

Climate-Smart and Innovative Approaches for Sustainable Forest Pest Management in Pakistan: A Comprehensive Review

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Abstract

In Pakistan, climate change and unsustainable forest management techniques are further endangering forest ecosystems due to outbreaks of pests. Increased temperatures, change in precipitation patterns and extreme weather conditions have added to the growth and development of populations of forest pests, which are becoming threatening to the biodiversity, stability of the ecosystem and forest productivity as well. This review evaluates climate wise and novel practices to forest pest management in Pakistan with the aim of sustainable and adaptive practices that may produce less impact on the environment. The research summarizes the literature on biological control, integrated pest management (IPM), remote sensing technology and community based forest management practices. Early warning systems, pest-resistant tree species, and adaptive silvicultural practices are mentioned as the examples of climate-smart strategies, which could help to reduce the risks associated with pests. Also, new technologies, including Geographic Information Systems (GIS), drones, and predictive modeling, are mentioned as means to enhance monitoring and decisions. The results show that conventional pest management practices cannot serve to meet the emerging challenges in the changing climatic conditions. Thus, the combination of modern technologies and sustainable practices is the key to efficient pest control in forests. The review wraps up by highlighting the necessity of policy backing, stakeholder involvement, and additional research in building robust forest management infrastructures in Pakistan.

Keywords: Forest pests, climate change, climate-smart forestry, integrated pest management, Pakistan.

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Introduction

The forest ecosystems are very crucial to maintain ecological balance, sustain biodiversity and economic and environmental advantages. Forests play a very important role in Pakistan in terms of sequestration of carbon, soil conservation and providing livelihood to the local communities. But, these ecosystems are becoming more threatened by climate change and human activities (Fayaz et al., 2025). One of the major challenges facing forest ecosystems is the increasing incidence of pest outbreaks. Forest pests, including insects, pathogens, and invasive species, can cause extensive damage to trees, leading to reduced forest productivity and ecosystem degradation. Climate change has further intensified this problem by creating favorable conditions for pest survival, reproduction, and spread (Hartmann et al., 2025). One of the most important biotic agents of forest health in the whole world is the Forest insect pests. The impacts of such pests may be massive as they defoliate the trees, bore holes into the stems and to plants; eventually resulting into lower productivity and massive loss of forests. Species like *Aeolesthes sarta* (Sart longhorned beetle) have been devastating economically useful tree species (*Populus*, *Salix* and *Juglans*) in Pakistan, and this represents increasing levels of pest-related threats in the area (Hayat et al., 2024).

In Pakistan, forest pest management has traditionally relied on conventional methods such as chemical control and manual interventions. However, these approaches are often ineffective, environmentally harmful, and unsustainable in the long term. The need for climate-smart and innovative solutions has become increasingly important to address the evolving challenges of pest management under changing climatic conditions. Climate change has emerged as a major factor influencing pest dynamics. Changes in temperature and precipitation patterns affect pest survival, reproduction, and distribution, leading to increased infestation risks (Nitta et al., 2024). In Pakistan, climate variability has intensified pest outbreaks, threatening forest sustainability and ecosystem services (Akhtar et al., 2022). Consequently, forest ecosystems are becoming susceptible to rampant and intense outbreaks of pests. It has been revealed that climate-driven alterations in pest dynamics such as a change in phenology and distribution are major challenges to forest management across the world (Battisti & Larsson, 2023).

Pakistan faces the effects of climate change especially because it has varied ecological zones and low adaptability. The shift in temperature and precipitation will modify the forest composition and predispose it to pests and diseases. In addition, forest cover has already been significantly diminished by deforestation and alteration in land-use whereby it has been reported that forest cover has been significantly lost in recent years, an aspect that undermines the ability of the ecosystem to respond to stresses. All these pressures have favorable conditions that promote the growth of the pests and decline of the forest (Acharya et al., 2025). Pest management practices in Pakistan have been traditional forest management, which mainly depended on reactive and chemical based control practices. Although this can relieve short term, these methods do not often work by countering the ecological mechanisms their causes and can also cause adverse effects on the environment. However, contemporary methods focus on climate-wise and sustainable management of pests combining ecological principles with technologies. These are early detection systems utilizing remote sensing and geographical information system (GIS), natural enemies that are used to control the pests, and prognostic modeling which predicts a pest outbreak.

