and farmer capacity building to ensure sustainable moringa cultivation under climate change.

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