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CLIMATE RESILIENCE IN COCONUT FARMING SYSTEMS: A SYSTEMATIC REVIEW AND BIBLIOMETRIC ANALYSIS OF VULNERABILITY AND ADAPTATION

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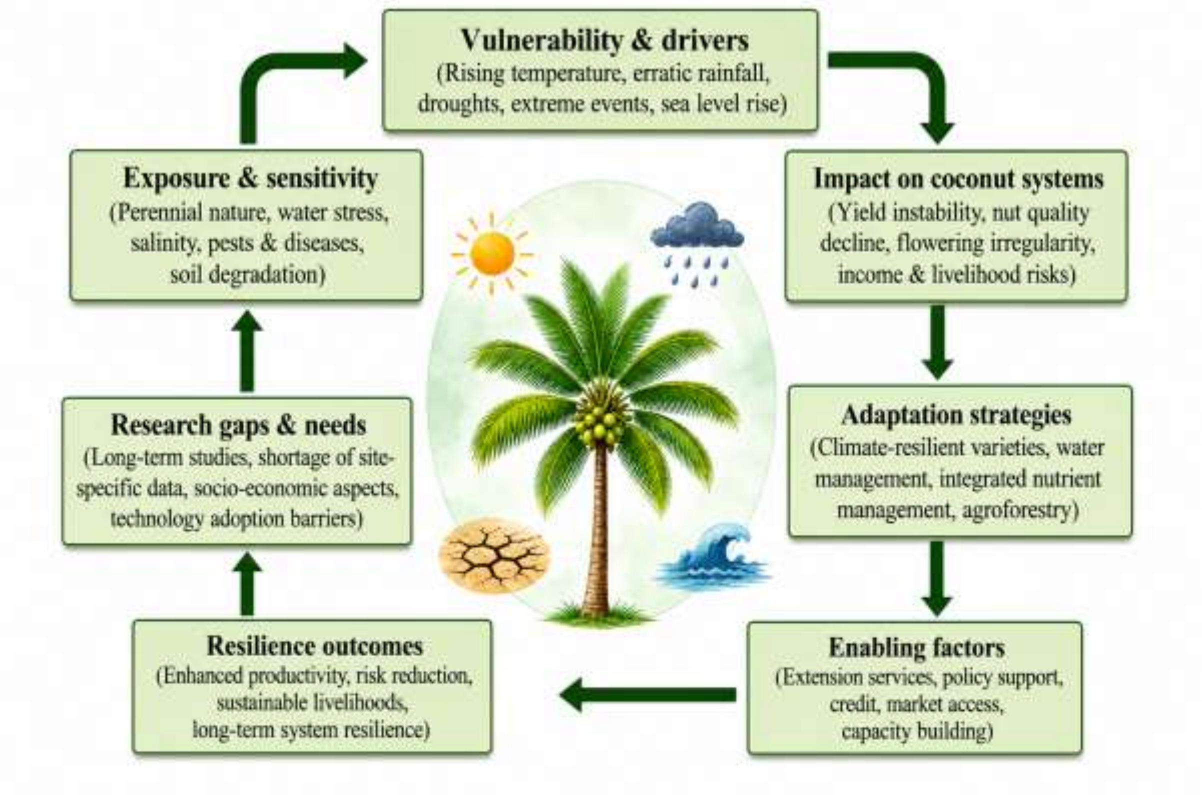

Highlights

- Coconut systems remain underrepresented in climate resilience research.
- Climate stress affects long-term productivity and stability in coconut farming.
- Agroforestry and climate-smart practices strengthen adaptive capacity.
- Long-term resilience frameworks are essential for perennial agriculture.

ABSTRACT

Climate change increasingly threatens coconut farming systems through rising temperatures, rainfall variability, prolonged droughts, and extreme climatic events, particularly in tropical regions dependent on coconut-based livelihoods. Perennial systems like coconuts are still underrepresented in adaptation research, which is dominated by annual cropping systems, despite growing interest in climate-resilient agriculture. Using an integrated bibliometric analysis and systematic literature synthesis, this study looked at research trends, resilience issues, and adaptation routes pertaining to coconut agricultural systems under climate change. Bibliometrix and VOSviewer were used to retrieve and analyze peer-reviewed articles published between 2016 and 2025. The results demonstrated that the majority of current resilience research focuses on short-term productivity-oriented adaptation, with little attention paid to perennial plantation systems' long-term vulnerability. Water stress, delayed climatic reactions, unstable productivity, and institutional limitations were the main issues found in coconut cultivation. Agroforestry integration, climate-resilient agronomic techniques, better water management, and genetic improvement techniques were important adaptation paths. In order to promote sustainable adaptation planning in tropical agriculture, the review emphasizes the need for long-term resilience frameworks that more accurately represent the ecological and socioeconomic dynamics of coconut-based farming systems.

KEYWORDS: coconut farming systems; climate resilience; climate change adaptation; perennial agriculture; agroforestry

1. INTRODUCTION

Climate change has become a significant threat to the sustainability of agriculture, especially in tropical areas where farming systems are highly dependent on climatic stability (IPCC, 2022). The productivity of crops, the availability of water, and the security of livelihoods are all being impacted by rising temperatures, shifting rainfall patterns, and the increasing frequency of severe weather occurrences in at-risk agricultural regions (Thornton et al., 2014). Although these effects are evident across many cropping systems, perennial agriculture faces unique dangers due to the accumulation of climate exposure throughout lengthy production cycles and the gradual recovery from climate stress.

One of the most important perennial plantation crops grown in tropical areas of Asia, Africa, and the Pacific is coconut, which provides millions of smallholder farmers with a means of subsistence (Adkins et al., 2006). Additionally, coconut-based farming systems make a significant contribution to rural employment, food security, and diverse livelihood options in tropical agricultural economies. Coconut plantations are frequently integrated with mixed cropping and agroforestry systems in many coconut-growing areas, with coconut serving as both an economic crop and a stabilizing element in climate-sensitive agricultural landscapes. Coconut is especially helpful for comprehending resilience dynamics in tropical plantation agriculture because of its perennial structure, extended productive life, and reliance on long-term climate stability. In contrast to annual crops, coconut palms are slower to respond to climate stress and need a long-term investment, which makes adaptation more difficult in a changing environment (Kumar, 2013). Productivity loss, physiological stress, and long-term instability in coconut-based agricultural systems have been increasingly linked to rainfall variability, heat stress, and drought.

In the last ten years, research on climate resilience and adaptation in agriculture has increased significantly, with more emphasis on climate-smart practices, adaptive capacity, and resilience-oriented interventions (Altieri et al., 2015; Partey et al., 2018; Tendall et al., 2015). However, the majority of this study continues to be focused on annual and short-cycle production systems (Gunathilaka et al., 2018). Thus, despite its ecological, economic, and livelihood value, perennial systems like coconut continue to be relatively under investigated in larger discussions on climate resilience.

With little synthesis of how resilience problems and adaptation routes are developing within coconut-based farming systems, existing studies on coconut and climate change are frequently distributed across agronomic, physiological, and adaptation-focused domains. In order to enhance long-term adaptation planning and better represent perennial agriculture in climate resilience research to address this gap, this review aims to

(i) Analyse research trends on climate resilience in coconut farming systems
(ii) Synthesize climate vulnerabilities and adaptation pathways and
(iii) Identify future research and policy priorities for building long-term resilience.

