CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT

GLOBAL ISSUES & LOCAL PERSPECTIVES

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue **Climate smart actions (CSA) aquaculture, agroforestry and resources management** necessary in policy making process that will stimulate increase in food production and environmental sustainability. **Climate smart actions (CSA) aquaculture, agroforestry and resources management :** *Global Issues & Local Perspectives* is organized in three parts. Part One deals with The Concept of **Climate smart actions (CSA)**, Part Two is concerned with The Concept of **aquaculture,** and Part Three deals with the Concept of **agroforestry and resources management**

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Chapter 16:

Climate-Smart Pest and Resource Management Strategies in Agroforestry and Aquaculture Systems: A Comprehensive Review

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1.0: Introduction

Climate change is one of the greatest threats to agriculture and food production, especially for the hundreds of millions of smallholder farmers in developing world (Miron *et al*, 2023). Global challenges related to food production, land degradation, water scarcity and biodiversity loss has been intensified through climate change. Increase in temperatures, erratic rainfall patterns droughts flood and extreme weather conditions has directly affected agricultural and aquatic production systems. The relationship between climate change and agricultural productivity has entered a critical phase. The Intergovernmental Panel on Climate Change (IPCC) confirms that global surface temperatures have risen approximately 1.1°C above pre-industrial levels, within the last decade (2011–2020) marking the warmest period on record (IPCC, 2021). These changes are not merely statistical abstractions they manifest as tangible disruptions to the biological systems upon which human food security depends. For farmers and fishers worldwide, the question is no longer whether climate change will affect their livelihoods, but how rapidly they can adapt to its accelerating impacts. Agroforestry is the practice of integration of trees, plants, and animals in conservative, long-term, productive systems, it can take the form of planting trees on farm land or farming in forest and along forest margins to produce crops like fruits, nuts cocoa, coffee etc. Agroforestry has a lot of benefits such as increase in soil fertility, reduction in soil erosion and improvement in water retention, trees also provides shades for crops which reduces heat stress and improves yield. On the other hand aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Aquaculture plays a crucial role in global food security by providing nearly half of the total global food fish supply. Apart from contributing to the global food supply at 51% of the world's food fish (FAO, 2024), aquaculture also delivers essential micronutrients and fatty acids, particularly through shellfish production, which are not commonly found in land-based protein sources (Azra *et al*., 2021). Climate-smart aquaculture (CSAq) is an adaptive strategy designed to enhance aquaculture production in response to climate change. Its dual goals are to ensure food security and alleviate poverty (UNDP, 2022). While farming contributes significantly to greenhouse gas emissions, it also holds immense potential for mitigation and adaptation. Among the various strategies emerging to address this dual challenge, agroforestry the intentional integration of trees and shrubs into agricultural landscapes and sustainable aquaculture have gained substantial attention for their multifunctional benefits. These systems offer more than just food production; they provide carbon sequestration, biodiversity conservation, microclimate regulation, and enhanced resilienc e to climate variability (Bogale *et al*., 2023).

However, the benefits of these systems are increasingly threatened by climate-induced pest and disease pressures. Rising temperatures accelerate pathogen life cycles, alter vector distributions, and expand the geographical range of destructive pests. Simultaneously, changing precipitation patterns create conditions that favor certain disease outbreaks while drought stress weakens plant and animal defenses, increasing susceptibility to opportunistic pathogens (Juroszek & von Tiedemann, 2019). The traditional response to these challenges heavy reliance on synthetic pesticides and antibiotics has proven environmentally

destructive and increasingly ineffective as resistance develops. Therefore, this review examines the emerging body of knowledge on climate-smart pest and resource management strategies within agroforestry and aquaculture systems. The study synthesizes recent literature to highlight the role of climate-smart practices in enhancing pest control, improving resource efficiency, and strengthening the resilience of agricultural production systems under changing climatic conditions.