Pest Management Scenario

Insects are important to the forest ecosystems ecologically. They contribute significantly to such significant activities as pollination, nutrient cycling, biodiversity regulation, natural

elimination of weak and senescent members, natural elimination of dead or decaying trees and forest regeneration. These functions play a critical role in maintaining the structural and functional integrity of the forest ecosystems in both the natural and managed sceneries. The insects may, nevertheless, cause a lot of biotic disturbances when they become larger than their ecological limits. These epidemics may result in substantial damage to forests, which leads to ecological disproportion and loss of money. Adverse environmental conditions and variability in climate often exacerbate them (Dixon, 2024). It has been demonstrated that forest insect pests affect trees in India, at multiple stages of their life cycle, such as inflorescences, fruits, and seeds on existing trees and the seeds stored in storage. Pest attacks are usual both in wild forests and plantations and seedlings are particularly susceptible in forest nurseries. In the long run, these pests may cause health hazards to forests and make afforestation difficult. (S.S. Patil et al., 2022) has provided an excellent account of insect pests in forests on a worldwide scale consisting of numerous species of considerable ecological and economical value. The compilations are important in guiding early warning systems, forest health checking and designing of integrated pest control plans specific to a given area (Ray & Amitava Banerjee, 2023).

Integrated Pest Management Strategies in Forest Ecosystem

The success and application of Integrated Pest Management (IPM) methods on forest ecosystems can be demonstrated by several successful examples all over the world. One of the examples of the pest whose population and subsequent damage have been greatly curtailed as a result of coordinated IPM efforts is the Masson pine caterpillar (*Dendrolimus punctatus*), a major defoliator of pine plantations in Vietnam. Brazil has also achieved success in applying IPM strategies to control the eucalyptus psyllids (*Ctenarytaina spatulata* and *Glycasips brimblecombei*) on large scale eucalyptus plantations. In a bid to achieve long term pest control and still preserve the ecological balance, the methods normally comprise biological control agents, surveillance, and selective application of chemicals (Gougherty & Davies, 2021). Similarly, longhorn beetles such as *Phoracantha semipunctata* and *Phoracantha recurva* commonly known as eucalyptus cerambycids have been managed through integrated strategies across tropical, subtropical, and even Mediterranean regions (Daniel et al., 2025). Another well documented case is the control of the Sirex wood wasp (*Sirex noctilio*), a serious invasive pest of pine species, including *Pinus radiata* and *P. taeda* in Australia. The IPM program for *Sirex noctilio* includes the release of parasitoids, use of entomopathogenic nematodes, and extensive surveillance efforts, showcasing how multi-pronged strategies can be tailored to specific forest ecosystems. These examples highlight the potential for broader adoption of IPM in forestry, provided there is adequate investment in research, monitoring infrastructure, and adaptive management frameworks. Globally, there is a growing shift toward integrated and climate-resilient pest management strategies that combine monitoring, prevention, and adaptive response. Innovative technologies, such as unmanned aerial vehicles (UAVs), machine learning, and spatial modeling, are increasingly being used to enhance pest surveillance and decision-making. At the same time, biological control and ecosystem-based approaches are gaining attention as environmentally sustainable alternatives to chemical pesticides.

Despite these advancements, the application of such innovative and climate-smart approaches in Pakistan remains limited. Institutional constraints, lack of technical capacity, and insufficient research integration hinder the adoption of modern pest management strategies. Consequently, there is a pressing need to review and synthesize current knowledge on forest pest management, particularly in the context of climate change, to identify research gaps and inform future directions. Therefore, this review aims to examine recent developments in climate-smart and innovative approaches for forest pest management, with a specific focus on their relevance and applicability in Pakistan. By integrating global perspectives with local challenges, this study seeks to contribute to the development of sustainable and resilient forest management practices in the

country. This review aims to explore climate-smart and innovative approaches for forest pest management in Pakistan by analyzing existing literature and identifying effective strategies for sustainable forest protection. The study also highlights research gaps and provides recommendations for future policy and practice.