2. MATERIALS AND METHODS

2.1 Structure of the Review

This study integrated a systematic literature review and bibliometric analysis to examine research trends, resilience challenges, and adaptation pathways in coconut farming systems under climate change. Bibliometric analysis was employed to explore thematic patterns, research trends, and knowledge structures within climate resilience literature relevant to perennial agricultural systems (Aria & Cuccurullo, 2017). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency and consistency in the study selection process (Page et al., 2021). Bibliographic data were retrieved from the Scopus database as it provides comprehensive coverage of peer-reviewed agricultural literature and included articles published in English between 2016 and 2025. The study selection process is illustrated in Figure 1.

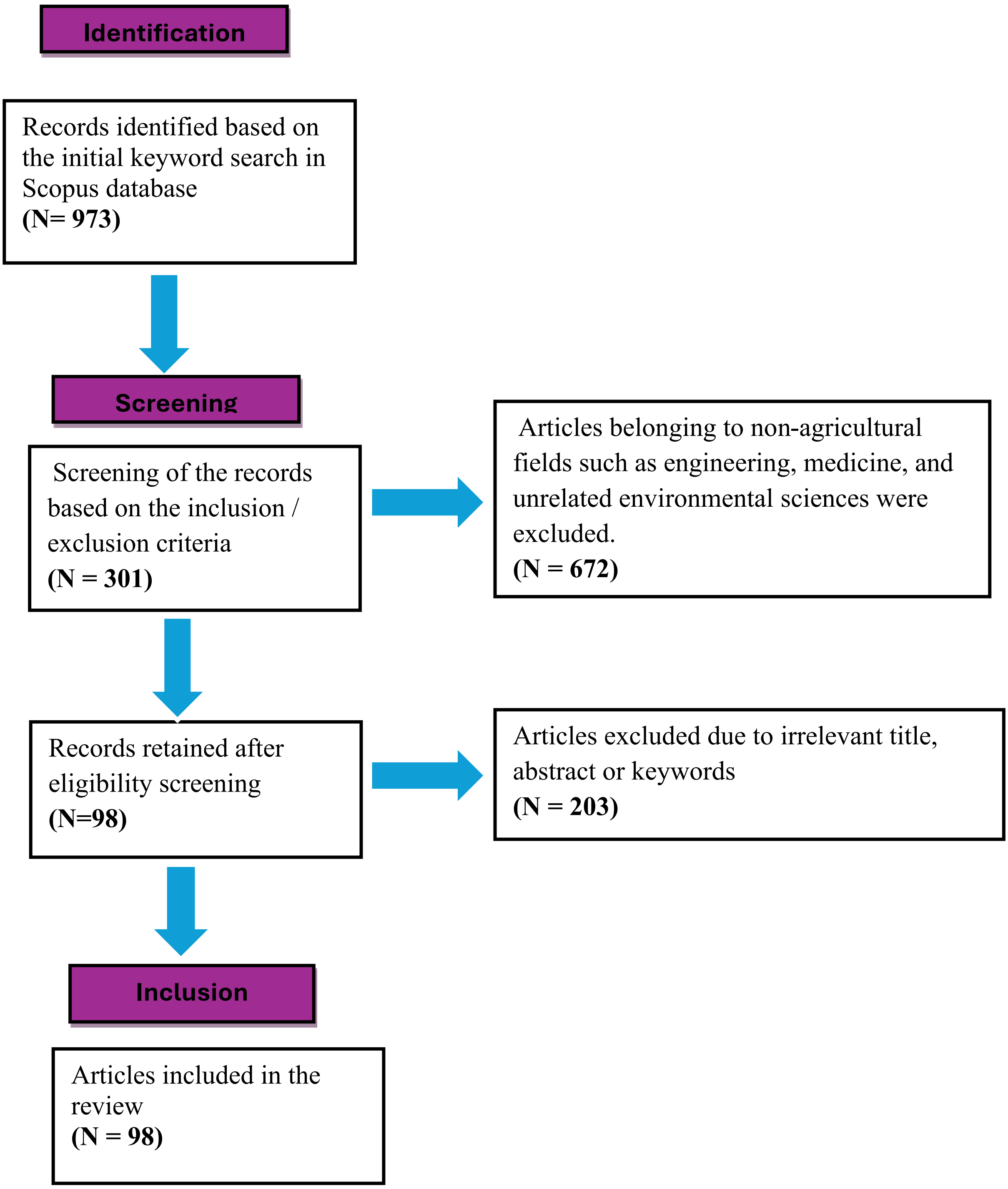

Figure 1. PRISMA flow diagram illustrating the study selection process

2.2 Search Strategy

Following the PRISMA framework, a comprehensive literature search was conducted to identify studies related to climate resilience, adaptation, and coconut farming systems. The search string applied was: ("climate resilience" OR "climate adaptation" OR "climate-smart agriculture") AND ("perennial" OR "plantation" OR "coconut"). The search was limited to peer-reviewed journal articles published in English between 2016 and 2025. The initial search yielded **973** records. After excluding **672** records belonging to non-agricultural subject areas, including engineering, medicine, and unrelated environmental sciences, **301** records were retained for screening. These records were further refined using predefined inclusion criteria based on document type (research articles) and source type (journals). Following title and abstract screening for relevance to climate resilience and perennial farming systems, **203** records were excluded, resulting in a final dataset of **98** studies for bibliometric analysis and qualitative synthesis, as illustrated in Figure 1.

Table 1. Combination of keywords used and the total number of publications from database

Database	**Search terms**	**Number of articles**

Scopus	("Climate resilience" OR "Climate adaptation" OR "Climate smart agriculture") AND ("Perennial" OR "Plantation" OR "Coconut")	973

Table 2. Inclusion and Exclusion criteria

Criteria	Inclusion	Exclusion
Time span	2016-2025	< 2016
Document type	Article	Conference papers, Book chapters, Editorial
Languages	English	Non- English
Source type	Journal	Trade journal

2.3 Bibliometric Analysis

Bibliometric analysis was conducted using the R programming environment (RStudio, version 2023.09.1+494) with the Bibliometrix package (version 4.2.1) and VOSviewer (version 1.6.19) to examine publication trends, thematic relationships, and knowledge structures within climate resilience and adaptation literature relevant to coconut farming systems (Aria & Cuccurullo, 2017; Van Eck & Waltman, 2010). Annual scientific production, keyword co-occurrence, thematic mapping, bibliographic coupling, and country-level co-authorship networks were analysed.

3. RESULTS

3.1 Evolution of Research Output over Time

Between 2016 and 2025, the time course of climate resilience and adaptation studies relevant to agricultural systems is depicted in Figure 2. Prior to 2019, the publication output remained comparatively restricted, reflecting the nascent and fragmented state of research in this field. Since 2020, there has been a significant rise in scientific output, indicating increased global focus on sustainable agricultural practices, climate adaptation, and resilience-oriented agricultural methods. The noticeable increase in publications throughout 2023 also points to a growing integration of climate resilience research into mainstream agricultural discourse. It's more likely that the minor drop seen in the most recent year is related to indexing delays than to a drop in research output. Overall, the trend emphasizes the increasing focus on agriculture research that is centered around adaptation and also illustrates the rising importance of climate resilience research.