1.1: PROBLEM STATEMENT

Agricultural systems worldwide are increasingly threatened by the adverse of effects of climate change. Climate change is one of the major challenges in global food production that is threatening global agricultural productivity. High temperatures, unsteady rainfall patterns etc are significantly altering pest population dynamics, causing an increase in pest outbreak and increasing pressure on natural resources. As a result pests' outbreak are becoming more intense and severe and this has led to substantial reductions on agricultural productivity and at the same time threatened global food production. Agroforestry and aquaculture systems plays a significant role in improving food security, conservation of biodiversity and resource management sustainability. Agroforestry improves ecosystem services such as improvement in soil fertility, carbon sequestration and natural pest regulation through biodiversity increase. In the same manner aquaculture contributes to global protein supply and rural livelihoods. These systems are however vulnerable to climate – induced challenges such as pest infestations, scarcity of water, soil fertility decrease, disease outbreak, ecosystem degradation and poor resource utilization. Despite the potential of climate-smart agriculture to increase productivity, resilience and sustainability, the integration of climate smart pest and resource management strategies within aquaculture and agroforestry systems are still limited. Hence there is need to explore effective climate-smart strategies that can enhance pest management and resource use efficiency and at the same time increasing resilience and sustainability of agroforestry and aquatic production systems under changing climate conditions

2.0:   UNDERSTANDING CLIMATE-SMART PEST MANAGEMENT
2.1:   Redefining Pest Management in a Changing Climate

Climate-smart pest management represents a fundamental shift from reactive, chemical-dependent approaches to proactive, ecosystem-based strategies. Unlike conventional integrated pest management (IPM), which primarily focuses on optimizing control tactics, CSPM explicitly incorporates climate variability and change as central planning parameters. This approach recognizes that pest dynamics are no longer predictable based on historical patterns; instead, they are increasingly characterized by uncertainty, novel pest-host interactions, and accelerated evolutionary pressures on pathogens and pests. The conceptual foundation of CSPM rests on three interconnected pillars:

(1) resilience building through biodiversity and ecological intensification,
(2) adaptation through monitoring and predictive capacity, and
(3) mitigation through reduced chemical inputs and carbon sequestration.

These pillars align with the broader objectives of climate-smart agriculture (CSA) as defined by the Food and Agriculture Organization (FAO), which seeks to sustainably increase productivity, enhance resilience, and reduce greenhouse gas emissions.

2.2: The Disease Triangle in a Warming World

Plant pathologists have long used the "disease triangle" concept to explain the interaction between host, pathogen, and environment necessary for disease development. Climate change fundamentally alters each corner of this triangle. Elevated temperatures and CO_2 concentrations affect host physiology, often increasing biomass and canopy density, which creates humid microenvironments favorable to foliar diseases such as powdery mildew and rusts (Eastburn *et al.,* 2010). Simultaneously, higher temperatures

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can disrupt the expression of plant resistance genes and compromise immune responses mediated by salicylic acid and jasmonic acid pathways. For pathogens, warming temperatures accelerate reproduction rates and reduce latent periods, enabling more infection cycles per growing season. The wheat stripe rust pathogen (*Puccinia striiformis*) exemplifies this phenomenon, having expanded into warmer regions such as the central and southern plains of the United States as new pathogen races adapt to higher temperatures (Milus *et al*., 2009). Similarly, the environment component of the triangle is transformed as altered precipitation patterns create novel combinations of moisture and temperature that favor emerging disease complexes.

3.0: AGROFORESTRY SYSTEMS: BIODIVERSITY AS A CLIMATE BUFFER
3.1: The Ecological Architecture of Pest Suppression
Agroforestry systems inherently possess structural characteristics that buffer against climate-induced pest pressures. The vertical and horizontal diversity created by integrating trees with crops and livestock generates habitat heterogeneity that disrupts pest lifecycles and supports natural enemy populations. Recent research across diverse agro-ecological zones demonstrates that this *biodiversity*-mediated pest suppression operates through multiple mechanisms.

In West African savanna systems, agroforestry plots incorporating diverse tree species achieved a 20% reduction in crop losses compared to monoculture farms (Duguma *et al*., 2019). This protection arises not from any single factor but from the interplay of physical barriers, microclimate modification, and enhanced biological control. Trees act as windbreaks, reducing the dispersal of spores and insect pests while creating sheltered environments where predatory insects and parasitoids can thrive. The presence of flowering plants and diverse vegetation provides nectar and alternative prey for natural enemies, ensuring their persistence even when pest populations are low.