Literature Review

1. Overview of Forest Pest Management

Forest ecosystems are dynamic and complex systems that are highly vulnerable to biotic disturbances, particularly insect pests. Forest pests, including defoliators, bark beetles, and wood borers, can significantly reduce forest productivity, alter species composition, and disrupt ecosystem functions. These pests damage trees by feeding on leaves, stems, and roots, often leading to large-scale forest degradation and economic losses. Globally, forest pest outbreaks have increased in frequency and severity over the past few decades, largely due to environmental changes and anthropogenic activities. Effective forest pest management is therefore essential for maintaining forest health, biodiversity, and ecosystem services. Traditional management approaches have relied heavily on chemical pesticides and mechanical control; however, these methods are often unsustainable and environmentally harmful. As a result, there has been a shift toward more sustainable and integrated approaches, including biological control and ecosystem-based management.

2. Climate Change and Forest Pest Dynamics

Climate change is widely recognized as a major driver of changes in forest pest behavior and distribution. Rising temperatures, altered precipitation patterns, and extreme climatic events have significantly influenced pest population dynamics. Warmer climates can accelerate insect development, increase survival rates, and allow pests to expand into new geographical areas. Research indicates that climate warming enhances pest outbreaks by enabling multiple generations per year and improving overwintering survival. Additionally, trees stressed by drought and heat become more susceptible to pest infestations, creating a feedback loop that intensifies forest degradation. Climate-induced shifts in pest phenology and distribution have been observed globally, making forests increasingly vulnerable to infestations. Predictive modeling studies further suggest that future climate scenarios may lead to earlier and more severe pest outbreaks, emphasizing the need for adaptive management strategies.

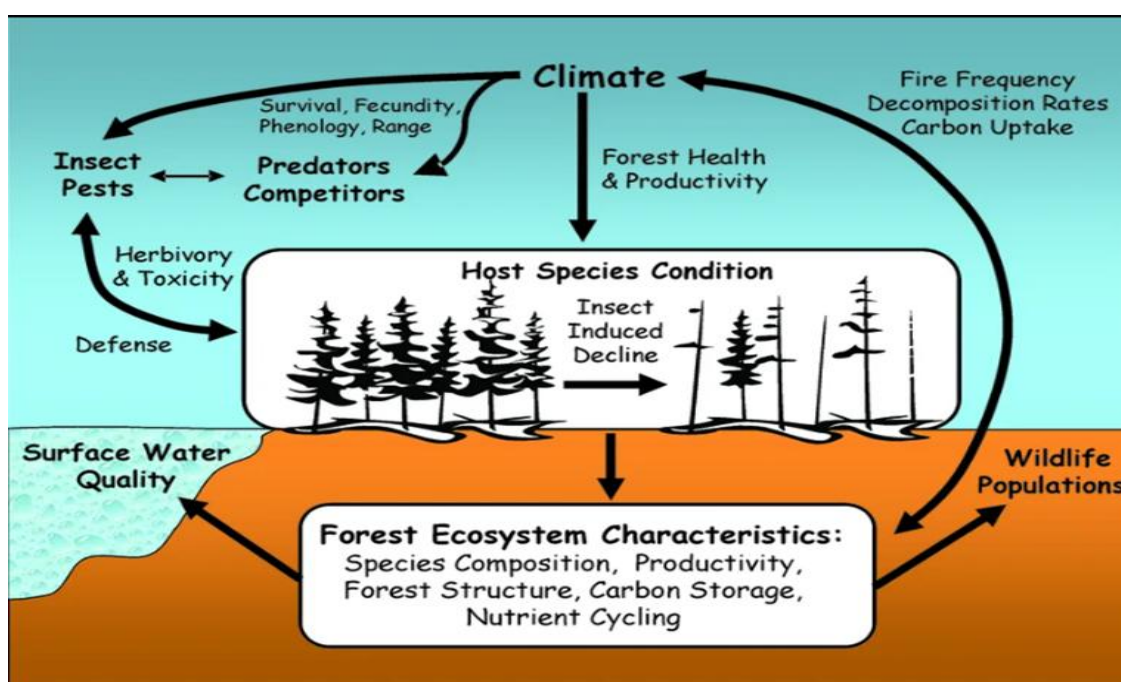


Figure 1. forest ecosystem characteristic**3. Major Forest Pests and Their Impacts in Pakistan**