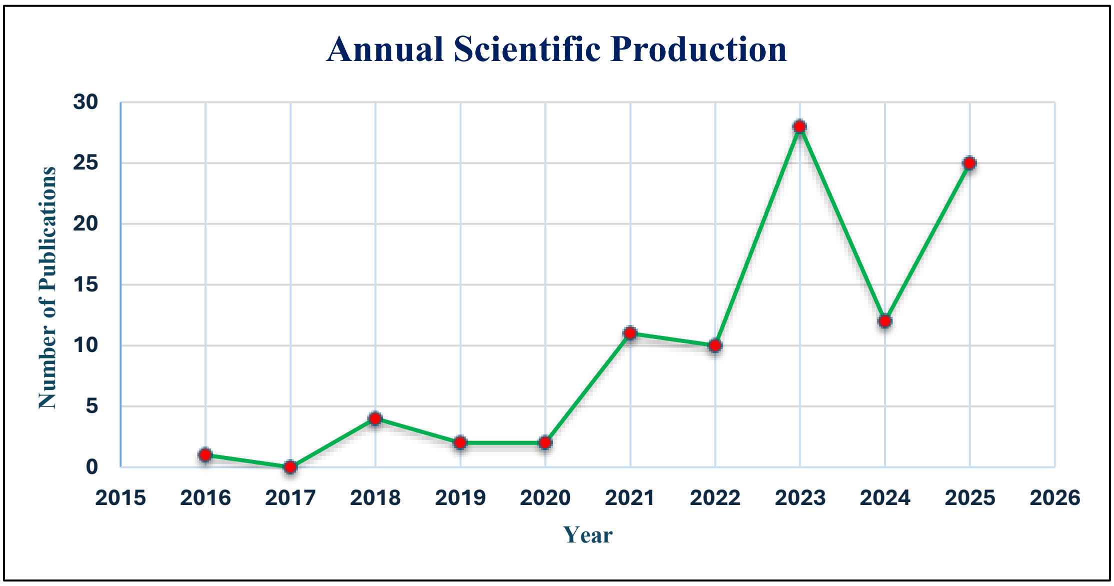

Figure 2. Annual Scientific Production

3.2 Keyword co-occurrence

The emphasis on adaptation-oriented concepts and resilience-building techniques in climate resilience research in agricultural systems is evident in the keyword co-occurrence structure presented in Figure 3. Common phrases

like climate-smart agriculture, adaptation, resilience, and climate change adaptation highlight the primary emphasis on climate risk management via adaptive agricultural approaches.
The network contained a number of linked thematic groupings. Important keywords such as adoption, perception, barriers, and smallholder farmers made up a significant group related to farmer decision-making and adaptation behavior, underscoring the relevance of socioeconomic and institutional aspects in climate adaptation research. Additional groupings were defined by practical methods like agroforestry, irrigation, and crop diversification, which are all strongly associated with increasing productivity stability and resilience. The expanding scope of resilience research beyond only agronomic results is further demonstrated by the links between concepts related to food security, adaptive capacity, livelihood resilience, and tradeoffs.

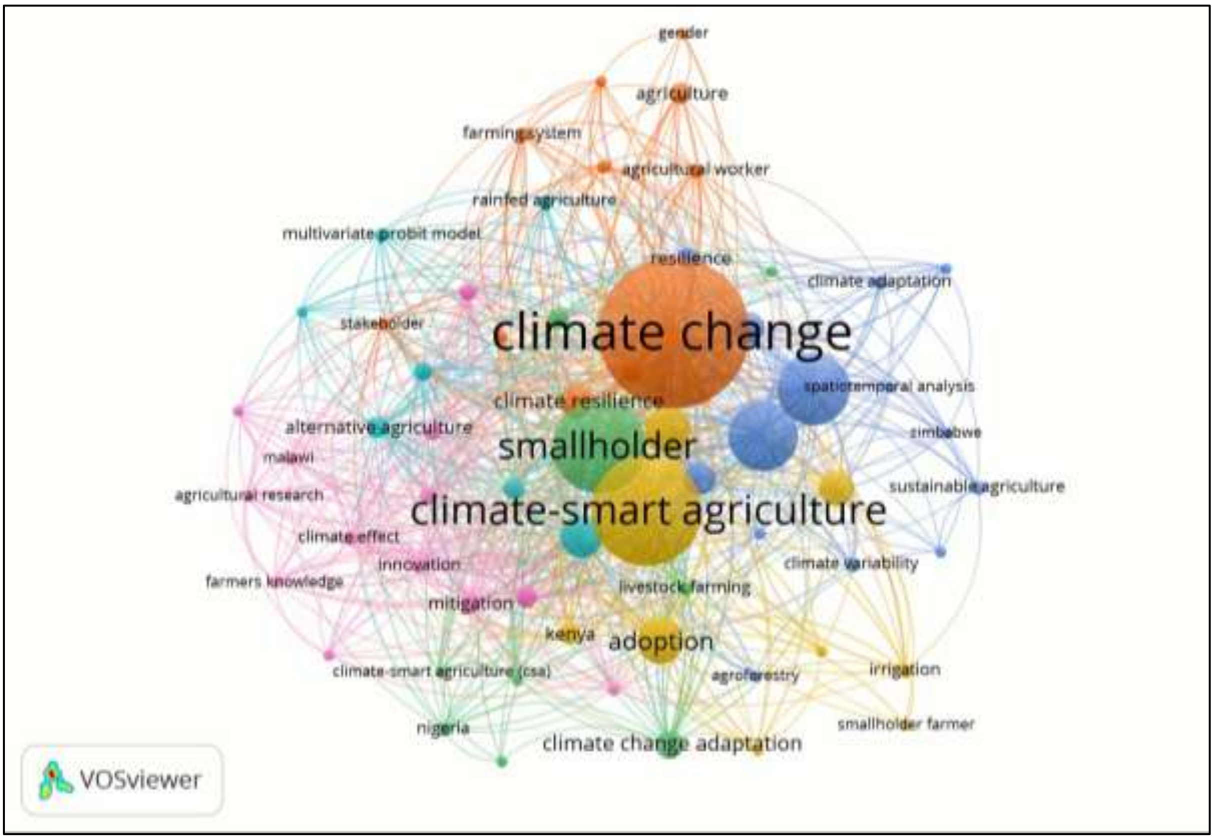

Figure 3. Keyword Co-occurrence Network

3.3 Thematic Map

The distribution of key research topics in the literature on climate resilience and adaptation is shown in Figure 4, which is based on thematic centrality and density. Food security, climate adaptation, and adaptive management all of which pointed to a high degree of research integration between resilience-building and agricultural sustainability were found to be well-developed and significant themes. These themes mostly echo the emphasis on enhancing adaptive capacity and lowering climate-related production risks in agricultural systems. The essential themes quadrant included key concepts like climate-smart agriculture, adoption, and smallholder farmers, emphasizing their crucial role in determining the larger research framework. The prevalence of these topics suggests continued research focus on climate-responsive agricultural interventions, farmer adaptation behavior, and resilience practices.
The niche themes quadrant included themes pertaining to agricultural extension, climate information services, and agricultural technology. These areas continue to be relatively less connected to the larger body of adaptation literature, even though they have analytical relevance in particular situations. New and underdeveloped themes included farmer perception, livelihood resilience, and long-term adaptation, implying that, despite their significance in comprehending climate vulnerability and adaptive responses in agricultural systems, these topics continue to get comparatively little research attention.