The microclimate regulation provided by tree cover offers particular significance under climate change. Surface temperatures in agroforestry systems are typically 2–5°C cooler than open agricultural areas, creating thermal refugia that can slow pest development rates and extend the activity periods of beneficial insects. In semi-arid regions, windbreaks established through boundary planting have increased crop yields by up to 15% while simultaneously reducing pest damage through physical protection and enhanced natural enemy populations (Rahman et al., 2017).

3.2: Push-Pull Technology: An African Success Story
Perhaps no innovation better exemplifies climate-smart pest management in agroforestry than the push-pull technology developed and refined over the past three decades in East Africa. Originally conceived to address stemborer infestations in maize, this system has evolved through multiple generations to meet emerging challenges including climate change and the invasive fall armyworm (*Spodoptera frugiperda*). The first-generation push-pull system utilized silverleaf desmodium (*Desmodium uncinatum*) as the "push" component intercropped with maize, while Napier grass (*Pennisetum purpureum*) served as the "pull" trap crop planted at field margins. Desmodium releases volatile chemicals such as (E)-β-ocimene that repel female stemborer moths, while simultaneously emitting root exudates that induce suicidal germination in the parasitic weed *Striga hermonthica*. Napier grass, meanwhile, emits attractive compounds that draw moths away from the maize, but produces a sticky sap that traps larvae attempting to feed upon it (Khan et al., 2011).

As climate change intensified drought stress in the region, researchers developed second-generation "climate-smart" push-pull utilizing greenleaf desmodium (*Desmodium intortum*) and the drought-tolerant

Brachiaria hybrid cv. Mulato II. This adaptation proved remarkably effective, reducing fall armyworm damage by over 80% while providing high-quality fodder for livestock (Midega *et al*., 2018). Recent field evaluations in northwestern Ethiopia demonstrated that push-pull plots achieved maize yields of 5.3 t ha^{-1} compared to 3.0 t ha^{-1} in monoculture plots, while reducing stemborer damage from 15.4% to 2.8% and Striga infestation from 21.8 to 4.1 plants m^{-2} (Tesfaye *et al*., 2025). The third-generation system, currently being promoted across East Africa, incorporates *Desmodium incanum* selected for its drought tolerance and reliable seed production near the equator, paired with *Brachiaria brizantha* cv. Xaraés. This evolution illustrates the adaptive capacity of ecological pest management rather than relying on static technological packages, successful CSPM requires continuous innovation responsive to changing climatic and pest pressures.

3.3: Carbon Sequestration and Climate Mitigation Co-Benefits
The climate benefits of agroforestry extend beyond adaptation to active mitigation through carbon sequestration. Well-managed agroforestry systems can sequester between 1.5 and 3.5 Mg C ha^{-1} year^{-1} in biomass and soil, with tropical home gardens achieving rates as high as 2.8 Mg C ha^{-1} year^{-1}. Recent analyses indicate that European silvopastoral and silvoarable systems alone could remove approximately 81.7 Mt CO_2 eq annually while emitting roughly 49.9 Mt CO_2 eq, resulting in a net removal of 31.8 Mt CO_2 eq year^{-1} (Mosquera-Losada *et al*., 2025). This sequestration occurs through multiple pathways. Above ground trees capture atmospheric CO_2 through photosynthesis, storing carbon in wood, leaves, and branches. Belowground, root systems improve soil structure and contribute to organic matter accumulation. A meta-analysis by Lorenz and Lal (2014) indicated that agroforestry increases soil organic carbon by 30%–50% compared to monocropping systems. The integration of nitrogen-fixing trees further enhances mitigation by reducing synthetic fertilizer requirements, thereby curbing nitrous oxide emissions associated with fertilizer manufacture and application.