Pakistan's forests are relatively limited in area but highly diverse, including coniferous forests, scrub forests, and riverine ecosystems. These forests are affected by a variety of insect pests, among which *Aeolesthes sarta* (Sart longhorn beetle) is one of the most destructive species. This pest primarily attacks economically important tree species such as poplar (*Populus spp.*), willow (*Salix spp.*), and walnut (*Juglans regia*), leading to significant economic losses. In addition to *A. sarta*, bark beetles and defoliating insects also pose serious threats to forest health in Pakistan. The impact of these pests is exacerbated by deforestation, land-use change, and weak forest management practices. However, compared to global literature, research on forest pests in Pakistan remains limited, particularly in terms of long-term monitoring and predictive modeling.

4. Conventional Pest Management Approaches

Traditional forest pest management in Pakistan has largely relied on reactive strategies, including chemical pesticides and manual removal of infested trees. While these methods may provide short-term control, they often fail to address the root causes of pest outbreaks. Chemical control can lead to environmental pollution, non-target species impacts, and the development of pesticide resistance. Moreover, these approaches are often costly and impractical for large forest areas. Consequently, there is growing recognition of the need for sustainable alternatives, such as integrated pest management (IPM), which combines multiple control strategies to minimize environmental impact.

5. Advances in Remote Sensing and GIS for Pest Monitoring

Recent technological advancements have transformed forest pest monitoring and management. Remote sensing and geographic information systems (GIS) have emerged as powerful tools for detecting and assessing forest health over large areas. Remote sensing technologies allow researchers to monitor vegetation health by analyzing spectral signatures, which can indicate stress caused by pest infestations. Changes in leaf color, moisture content, and chlorophyll levels can be detected using satellite imagery, enabling early identification of pest outbreaks. GIS further enhances pest monitoring by integrating spatial data and enabling the analysis of pest distribution patterns. These tools support decision-making by identifying high-risk areas and guiding targeted interventions.

6. UAVs and Emerging Monitoring Technologies

Unmanned Aerial Vehicles (UAVs), commonly known as drones, represent a major advancement in forest monitoring. UAVs provide high-resolution imagery and flexible data acquisition, allowing for detailed assessment of forest health. Studies have shown that UAVs are highly effective for detecting pest infestations, monitoring tree stress, and assessing forest conditions in real time. Their ability to capture high-resolution data at low cost makes them particularly suitable for large and inaccessible forest areas. Furthermore, the integration of UAVs with machine learning and artificial intelligence has enhanced the accuracy and efficiency of pest detection. AI-based models can analyze large datasets to identify patterns and predict pest outbreaks, providing valuable insights for forest management.

7. Biological Control and Eco-Friendly Approaches

Biological control is an environmentally sustainable alternative to chemical pest management. It involves the use of natural enemies, such as predators, parasitoids, and pathogens, to control pest populations. Entomopathogenic fungi, bacteria, and nematodes have shown promising results in controlling forest pests. These biological agents are environmentally friendly and reduce the risk of resistance development. Additionally, habitat management practices, such as maintaining biodiversity and promoting natural predator populations, can enhance ecosystem resilience. Eco-friendly approaches also include the use of pheromone traps, resistant tree species,

and silvicultural practices that reduce pest susceptibility. These strategies are increasingly being integrated into IPM frameworks to achieve sustainable pest management.

8. Integrated Pest Management (IPM) and Climate-Smart Approaches

Integrated Pest Management (IPM) is a holistic approach that combines biological, cultural, mechanical, and chemical methods to manage pest populations in an environmentally sustainable manner. IPM emphasizes prevention, monitoring, and targeted interventions, reducing reliance on chemical pesticides. Climate-smart pest management builds on IPM principles by incorporating climate change considerations into management strategies. This includes the use of predictive models to forecast pest outbreaks, adaptive management practices, and the integration of modern technologies such as remote sensing and UAVs. The adoption of climate-smart approaches is essential for enhancing forest resilience and ensuring sustainable forest management under changing environmental conditions.