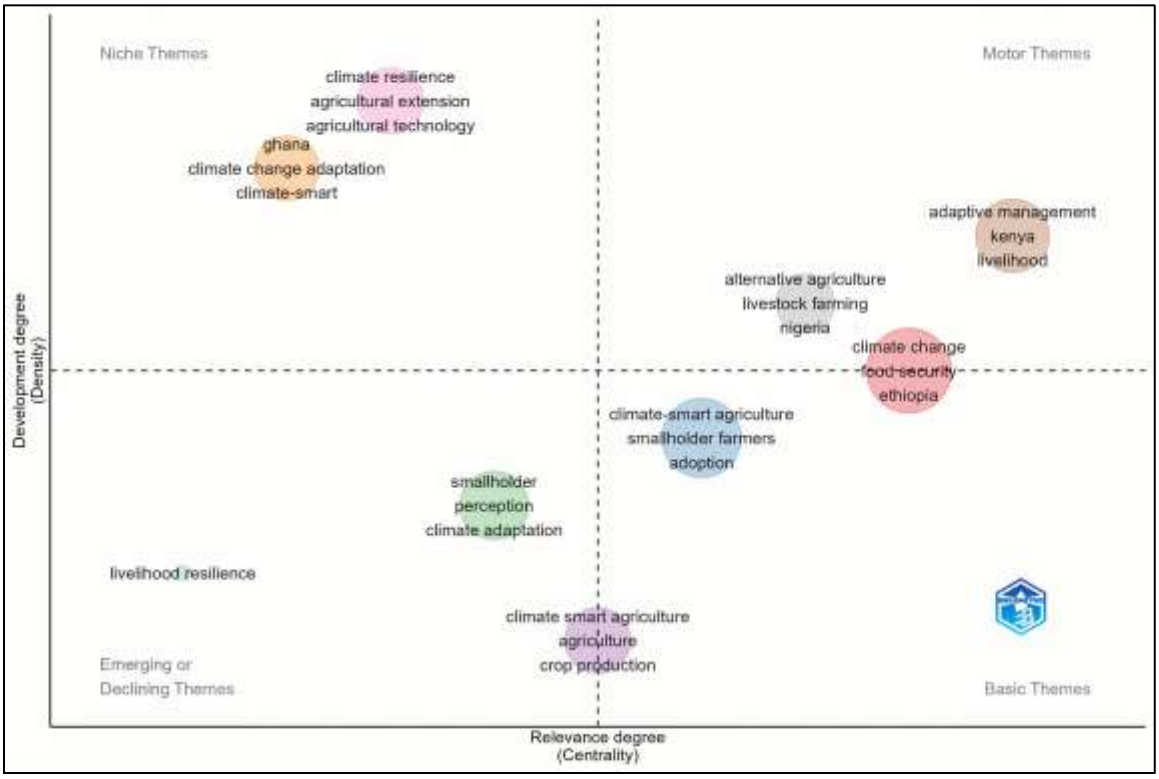

Figure 4. Thematic Map

3.4 Most Relevant Sources

The top publication sources in climate resilience and agricultural adaptation research are shown in Figure 5. The journal Sustainability (Switzerland) had the second-highest number of articles (10), behind Frontiers in Sustainable Food Systems, which had the most (19). Six publications from each of Cogent Food and Agriculture and Climate Risk Management made up the dataset. The interdisciplinary character of climate resilience research is reflected in the concentration of publications in journals devoted to sustainability, agriculture, and the environment. The growing integration of adaptation, livelihood resilience, and sustainable development perspectives in agricultural research is also evident in the existence of journals like World Development Sustainability, International Journal of Agricultural Sustainability and Regional Sustainability. In general, the source distribution reflects the increasing academic focus on resilient-oriented methods for managing climate risk and sustainable agricultural systems.

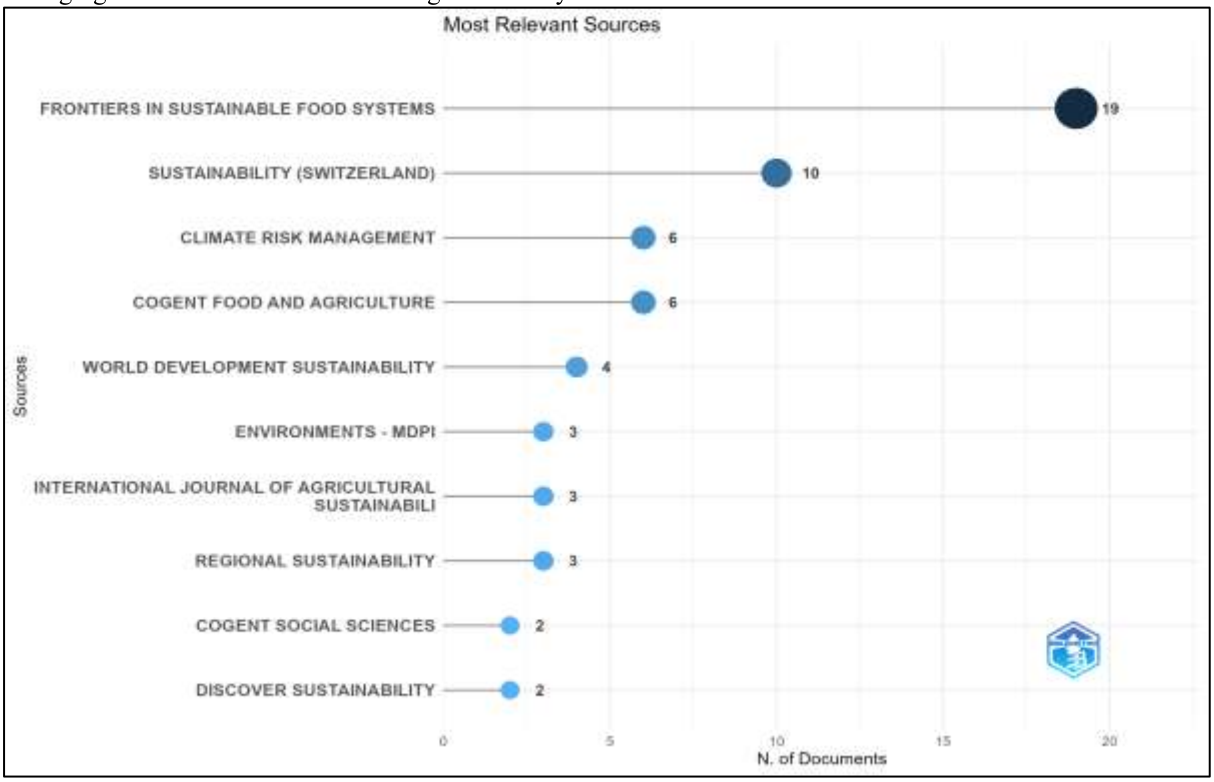

Figure 5. Most Relevant Sources

3.5 Country-Level Co-authorship Network

The geographic distribution and collaborative framework of study on climate resilience and agricultural adaptation are shown in the co-authorship network at the national level. Regions most at risk from climate change, notably Sub-Saharan Africa, have seen a disproportionate amount of research due to the prevalence of smallholder farming systems that are sensitive to the climate. Because of their important contribution to study results related to adaptation and resilience, nations like Ethiopia, Kenya, Ghana, and South Africa became key hubs for cooperation within the network.

The increasing significance of international research partnerships in promoting climate adaptation research is demonstrated by the strong collaborative connections between African nations and European and North American organizations. These partnerships have aided in the development of comparative studies, methods, and the widespread promotion of resilient agricultural frameworks throughout various areas. Conversely, areas where plantation and perennial cropping systems prevailed seemed comparatively less integrated into the larger collaborative network. Despite the representation of nations like India and Sri Lanka, their comparatively poor connectedness points to a lesser integration of research on plantation-oriented adaptation inside current international collaboration structures. The bibliometric data supports the necessity for a specific synthesis on coconut-based agricultural systems by showing that perennial plantation systems continue to be underrepresented in overall climate adaptation studies.