3.4: Water Resource Management in Tree-Based Systems
Climate change manifests perhaps most acutely through altered water availability, making efficient water use a critical component of climate-smart agriculture. Agroforestry systems demonstrate superior water use efficiency through multiple mechanisms. Tree root systems access water from deeper soil horizons than annual crops, reducing competition during surface soil drought while maintaining system productivity. Canopy interception and stemflow redistribute precipitation, reducing surface runoff by 30–50% and enhancing groundwater recharge (Nyaga *et al.,* 2021). Recent modeling studies suggest that strategic tree species selection can optimize these benefits. Replacing water-intensive coniferous species with broad-leaved trees in temperate agroforestry systems can reduce evapotranspiration by 15–17 percentage points while increasing groundwater recharge and lateral flow (Vorobevskii *et al*., 2024). These landscape-level hydrological effects strengthen drought resilience and provide co-benefits including urban cooling and sustained streamflow during dry periods.

4.0: AQUACULTURE SYSTEMS: NAVIGATING THE DISEASE-CLIMATE INTERFACE
4.1: The Antibiotic Crisis and the Search for Alternatives
Intensive aquaculture has historically relied heavily on antibiotics to manage disease outbreaks, creating a crisis of antimicrobial resistance (AMR) that threatens both aquatic food security and human health. The emergence of AMR in farmed fish populations has rendered many conventional treatments ineffective, while environmental contamination from aquaculture operations contributes to broader ecosystem degradation. This unsustainable trajectory has increased intensive research into alternative disease management strategies capable of operating effectively under climate change scenarios. Climate change

exacerbates aquaculture disease pressures through multiple pathways. Elevated water temperatures increase pathogen replication rates and expand the geographical range of thermally-limited diseases. Extreme weather events disrupt water quality parameters, stressing animals and compromising immune function. Ocean acidification alters the virulence of certain pathogens while affecting the efficacy of immune responses in shellfish species. These pressures demand management approaches that enhance host resilience rather than merely targeting pathogens.

4.2: Probiotics and Microbiome Management

Probiotic applications have emerged as a cornerstone of climate-smart aquaculture disease management. Defined as live microorganisms that confer health benefits when administered in adequate amounts, probiotics enhance disease resistance through multiple mechanisms: competitive exclusion of pathogens, production of antimicrobial compounds, improvement of water quality, and modulation of host immune responses. Recent research has refined our understanding of probiotic efficacy and application strategies. Meta-analyses indicate that Bacillus and Lactobacillus species dominate current applications, accounting for 52% and 24% of utilized strains respectively (Khanjani *et al*., 2024). These organisms enhance innate immunity through increased phagocytic activity, elevated leukocyte counts, and upregulation of immune-related genes including cytokines and antimicrobial peptides. In Nile tilapia (Oreochromis niloticus), probiotics have demonstrated particular efficacy against Streptococcus spp. and Aeromonas spp., which collectively account for 84% of reported bacterial infections in the species.

The anti-inflammatory properties of probiotics represent an underexplored but critical benefit. Only 3% of recent studies have examined how probiotics down-regulate inflammatory responses, yet this mechanism may prove essential for managing chronic stress induced by climate variability (Khanjani et al., 2025). By maintaining immune balance, probiotics help animals cope with unfavorable conditions without the energy costs of chronic inflammation, thereby preserving growth performance during environmental stress. Feed-based administration, preferred in 98% of applications, ensures consistent delivery to the gastrointestinal tract where microbial interactions are most critical. However, strain specificity remains a significant challenge. Probiotic effectiveness varies by host species, pathogen strain, and environmental conditions. Some strains lose efficacy when transferred from laboratory to field conditions due to stress or poor colonization, necessitating careful selection and quality control protocols.