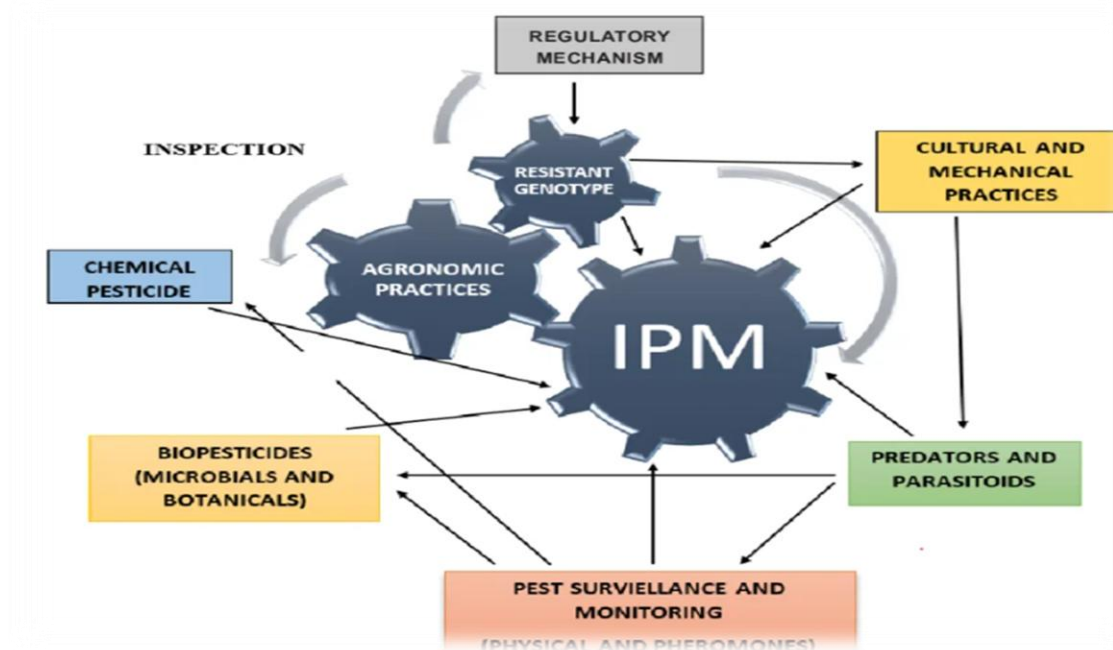


Figure 2. Integrated Pest Management (IPM) and Climate-Smart Approaches

9. Research Gaps and Challenges in Pakistan

Despite global advancements, the adoption of innovative pest management approaches in Pakistan remains limited. Key challenges include:

- Lack of long-term monitoring data
- Limited use of advanced technologies such as UAVs and GIS
- Weak institutional capacity and policy implementation
- Insufficient integration of research and management practices

Additionally, there is a significant gap in understanding the interaction between climate change and pest dynamics in Pakistan's forest ecosystems. Addressing these gaps is crucial for developing effective and sustainable pest management strategies.

10. Future Directions

Future research should focus on developing integrated and climate-smart pest management systems tailored to Pakistan's ecological conditions. This includes:

- Expanding the use of remote sensing and UAV technologies
- Developing predictive models for pest outbreaks
- Promoting biological control and eco-friendly practices
- Strengthening institutional frameworks and policy support

Methodology

1. Study Design

The paper will use a systematic literature review method to examine climate-smart and innovative sustainable forest pest management strategies in Pakistan. It was done in a systematic way so that it would be transparent, reproducible, and cover all the relevant studies.

2. Data Sources and Search Strategy

Large academic databases have been used to get pertinent literature, including Google Scholar, Science Direct, Springer Link, and Research Gate. The search terms included forest pest management Pakistan, climate change forest pests, integrated pest management forestry, biological control forest insects, and climate-smart agriculture and forestry Pakistan with Boolean operators (AND, OR) used to refine the search results.