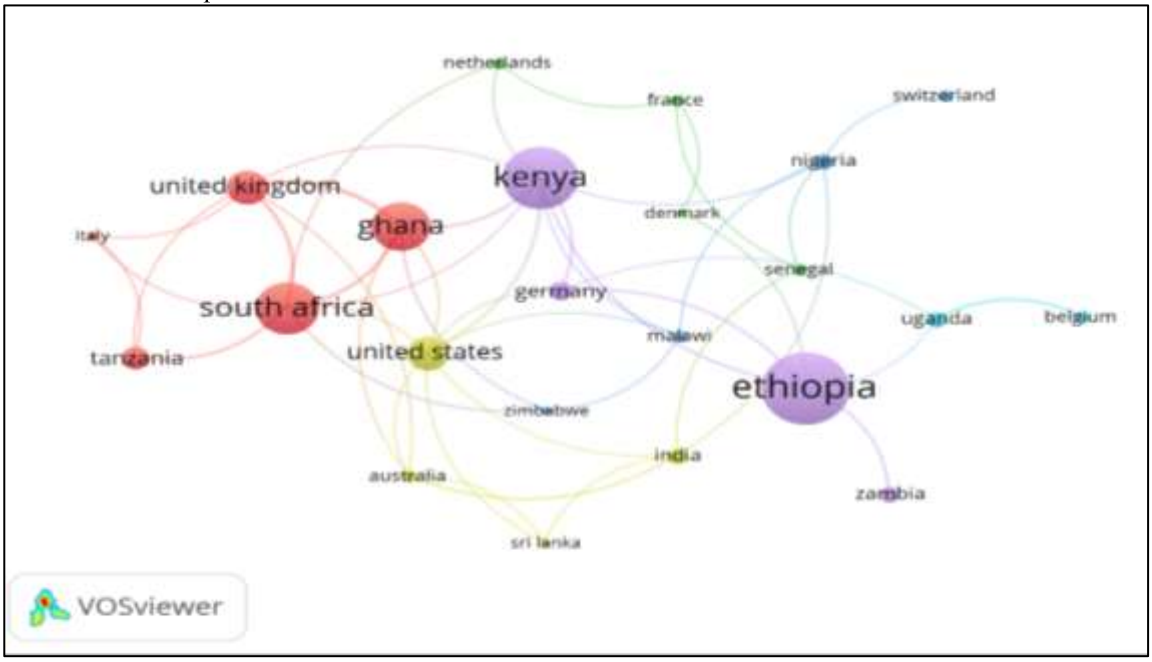

Figure 6. Country- Level Co- authorship Network

4. DISCUSSION

4.1 Climate Vulnerability and Resilience Dynamics in Coconut Farming Systems

In tropical areas, coconut farming systems are becoming more and more susceptible to erratic production conditions as shifting rainfall patterns and increasing temperatures upset the environmental equilibrium needed for consistent palm development (IPCC, 2022). Plantations in many coconut-producing regions continue to rely heavily on seasonal rainfall, which makes them especially susceptible to extended droughts, erratic rainfall patterns, and rising atmospheric moisture needs (Hebbar et al., 2022). Prolonged rainfed conditions can cause moisture stress during susceptible reproductive stages, which can result in a decline in female flower production, an increase in immature nut shedding, and a lower final nut set (Naresh Kumar et al., 2013; Hebbar et al., 2020). The long-term nature of coconut plantations restricts the options for quick adaptation in the face of repeated climate disruptions by means of crop substitution or significant infrastructural changes (Kumar, 2013).

As a result, climate-related stress in coconut farms is manifested less through abrupt crop failure than through a steady decline in plantation output over many production cycles. Irregular moisture availability has an impact on linked processes such as soil-water balance, canopy activity, nutrient uptake, and reproductive development, which results in inconsistent bunch production and variable harvest yield over time (Hebbar et al., 2013). Due to the fact that reproductive responses frequently appear months after the initial stress exposure, the delayed manifestation of climatic stress in coconut makes plantation management even more difficult (Carr, 2011). Coconut palms have continuous inflorescence initiation, flower differentiation, and nut formation throughout the year, hence drought or heat stress experienced at one developmental stage can affect yield expression months later (Ranasinghe, 2013). These impacts are especially noticeable in smallholder coconut environments, where consistent nut production throughout the year continues to be strongly associated to household income and livelihood continuity (Adkins et al., 2006). The adaptive flexibility of resource-constrained coconut growers during prolonged climatic stress periods is frequently diminished by aging plantations, fragmented landholdings, and restricted irrigation access (Gunathilaka et al., 2018).

In such circumstances, the capacity of coconut landscapes to buffer environmental stress is more crucial for sustaining plantation productivity in the face of repeated climatic pressures. Mitigating exposure to rainfall irregularity and prolonged dry periods is aided by soil-moisture retention, diverse cropping patterns, and ecologically regulated plantation environments (Kumar & Kunhamu, 2022). Mixed farming systems based on coconuts and agroforestry systems that include crops like cocoa, bananas, pineapples, spices, and fodder species have been linked to better microclimate regulation, improved soil moisture retention, and increased economic stability in a variety of climatic circumstances (Dissanayaka et al., 2023). Increased ecological buffering and enhanced adaptive stability in the face of climate change have also been linked to varied perennial systems (Altieri et al., 2015). Nonetheless, the efficacy of diversification strategies can differ depending on rainfall distribution, soil quality, plantation density, and farm management skills, suggesting that adaptation results continue to be highly context-specific throughout coconut-growing areas. Consequently, in coconut-based systems, resilience is reflected less in the ability of plantations to recover quickly after stress than in their capacity to maintain reproductive output and livelihood stability despite recurrent climatic disruptions (Tendall et al., 2015).

4.2 Physiological and Productivity Responses of Coconut Under Climate Stress

Climate-related declines in coconut production are mostly caused by disruptions in the physiological and reproductive mechanisms that govern the palm's long-term performance in tropical environments (Birthal et al., 2014). Because coconut palms have continuous flower initiation and overlapping developmental phases year-round, changes in water availability and temperature can affect several growth processes at the same time. Rather than resulting in an immediate visible decrease, erratic weather conditions gradually impair the photosynthetic efficiency, assimilate distribution, and canopy function, which leads to a gradual weakening of bunch development and nut production across successive harvest cycles (Lobell et al., 2006). Thermal and moisture stress can impair carbohydrate partitioning, according to physiological studies. Under variable climate conditions, these changes lessen the buildup of dry matter in growing reproductive structures and impair the formation of bunches over the long term (Naresh Kumar et al., 2013).

Moisture deficit is one of the primary environmental limitations that has a disproportionately significant impact on the metabolism and reproductive output of palms. Decreasing soil water availability limits transpiration and stomatal conductance, which lowers carbon fixation and reduces the amount of assimilates available for vegetative and reproductive development (Nainanayake & Morison, 2007). The capacity of palms to endure protracted soil moisture deficiency under rainfed conditions is further impacted by the diversity in water extraction efficiency, stomatal control, and root distribution across coconut genotypes (Arumugam & Hatta, 2022). When palms are exposed to extended periods of dryness, they prioritize survival maintenance over active growth, leading to decreased nut retention and lower blooming intensity. Higher temperatures exacerbate the demand for evapotranspiration, which exacerbates the moisture imbalance in the root zone and exacerbates the effects of stress in rain-dependent production systems (Rivero et al., 2022). In addition, continuous exposure to high temperatures may reduce the effectiveness of physiological recovery in perennial palms following extended climatic stress by increasing respiratory losses and compromising cellular stability (Yang et al., 2018).