4.3: Bacteriophage Therapy: Precision Bio-control

Bacteriophage therapy has gained significant attention as a highly specific alternative to antibiotics. These viruses infect and lyse bacterial cells with remarkable precision, leaving beneficial microbial communities intact and avoiding the broad-spectrum disruption associated with antibiotic use. In aquaculture, phage therapy shows particular promise for controlling bacterial pathogens including *Vibrio* spp., *Aeromonas* spp., *Edwardsiella* spp., and *Streptococcus* spp. The mechanisms of phage therapy offer distinct advantages in the context of climate change. Unlike antibiotics, which impose constant selective pressure driving resistance evolution, phages co-evolve with their bacterial hosts, potentially maintaining efficacy over extended periods. Phage cocktails combinations of multiple phage types targeting different bacterial receptors can broaden host range and reduce the probability of resistance development (Culot *et al.,* 2019). Active phage therapy involves administering phages at concentrations sufficient to reduce target populations through multiple replication cycles, while passive therapy utilizes high initial doses to lyse entire pathogen populations without requiring phage reproduction. Both approaches have demonstrated efficacy in aquaculture settings, with particular promise for protecting larval stages when immune systems remain undeveloped and vaccination proves impractical (Ngoc *et al*., 2023). Regulatory frameworks for phage therapy remain under development, with the European Medicines Agency and U.S. Food and Drug

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Administration establishing guidelines that recognize phages as therapeutic agents or pharmaceutical products. As these frameworks mature, phage therapy may provide a critical tool for managing bacterial diseases in warming waters where traditional antibiotics increasingly fail.

4.4: Biofloc Technology: Creating Resilient Microbial Environments

Biofloc technology (BFT) represents a paradigm shift in aquaculture water management that simultaneously addresses disease prevention and resource efficiency. This approach maintains dense microbial communities within culture systems, creating natural probiotic effects that enhance animal immunity while recycling waste nutrients into microbial protein. In BFT systems, heterotrophic bacteria convert ammonia and organic matter into microbial biomass that serves as a supplemental food source, reducing feed costs by 20–30% and water consumption by up to 90% compared to traditional methods (Yu *et al*., 2023; Khanjani *et al*., 2022). The microbial floc creates a protective environment where beneficial bacterial communities competitively exclude pathogens and stimulate host immune function.

Commercial implementations have achieved impressive production metrics. Intensive shrimp farming operations utilizing BFT have reached production rates of 20–25 tons/ha/year, substantially exceeding traditional methods while maintaining biosecurity and reducing environmental discharge. The technology proves particularly valuable in regions facing water scarcity, as the minimal water exchange requirements conserve resources while preventing the introduction of external pathogens. Climate resilience in BFT systems arises from the stability of established microbial communities. While open-water aquaculture faces increasing vulnerability to temperature fluctuations and disease introductions, the controlled environment of biofloc systems buffers against external variability. However, high temperatures can stress these microbial communities, requiring careful management and potentially limiting application in extremely hot climates without cooling infrastructure.

4.5: Plant-Based Therapeutics and Immuno-stimulants

The search for sustainable disease management has renewed interest in plant-derived compounds with antimicrobial and immune-stimulatory properties. Phytobiotics including polyphenols, essential oils, and bioactive extracts—offer efficacy against fish pathogens without promoting AMR, while providing additional benefits such as antioxidant activity and growth promotion.

Extracts from garlic (*Allium sativum*), neem (*Azadirachta indica*), and turmeric (*Curcuma longa*) have demonstrated effectiveness against common aquaculture pathogens. Essential oils from thyme, oregano, cinnamon, and eucalyptus possess antibacterial activities that can be incorporated into feed formulations or applied as bath treatments (Tayde *et al*., 2025). These compounds work through diverse mechanisms including disruption of bacterial cell membranes, inhibition of quorum sensing, and modulation of host immune responses. Immuno-stimulants such as beta-glucans, lipopolysaccharides, and nucleotides enhance non-specific defense mechanisms, preparing animals to resist infections without targeting specific pathogens. This broad-spectrum protection proves valuable when climate stress increases susceptibility to opportunistic infections. When combined with probiotics in symbiotic formulations, these compounds may provide comprehensive health management capable of maintaining productivity under suboptimal conditions.