3. Inclusion and Exclusion Criteria

a. Inclusion Criteria

The inclusion criteria comprised peer-reviewed journal articles published between 2000 and 2024, research focusing on forest pests, climate change, or pest management, and studies relevant to Pakistan or similar ecological regions.

b. Exclusion Criteria

The exclusion criteria included non-peer-reviewed sources such as blogs and informal reports, studies unrelated to forestry, and duplicate or outdated studies.

4. Data Extraction and Analysis

Selected studies were carefully reviewed, and key information including study objectives, methodologies used, key findings, and recommended pest management strategies was extracted; subsequently, a thematic analysis approach was applied to categorize the findings into major themes, including climate change impacts, traditional pest management, climate-smart strategies, and technological innovations.

5. Synthesis of Findings

The extracted data were synthesized qualitatively to compare different studies, identify trends and patterns, highlight research gaps, and evaluate the effectiveness of various strategies; this approach enabled a comprehensive understanding of sustainable pest management practices in Pakistan.

6. Limitations of the Study

The study is subject to several limitations, including the limited availability of forest-specific pest studies in Pakistan, a reliance on secondary data sources, and the possibility of publication bias; however, despite these constraints, the review still provides a strong and valuable foundation for future research in the field.

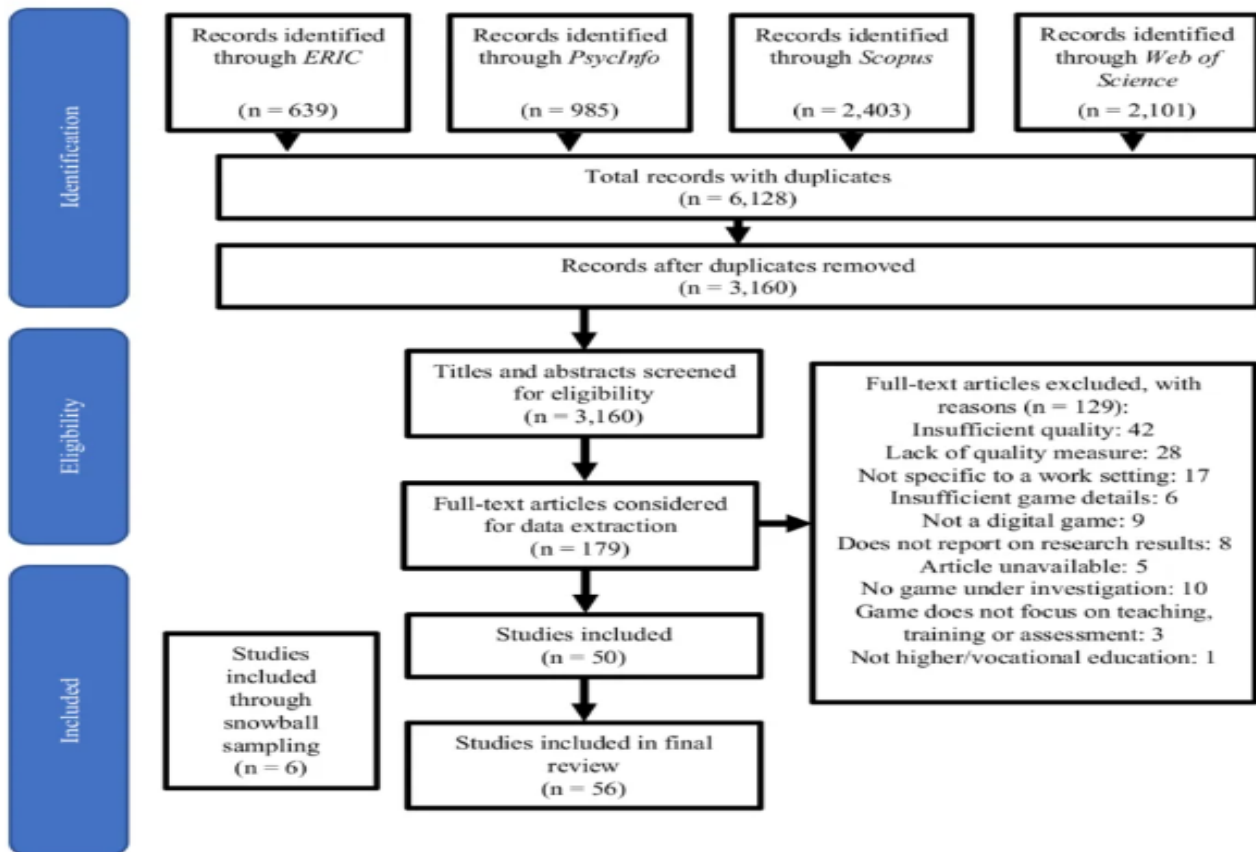


Figure 3.PRISMA diagram

Results and Discussion

This review highlights the increasing impact of climate change on forest pest dynamics in Pakistan and emphasizes the urgent need for sustainable and adaptive management strategies. The findings from the literature indicate that rising temperatures, changing precipitation patterns, and extreme climatic events are significantly influencing pest populations, leading to increased infestation rates and expanded geographical distribution (Prabhakar et al., 2024). These changes not only threaten forest health but also compromise ecosystem services and biodiversity. Traditional pest management practices, particularly the heavy reliance on chemical pesticides, are no longer sufficient to address these emerging challenges. Although chemical control provides immediate results, its long-term consequences such as environmental degradation, pest resistance, and harm to non-target species limit its sustainability (Knols, 2024). In contrast, biological and cultural methods offer environmentally friendly alternatives but are often underutilized due to lack of awareness, resources, and technical expertise in Pakistan (Noman et al., 2024). The review further demonstrates that climate-smart strategies, especially Integrated Pest Management (IPM), provide a more balanced and sustainable approach. IPM integrates multiple control methods and emphasizes monitoring and threshold-based interventions, reducing dependence on chemical inputs while maintaining ecological balance (Ahirwar & Ahirwar, 2025). Additionally, climate-resilient forestry practices, such as promoting species diversity and selecting