Additionally, changes in temperature can impact reproductive efficiency during crucial periods of flower and pollen development. Excessive heat exposure can lower pollen viability, impair fertilization success, and promote early nut shedding, all of which can lead to erratic bunch production and variable harvest production (Akter et al., 2025). Furthermore, experimental data indicates that reproductive functions, like pollen tube growth and pollen germination, are very temperature sensitive, which might lead to more reproductive instability in future warming scenarios (Kumarathunge et al., 2024). Because the reproductive stages of coconut trees overlap continuously, stress exposure during one developmental period may affect yield expression months later. This temporal disconnect between the onset of stress and the response of the harvest makes it difficult to understand how climate change affects coconut plantations and partially accounts for the inconsistent yield behavior frequently seen under changing climate circumstances (Ray et al., 2015).

The physiological consequences of climatic stress in coconut, therefore, gradually build up via repeated disruptions in water relations, assimilate allocation, and reproductive development. As a result, the progressive deterioration of biological mechanisms that govern sustained palm productivity under changing tropical conditions has a greater impact on yield instability in coconut farms than individual climatic occurrences (Lesk et al., 2016).

4.3 Agronomic and Ecological Adaptation Pathways in Coconut-Based Systems

In coconut farms, management strategies for dealing with climate stress are becoming more dependent on practices that improve ecological buffering inside the production environment, rather than just relying on outside inputs (Partey et al., 2018). The ability of plantations to control moisture, preserve soil quality, and mitigate microclimatic changes is essential for maintaining production output under changing climatic circumstances since coconut is grown as a long-duration perennial crop. As a result, adaptation in coconut-based systems is gradually moving towards integrated plantation management techniques that improve resource retention and lessen exposure to recurrent environmental stress (Gunathilaka et al., 2018). Increasingly, integrated coconut farming systems that combine livestock, intercrops, organic recycling, and soil-moisture conservation strategies have been promoted as climate-smart methods for enhancing resource utilization efficiency and maintaining farm income in the face of climate change (Sudha et al., 2021).

In enhancing the adaptive behavior of coconut environments, varied manufacturing structures have become especially crucial. Farmers can spread climatic and financial risk among several crop components by using agroforestry systems and intercropping to enhance structural and functional variety within plantations (Lin, 2011). Coconut-based mixed systems, which include cocoa, spices, fodder crops, or fruit trees, increase land-use efficiency while also improving root-zone moisture retention, nutrient recycling, and understory coverage (Kumar & Kunhamu, 2022). Coconut farming with an agroforestry focus has also been identified as a natural climate adaptation approach that can enhance biodiversity protection, moderate plantation microclimates, and boost ecological resilience in tropical agricultural environments (Atapattu & Udumann, 2024).

These interactions lessen the severity of soil moisture loss during extended dry spells and aid in the improved regulation of plantation microclimates. Furthermore, diversification offers additional income streams that help protect small farmers against changes in coconut yields caused by erratic climate patterns (Birthal et al., 2019). In addition to promoting long-term environmental sustainability, cover cropping and multi-story cropping techniques in coconut plantations have also been linked to better soil fertility, less erosion risk, and increased biological activity in plantation ecosystems (Dissanayaka et al., 2022).

In rainfed coconut-growing environments, water management continues to be just as crucial for maintaining plantation productivity. Drip irrigation, basin management, mulching, and organic material incorporation are some of the strategies that enhance soil-water conservation and alleviate moisture stress during prolonged dry periods (Carr, 2011). Solar-powered irrigation systems and low-input water management techniques have also recently gained attention. These technologies are designed to increase irrigation efficiency and lessen long-term reliance on erratic rainfall patterns in perennial agricultural systems (Hebsale Mallappa& Bansal, 2026). Nevertheless, the efficacy of these strategies is significantly impacted by local soil qualities, the age of the plantation, the pattern of rainfall, and the farmers' financial ability to support an input-intensive management approach over time. Even when similar management practices are used, this results in significant differences in adaptation results between coconut-producing areas (Mihrete et al., 2025). Despite their ecological benefits, the long-term continuity of adaptation techniques in many smallholder coconut systems is further hampered by labor shortages, growing maintenance expenses, and a lack of technical assistance (Omar et al., 2023).

As a result, adaptation in coconut systems relies more on the combined ability of plantations to maintain productive function while simultaneously conserving moisture, controlling microenvironmental factors, and withstanding repeated climate stress than on standalone interventions. Additionally, diversified plantation buildings serve as ecological controllers that mitigate climatic exposure in coconut-growing environments, not only as income-support systems (Vilakazi et al., 2025).

4.4 Genetic Improvement and Breeding Strategies for Climate Adaptation

In the face of increasing thermal and moisture stress, genetic improvement to enhance climate tolerance has grown more and more crucial for maintaining coconut production (Batugal et al., 2009). Due to the lengthy period between planting, reproductive maturity, and yield assessment, selection cycles are significantly slowed, which restricts the rate at which enhanced planting materials may adapt to quickly changing climatic circumstances (Foale, 2003). Because a trustworthy assessment of stress tolerance and yield stability frequently necessitates long-term field observation across several environmental circumstances and production cycles, the coconut's continuous growth habit makes breeding programs even more difficult (Arumugam & Hatta, 2022).

The focus of breeding programs has shifted more and more toward characteristics linked to environmental tolerance and consistent production in stressful situations. Major selection aims for coconut improvement programs have included drought tolerance, water use efficiency, heat tolerance, and reproductive stability (Maskromo et al., 2023). In tropical production settings, where there are extended periods of drought and high temperatures, more research has been focused on finding genotypes that can maintain consistent reproductive performance and physiological activity (Yang et al., 2018). The fact that coconut genotypes exhibit a wide range of stress-response behaviors suggests that the existing germplasm resources contain valuable adaptive diversity that may be exploited (Perera et al., 2018). As a result, hybridization between tall and dwarf cultivars has become an important approach for integrating stress tolerance, early bearing potential, and consistent yield performance across diverse growing conditions (Oropeza et al., 2005). Additionally, hybrid breeding methods have been investigated for enhancing copra quality, nutrient utilization efficiency, and environmental resilience, especially in smallholder coconut systems that are susceptible to climate variability (Arumugam & Hatta, 2022).

The physiological complexity of stress-response traits and their strong interaction with local environmental factors continue to make it difficult to breed coconuts for climate resilience, notwithstanding these advancements. Phenotypic selection is less predictable across tropical production areas since many adaptive traits are polygenic and highly impacted by variations in precipitation, temperature, and soil conditions (Evangelista et al., 2021). The expression of stress-tolerance characteristics sometimes differs between agroecological zones, making it harder to find stable, climate-responsive genotypes that are appropriate for large-scale farming. In coconut improvement, this genotype × environment interaction continues to be a significant problem because palms that grow well in one climatic system may display significantly different physiological and reproductive behavior in a different environment (Perera et al., 2018). Furthermore, the extended reproductive cycle limits the ability of improvement initiatives to react quickly to new climate threats, especially in regions where environmental stress patterns are becoming increasingly erratic and location-specific (Rajesh et al., 2022).

However, recent advances in genomic analysis and molecular breeding have made it possible to increase selection effectiveness in coconut breeding programs. Earlier trait screening and a better understanding of climate-response mechanisms inside coconut germplasm may be facilitated by the discovery of molecular markers and stress-responsive genes linked to water-use regulation, reproductive stability, and drought tolerance (Xiao et al., 2017). Nevertheless, improving the coconut's climate tolerance will ultimately depend on integrating genetic improvement with agronomic management at the plantation level under varied tropical conditions, maintaining a wide genetic variety, and enhancing long-term breeding continuity (Johnson et al., 2020).