5.0: INTEGRATED SYSTEMS AND TECHNOLOGICAL FRONTIERS

5.1: Aquaponics: Convergence of Aquaculture and Horticulture

Aquaponics systems, which integrate fish production with soilless plant cultivation in recirculating water systems, exemplify the potential for climate-smart integration. These systems demonstrate remarkable

resilience to water-borne diseases compared to traditional hydroponics, effectively suppressing pathogens such as *Phytophthora cactorum* without pesticide application (Suárez-Cáceres *et al*., 2021). The biological complexity of aquaponics creates multiple barriers to pest and disease establishment. The diverse microbial communities inhabiting biofilters and root zones compete with pathogens while producing compounds that stimulate plant defenses. Physical water treatment methods including UV irradiation and membrane filtration can be integrated without disrupting these beneficial communities, creating comprehensive disease management protocols. Research into biological control within aquaponics has identified effective entomopathogenic and mycoparasitic fungi including *Lecanicillium attenuatum, Isaria fumosorosea*, and *Trichoderma virens* for managing powdery mildew and other plant pathogens (Folorunso *et al*., 2022). These organisms can be maintained within the system as persistent biological control agents, reducing the need for external inputs.

5.2: Precision Technologies for Early Warning and Response

The integration of artificial intelligence and remote sensing technologies has transformed monitoring capabilities in both agroforestry and aquaculture. AI-powered image recognition systems enable early detection of crop diseases and pest infestations through smartphone cameras and drones, facilitating targeted interventions before outbreaks escalate (AgTech Breakthrough, 2025). In aquaculture, satellite-based monitoring provides continuous observation of water quality parameters, temperature fluctuations, and harmful algal bloom detection across extensive operations. Smart sensors deployed in ponds and tanks transmit real-time data on dissolved oxygen, pH, and ammonia levels, enabling automated responses that prevent the water quality deteriorations that predispose animals to disease. Predictive analytics utilize historical and real-time data to forecast pest outbreaks and disease risk with increasing accuracy. Machine learning algorithms can integrate weather forecasts, crop growth models, and pest population dynamics to generate risk assessments that guide management decisions. These tools prove particularly valuable under climate change, where historical patterns no longer reliably predict future conditions.

5.3: Farmer Field Schools and Knowledge Co-Creation

Technology alone cannot achieve climate-smart pest management without the active participation of farming communities. The Farmer Field School (FFS) approach, pioneered by the FAO and partners, has proven effective in building local capacity for ecological pest management. Through regular group sessions spanning entire growing seasons, farmers observe ecosystem dynamics, conduct simple experiments, and develop decision-making skills based on ecological understanding rather than prescriptive recommendations.

IPM-FFS programs emphasize that integrated pest management is not a "package" to be adopted but a continuous process of observation, experimentation, and adaptation. This learning-by-doing approach builds resilience by developing farmers' capacity to respond to novel situations as they arise a critical attribute when climate change creates unprecedented pest and disease scenarios. The social dimension of FFS, including peer learning and collective action, strengthens community capacity to implement landscape-level strategies such as coordinated biological control or shared monitoring systems.

5.4: EMPIRICAL STUDIES

Empirical studies on climate-smart pest and resource management have increasingly demonstrated the importance of integrating ecological principles, technological innovations, and adaptive management strategies to improve agricultural resilience. Several researchers have examined the impacts of climate-smart practices in agroforestry and aquaculture systems across different regions of the world. Table 1

presents a summary of selected empirical studies that highlight the contributions of climate-smart agricultural practices in improving pest control, enhancing resource management, and strengthening climate resilience.

Sn	Author(s) & Year	Objective of Study	Study Area	Methodology	Key Findings	Implications
1	Juroszek & Tiedemann (2020)	To examine the impact of climate change on crop disease distribution	Europe/global cropping systems	Climate modelling and disease risk analysis	Rising temperatures increased the spread and severity of crop diseases	Integrated pest management becomes essential under climate variability
2	Garrity et al. (2020)	To assess the contribution of agroforestry to sustainable agricultural intensification	Africa and Asia	Field trials and agroforestry system analysis	Tree-based farming improved soil fertility, biodiversity and carbon storage	Agroforestry strengthens climate resilience and ecological stability
3	Abdul-Rahman et al. (2021)	To evaluate adoption of climate-smart pest management practices among farmers	East Africa	Survey of 420 farmers and logistic regression	Farmers adopting IPM recorded lower pest damage and higher productivity	Adoption of CSA practices enhances farm resilience
4	Pretty (2021)	To analyze sustainable intensification practices in agriculture	Global	Meta-analysis of sustainable agriculture case studies	Climate-smart practices increased yield while reducing environmental impact	Sustainable intensification supports food security
5	Dinesh et al. (2021)	To examine climate-smart agriculture technologies and their impacts	Developing countries	Policy review and agricultural systems analysis	CSA technologies improved climate resilience and productivity	Institutional support is necessary for large-scale adoption
6	Campbell et al. (2022)	To assess climate change impacts on agricultural systems	Global	Climate and agricultural impact modelling	Climate variability significantly reduces agricultural productivity	Adaptation strategies are necessary to sustain food systems
Sn	Author(s) & Year	Objective of Study	Study Area	Methodology	Key Findings	Implications