pest-resistant tree species, enhance forest resilience against pest outbreaks (Lu, 2025). Technological innovations, including remote sensing, Geographic Information Systems (GIS), Artificial Intelligence (AI), and Internet of Things (IoT)-based monitoring systems, have shown great potential in improving pest detection and management. These tools enable early warning systems and data-driven decision-making, which are essential under changing climatic conditions (Fiza et al., 2025). However, their adoption in Pakistan remains limited due to financial, technical, and institutional constraints. Despite these advancements, several

challenges persist. Limited research on forest-specific pests, lack of long-term climate-pest interaction studies, and insufficient integration of modern technologies hinder effective pest management. Moreover, weak policy implementation and inadequate capacity building further restrict the adoption of sustainable practices. Overall, the discussion suggests that a shift from conventional methods to integrated, climate-smart, and technology-driven approaches is necessary for effective forest pest management in Pakistan.

Conclusion

Conclusively, climate change has been having immense impacts on the dynamics of forest pests in Pakistan, which are threatening the sustainability of forests, as well as their biodiversity and ecosystem services. The current and changing issues require more than the conventional methods of managing pests. This review suggests climate-intelligent approaches, especially Integrated Pest Management (IPM), biological control, climate-friendly forestry management, and digital monitoring technologies as effective and sustainable solutions. These strategies not only minimize environmental effects, but also increase the strength of the forest ecosystems. Nevertheless, these strategies should be supported by powerful institutions, more research, and capacity building on stakeholders to be successful. Increased investment in the highly developed technologies and creation of region-specific pest management models are also needed. The following areas should be prioritized in future studies: long-term climate-pest-interactions, incorporation of modern technologies, and designing adaptive management frameworks in response to the ecological realities of Pakistan. Finally, there is a need to embrace new and climate-smart strategies that can make the country's forest ecosystems sustainable and resilient to climate change in the long run.

Conflicts of Interest

The authors declare no conflict of interest.

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Author contribution

Conceptualization, methodology, validation: Abdus Sami formal analysis, investigation data curation; writing-original draft preparation; writing-review and editing, visualization Maria Said: All authors have read and agreed to the published version of the manuscript.

Declaration of generative AI in scientific writing

The author acknowledges having used the Generative AI tool Grammarly-AI for grammar/language improvement, summarizing supporting literature. The author is solely responsible for all published content and has verified the accuracy and authenticity of the AI output.

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