4.5 Institutional and Adoption Constraints in Climate Adaptation

The financial and structural constraints of perennial plantation systems have a significant impact on the implementation of climate-responsive methods in coconut cultivation (Thornton et al., 2018). Many adaptation measures, such as irrigation expansion, plantation rehabilitation, soil moisture retention, and diversification strategies, are intended to lessen climate vulnerability, but they frequently need significant long-term investment before their economic advantages are seen. Maintaining such investments in the face of volatile weather and market circumstances remains financially problematic in many smallholder coconut systems, where seasonal nut revenue is a major source of income (Antwi-Agyei & Amanor, 2023). The willingness of small farmers to invest in long-term adaptation strategies that need delayed economic returns has been further diminished by erratic copra prices and lower plantation profitability in many coconut-growing areas (Omar et al., 2023).

In aging plantations and fragmented holdings, where low palm productivity already undermines farm profitability, these problems are exacerbated (Gunathilaka et al., 2018). Newly planted palms often need lengthy immature phases before producing returns, which causes temporary income gaps that many farmers are unable to handle, resulting in frequent replanting delays (Joseph & Joseph, 2016). Consequently, the extended juvenile stage of coconut presents a significant structural obstacle to plantation renewal, especially for resource-constrained farmers who do not have access to credit support or alternative sources of income during the transition. Additionally, increased labor costs and shortages of trained agricultural workers undermine the consistency of plantation upkeep, especially for labor-intensive tasks like irrigation management, soil conservation, and intercrop maintenance (Mthethwa et al., 2022). As a result, farmers frequently implement adaptation strategies slowly rather than engaging in significant plantation change under uncertain economic circumstances (Teklu et al., 2023). Therefore, coconut systems often adapt via incremental management changes as opposed to radical technological shifts, reflecting the long-term financial risk associated with restructuring perennial plantations.

The results of adaptation vary between coconut-growing areas depending on institutional capacity. Farmers who have better access to extension networks, credit facilities, irrigation assistance, and well-organized producer organizations are typically better able to maintain long-term plantation investments during times of climate stress (Partey et al., 2018). As a result, it has become more and more necessary to improve farmer awareness of drought management, replanting techniques, and climate-responsive plantation methods in coconut-growing areas via the strengthening of localized extension services and climate advisory systems (Khatri-Chhetri et al., 2017).

However, many smallholders with limited resources continue to struggle with insufficient technical advice and limited financial assistance for long-term plantation improvement (Waaswa et al., 2024). Studies from Sri Lanka have similarly shown that although coconut growers possess relatively high awareness and perception regarding climate change impacts, the actual adoption of climate adaptation measures remains comparatively low due to financial, informational, and institutional limitations. Limited access to extension services, weather information, and affordable credit has been identified as a major constraint affecting the implementation of long-term adaptation practices among coconut growers in vulnerable regions (Godage et al., 2021). In perennial farming systems, existing agricultural support programs often prioritize short-term productivity gains over plantation aging, replanting vulnerability, and long-term climate risk management (Eriksen et al., 2021). The ongoing disparity between short-term agricultural policy frameworks and the long biological and economic cycles of coconut production continues to impede the creation of sustainable climate adaptation strategies in perennial plantation agriculture.

These circumstances point to the fact that the availability of climate-responsive technology alone does not determine how coconut farming adapts; rather, it also depends on the farmers' economic and institutional ability to sustain plantation continuity in the face of protracted uncertainty. As a result, institutional structures that can mitigate replanting risks, enhance the long-term viability of farms, and facilitate a phased plantation shift in the face of increasingly volatile climatic circumstances are necessary to bolster resilience in coconut-growing areas (Juhola et al., 2016). Many smallholder producers may continue to be unable to carry out the gradual restructuring necessary for long-term climate adaptation without ongoing institutional and financial backing.

4.6 Reframing Climate Resilience for Perennial Coconut Systems

The methods currently used to assess climate resilience in agriculture are mostly based on yearly cropping systems, in which production responses, management adjustments, and recovery processes can be seen over comparatively short agricultural cycles (Tendall et al., 2015). As a result, resilience assessments often concentrate on seasonal productivity, quick recovery following disruptions, and short-term adaptation results. When climatic disruptions interact with biological, ecological, and reproductive processes over lengthy developmental periods, as is the case with perennial plantation crops like coconut, such frameworks are less effective (Suweis et al., 2015). The long interval between stress exposure, reproductive response, and observable yield decline in coconut systems makes it even harder to interpret resilience since plantation performance frequently mirrors cumulative climatic impacts that accumulate over several production cycles.

Climatic stress in coconut farms is more often manifested through slow decreases in reproductive performance, palm vigor, soil quality, and harvest consistency rather than abrupt production decline (Ray et al., 2015). Since underlying physiological stress and ecological degradation may continue to build up over successive production cycles, the short-term maintenance of yield cannot always be seen as evidence of resilience in these circumstances (Lin, 2011). As a result, coconut palms may continue to yield harvestable harvests even as moisture stress increases and physiological efficiency declines, perhaps concealing a long-term vulnerability within plantation systems. Thus, evaluation methodologies that place an excessive emphasis on short-term production responses may fail to adequately account for the long-term climatic exposure that impacts perennial plantation systems (Thornton et al., 2014).

According to coconut-based systems' behavior, resilience in perennial agriculture is more closely linked to the ability to maintain plantation operations under repeated environmental disruption than to a quick response to specific climatic catastrophes (Vermeulen et al., 2012). The capacity of coconut landscapes to sustain reproductive stability under changing hydroclimatic circumstances is influenced by a combination of factors such as soil moisture regulation, plantation age structure, crop diversification, and continuity of farm management (Kumar & Kunhamu, 2022). Therefore, the long-term stability of coconut landscapes is determined not only by short-term adaptive interventions but also by the capacity of plantations to maintain ecological function, reproductive continuity, and livelihood stability over the long run in the face of recurring climatic disruption. This extends resilience evaluation beyond simple event recovery indicators to include the long-term continuity of productive and ecological processes in plantation settings.

Reframing resilience in coconut farming therefore necessitates analytical methods that can capture cumulative stress exposure, delayed biological responses, and progressive ecological change throughout lengthy plantation cycles. Compared to evaluation models that rely primarily on productivity markers from short periods, increased focus on longitudinal monitoring, plantation continuity, and reproductive stability would give a more accurate picture of climate susceptibility in perennial agriculture (Folke et al., 2016). In order to plan for future resilience in coconut-based systems, climate adaptation studies may need to incorporate more integration of long-term physiological monitoring, plantation demographic structure, and cumulative environmental stress evaluation.

4.7 Future Research and Policy Directions for Coconut Climate Resilience

The growing climatic unpredictability in coconut-producing areas emphasizes the necessity for research methodologies that can assess plantation responses beyond single seasonal observations (Rosenzweig et al., 2014). The lack of long-term field data linking rainfall irregularity, thermal stress, reproductive behavior, and yield variation across multiple harvest cycles continues to limit our current understanding of climate effects in coconuts (Lesk et al., 2016). Therefore, future research should focus on longitudinal plantation monitoring that can identify stress accumulation patterns, delayed yield responses, and recovery behavior in diverse tropical settings (Verchot et al., 2021). The prediction of climate-related productivity variability in coconut systems would be significantly enhanced by increased access to long-term plantation datasets that incorporate climatic variables, flowering behavior, nut production, and physiological reactions.