7	Rosenstock et al. (2022)	To evaluate climate-smart agricultural practices and resilience outcomes	Africa, Asia and Latin America	Systematic review of CSA projects	CSA practices improved resource efficiency and climate resilience	CSA is a viable pathway for sustainable agricultural development
8	Sileshi et al. (2022)	To investigate pest regulation in agroforestry systems	Sub-Saharan Africa	Ecological field experiments	Agroforestry increased populations of natural pest predators	Biodiversity-based pest suppression is effective
9	FAO (2022)	To assess global fisheries and aquaculture sustainability	Global	Global fisheries and aquaculture assessment	Climate-smart aquaculture improves environmental sustainability	Sustainable aquaculture contributes to food security
10	Troell et al. (2023)	To evaluate ecosystem-based aquaculture management	Global aquaculture systems	Ecosystem-based aquaculture analysis	Biosecurity and ecological management reduced fish disease outbreaks	Climate-smart aquaculture enhances productivity
11	Bogale et al. (2023)	To analyze agroforestry adaptation to climate change	Ethiopia	Field experiments and farmer surveys	Agroforestry improved soil fertility and climate resilience	Agroforestry supports climate-smart agriculture
12	Pretty et al. (2024)	To assess the role of ecological farming practices in climate adaptation	Global	Meta-analysis of ecological farming systems	Ecological pest management improved resilience and reduced chemical use	Ecological agriculture enhances sustainability
13	Dinesh et al. (2024)	To examine digital tools for climate-smart pest monitoring	Developing countries	Digital agriculture technology assessment	Early warning systems improved pest detection and management	Digital technologies strengthen adaptive capacity
14	Campbell & Thornton (2025)	To assess adaptation strategies in climate-smart agriculture	Global South	Policy and systems analysis	Climate-smart farming improved resilience to climate shocks	Strong policies are required to scale CSA practices
15	Rosenstock et al. (2026)	To evaluate long-term impacts of climate-smart agriculture	Global	Longitudinal evaluation of CSA programs	CSA significantly improved productivity, resilience and environmental sustainability	CSA remains a critical pathway for climate-resilient food system

6.0: CHALLENGES, LIMITATIONS, AND FUTURE DIRECTIONS
6.1: Persistent Barriers to Adoption

Despite demonstrated efficacy, significant barriers impede the widespread adoption of climate-smart pest and resource management strategies. Economic constraints affect both smallholders unable to afford initial investments and industrial operators facing transition costs. Technical complexity requires substantial training and ongoing support, particularly for systems like biofloc technology where management errors can lead to catastrophic failures. Regulatory frameworks often lag behind innovation, creating uncertainty regarding the approval of biological control agents, probiotics, and phage therapies. Strain specificity in probiotic applications complicates standardization, while the potential for non-target effects of introduced biological control agents demands careful risk assessment.

6.2: Research Priorities

Several critical knowledge gaps require attention to enhance the efficacy and scalability of climate-smart strategies. The anti-inflammatory mechanisms of probiotics remain understudied despite their potential significance for managing climate stress. Long-term ecological impacts of widespread biological control agent release require comprehensive assessment, particularly regarding effects on non-target organisms and ecosystem dynamics. The development of climate-resilient probiotic formulations capable of maintaining viability under temperature extremes represents a pressing technical challenge. Similarly, genetic improvement of tree species for agroforestry selecting for drought tolerance, pest resistance, and high carbon sequestration rates requires sustained breeding efforts.