Significant knowledge gaps still exist about how climatic exposure varies spatially throughout coconut-growing regions. The effectiveness of management interventions can be significantly impacted by variations in soil properties, coastal influence, groundwater availability, plantation age profile, and mixed-cropping intensity (Morton, 2007), as well as the degree of environmental stress. Spatial variations in plantation susceptibility under future climate scenarios may be made worse by rising groundwater depletion in certain tropical coconut-growing areas, cyclone exposure, and coastal salinity intrusion.

By placing a greater emphasis on region-specific research, we would gain a better understanding of how plantation performance varies across agroecological conditions and lessen our dependence on generalized adaptation advice that may not be as successful in different coconut-growing environments (Altieri et al., 2015).

Furthermore, future research should improve the connection between crop physiology, plantation management, ecological diversification, and farm-level economic analysis. Despite the tight integration of these components within coconut production systems, previous research has often examined them separately (Thornton et al., 2018). A more interdisciplinary approach will help us better comprehend how moisture stress, reproductive stability, soil condition, diversification techniques, and farmer decision-making all interact to affect plantation performance under changing hydroclimatic conditions (Partey et al., 2018). Under repeated environmental stress, more focus is needed on spotting climate thresholds linked to reproductive decline, moisture stress susceptibility, and long-term plantation productivity (Ray et al., 2015).

From a policy standpoint, improving climate preparedness in coconut cultivation necessitates support systems that go beyond initiatives focused on short-term productivity (Eriksen et al., 2021). In climate-sensitive coconut-growing regions, greater attention on plantation rehabilitation, water resource conservation, replanting aid, localized extension support, and region-specific breeding programs will be increasingly necessary (Juhola et al., 2016). Enhancing the adaptive capacity of smallholder coconut farmers in the face of rising climate uncertainty may also be accomplished by increasing access to climate advisory services, risk-sharing financial methods, and long-term rehabilitation support initiatives. In order to maintain production continuity in the face of shifting environmental circumstances, policies that promote long-term germplasm preservation and continuous plantation regeneration are also likely to be essential (Batugal et al., 2009). Consequently, a closer alignment between long-term scientific evidence, plantation management realities, and region-specific institutional support systems will be necessary for future resilience planning for coconut agriculture. Therefore, increasing cooperation between researchers, breeding organizations, extension services, and plantation communities will be necessary to create climate adaptation routes that can support long-term productivity and livelihood resilience in tropical coconut systems. Based on the findings and synthesis, an integrated conceptual framework was developed to illustrate the relationships among climate change drivers, vulnerability pathways, adaptation strategies, institutional support, and resilience outcomes in coconut farming systems. The framework summarizes the principal findings of the review and provides a holistic perspective on long-term resilience in perennial plantation agriculture.

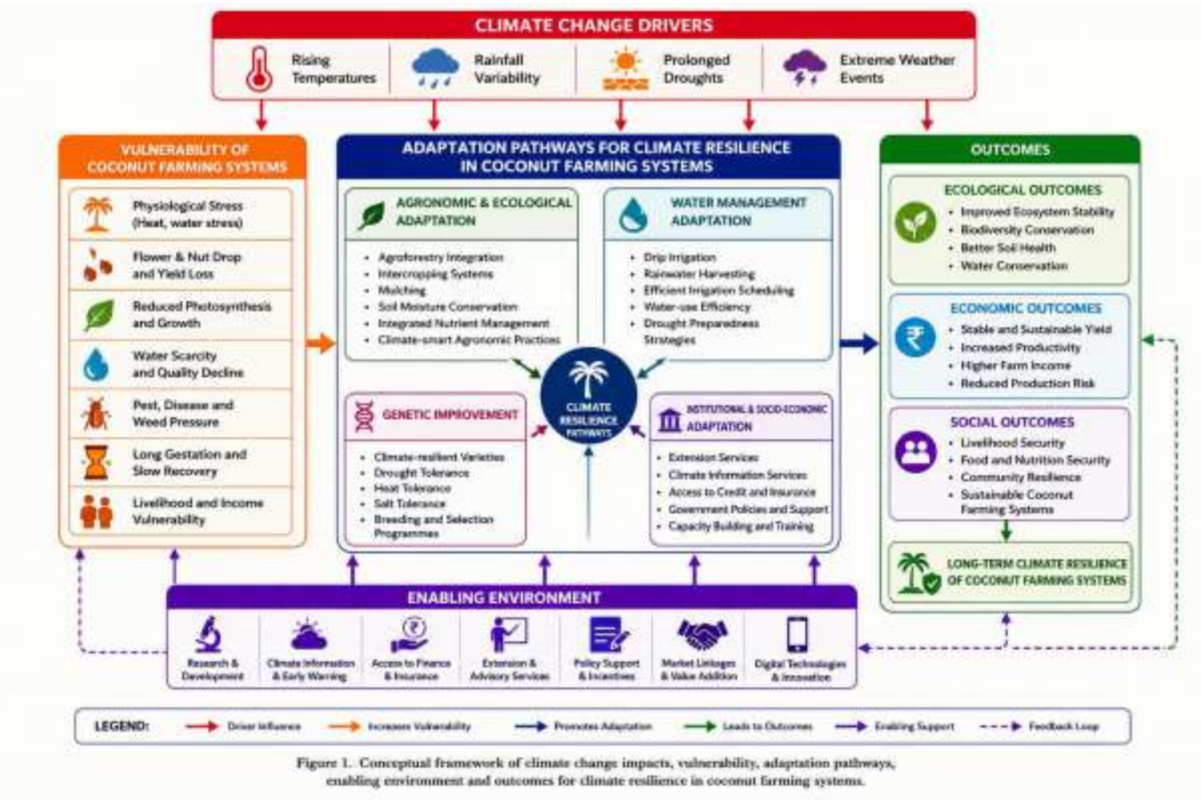

Figure 7. Integrated Conceptual Framework for Climate Resilience in Coconut Farming Systems

5. CONCLUSION

This review shows that despite significant growth in climate-resilient agriculture research in recent years, current adaptation frameworks continue to be primarily centered on annual cropping systems and short-term productivity-focused interventions. Despite their ecological, economic, and livelihood significance in tropical areas, perennial plantation systems like coconut continue to be relatively underrepresented in general climate resilience studies, according to bibliometric and qualitative synthesis. According to the results, delayed physiological and reproductive responses, lengthy production cycles, moisture stress, productivity variability, and structural restrictions related to perennial cultivation all contribute to climate vulnerability in coconut farming. Therefore, resilience in coconut-based systems is more understood through the ability to maintain long-term plantation functionality, livelihood stability, and ecological balance under repeated climatic disruptions rather than through immediate recovery or short-term yield improvement alone. In addition, the review emphasizes the significance of diverse agricultural systems, climate-resilient agronomic methods, water management techniques, genetic enhancement, and institutional support in enhancing adaptive capacity in coconut-growing areas. The findings are particularly relevant for tropical coconut-growing regions, where perennial farming systems remain highly vulnerable to increasing climate variability and long-term ecological stress.

Author Contribution:

Pragathi Nallamuthu: Conceived and designed the study, performed the review and analysis, collected, curated, and analyzed the data, interpreted the findings, developed the conceptual framework and wrote the original manuscript.
N. Sriram: Contributed to conceptualization, supervision, critical revision of the manuscript, and overall guidance.
C. Karthikeyan: Provided continuous guidance during the research process and assisted in clarifying methodological and conceptual issues.
D. Keisar: Assisted during the research process and contributed to manuscript preparation.**M. M. Prahadeeswaran:** Provided critical suggestions to improve the manuscript.

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