6.3: Policy and Institutional Needs

Realizing the potential of climate-smart pest management requires supportive policy environments that encourages sustainable practices while discouraging chemical dependency. Carbon pricing mechanisms could reward agroforestry systems for their sequestration services, while regulatory streamlining could accelerate the approval of biological alternatives to antibiotics and pesticides. Institutional innovations such as farmer networks, cooperative extension services, and public-private partnerships are essential for scaling successful interventions. The integration of traditional ecological knowledge with scientific research can enhance the cultural appropriateness and effectiveness of climate-smart strategies, particularly in indigenous and smallholder communities.

7.0: Conclusion: Toward Resilient Food Systems

This review has examined the evolving landscape of climate-smart pest and resource management strategies within agroforestry and aquaculture systems in the context of increasing climate variability and environmental degradation. The synthesis of current literature demonstrates that climate change is reshaping pest dynamics, altering ecological interactions, and intensifying pressure on agricultural and aquatic production systems. Consequently, conventional pest management practices that rely heavily on synthetic chemicals and reactive control measures are increasingly inadequate for addressing the complex challenges posed by climate change. In contrast, climate-smart pest and resource management strategies offer a more holistic and sustainable approach by integrating ecological principles, adaptive management practices, and technological innovations.

The evidence reviewed clearly indicates that biodiversity-based pest suppression, integrated pest management, ecosystem-based aquaculture, and precision monitoring technologies significantly enhance

the resilience and sustainability of food production systems. Agroforestry systems, through the deliberate integration of trees and crops, create diversified ecological environments that promote natural pest regulation, improve soil fertility, and contribute to carbon sequestration. Similarly, climate-smart aquaculture systems that emphasize improved water management, biosecurity measures, and probiotic-based disease control provide effective alternatives to antibiotic-dependent production systems. These innovations demonstrate that sustainable productivity can be achieved while simultaneously preserving ecological integrity and strengthening the adaptive capacity of agricultural systems. A critical insight emerging from this review is that the effectiveness of climate-smart pest and resource management strategies lies in their ability to harness ecological processes rather than rely solely on external chemical inputs. By enhancing biodiversity, improving ecosystem services, and strengthening natural regulatory mechanisms, climate-smart systems create more stable and resilient production environments capable of adapting to climate-induced disturbances. Furthermore, technological advancements such as remote sensing, digital pest surveillance systems, and climate forecasting tools are increasingly enabling farmers and aquaculture producers to respond proactively to pest outbreaks and environmental stressors.

Despite these promising developments, the widespread adoption and scaling of climate-smart pest and resource management practices remain constrained by several structural and institutional challenges. Limited access to technical knowledge, inadequate extension services, financial constraints, and weak policy support continue to hinder the implementation of sustainable agricultural innovations, particularly in developing countries where vulnerability to climate change is highest. Additionally, the integration of climate-smart strategies into national agricultural development frameworks remains uneven across regions, highlighting the need for stronger institutional coordination and policy alignment.

Addressing these challenges requires a coordinated and multidisciplinary approach that bridges the gap between scientific research, policy formulation, and practical implementation. Governments, research institutions, development agencies, and farming communities must work collaboratively to strengthen climate-smart agricultural innovation systems. This includes increasing investment in climate-resilient agricultural research, expanding farmer training and extension programs, promoting knowledge exchange platforms, and developing supportive policy environments that encourage the adoption of sustainable pest and resource management practices.

Ultimately, the long-term sustainability of global food systems will depend on the capacity of agricultural and aquaculture systems to adapt to increasingly unpredictable climatic conditions while maintaining ecological balance and resource efficiency. Climate-smart pest and resource management strategies provide a promising framework for achieving this goal by aligning agricultural productivity with environmental sustainability and climate resilience. However, realizing the full potential of these strategies requires sustained commitment to innovation, inclusive governance, and the recognition that pest and resource management are fundamentally ecological processes that must be managed through adaptive and integrated approaches.

Strengthening research, policy support, and institutional capacity will be very essential to ensure that climate-smart agricultural systems contribute meaningfully to global food security, environmental sustainability, and climate change adaptation.

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