Journal of Environment and Pollution ISSN: 3068-9295

PRIME OPEN ACCESS

Volume 2, Issue 1

Research Article

Date of Submission: 14 Feb, 2026
Date of Acceptance: 10 Mar, 2026
Date of Publication: 20 Mar, 2026

Climate Change Impacts on Oil Palm Productivity: A Review of Adaptation Strategies and Knowledge Systems for Resilience

Loso Judijanto*

IPOSS Jakarta, Indonesia

***Corresponding Author:** Loso Judijanto, IPOSS Jakarta, Indonesia.

Citation: Judijanto, L. (2026). Climate Change Impacts on Oil Palm Productivity: A Review of Adaptation Strategies and Knowledge Systems for Resilience. *J Environ Pollut, 2*(1), 01-13.

Abstract
Climate change has emerged as a key factor influencing the stability of oil palm productivity, particularly through its effects on temperature regimes, rainfall variability, and hydrological conditions. Understanding how these climatic pressures interact with adaptation strategies and knowledge systems is essential for strengthening resilience across oil palm production systems. This study aims to systematically synthesize peer-reviewed evidence on the impacts of climate change on oil palm productivity, with specific attention to documented adaptation measures and the role of knowledge systems in supporting adaptive capacity. A Systematic Literature Review (SLR) approach was employed following a structured and transparent protocol. Data were collected exclusively from peer-reviewed journal articles indexed in Scopus and published between 2020 and 2026. A total of 38 articles meeting predefined inclusion criteria were analyzed using thematic synthesis and cross-study comparison to identify dominant climate stressors, productivity responses, adaptation strategies, and mechanisms of knowledge systems. The results indicate that climate change affects oil palm productivity through interacting biophysical pathways, with yield responses strongly mediated by management intensity and adaptive practices. Water management, soil and nutrient optimization, and climate-resilient planting materials consistently reduced yield variability, while formal and experiential knowledge systems enhanced the effectiveness of adaptation. Overall, productivity resilience was shaped by the integration of climatic information, adaptive management, and knowledge exchange rather than by climatic factors alone. Future research is recommended to quantitatively assess the combined effects of multiple adaptation strategies and to further examine the contributions of knowledge systems across diverse production contexts.

Keywords: Climate Change, Oil Palm Productivity, Adaptation Strategies, Knowledge Systems, Resilience

Introduction
Climate change has emerged as one of the most significant global challenges influencing agricultural systems, food security, and rural livelihoods across tropical and subtropical regions. Increasing temperatures, shifting rainfall patterns, and the growing frequency of extreme weather events are reshaping biophysical growing environments and altering crop productivity dynamics worldwide [1]. For perennial crops, climate-related stressors often exert delayed and cumulative effects, complicating both impact assessment and adaptive response planning. As a result, understanding how climate change interacts with long-lived agricultural systems has become a central concern within sustainability and resilience-oriented research agendas [2].

Within this broader context, oil palm (*Elaeis guineensis*) occupies a prominent position as a globally important agricultural commodity. Oil palm cultivation supports millions of livelihoods and plays a key role in vegetable oil supply chains, particularly in Southeast Asia, Africa, and parts of Latin America [3]. The productivity of oil palm systems is shaped by a combination of climatic suitability, agronomic management, and long-term investment cycles. Given its perennial nature and extended production lifespan, oil palm productivity is particularly sensitive to cumulative climatic variability rather than short-term fluctuations alone [4]. Consequently, climate change introduces both challenges and opportunities for productivity management, depending on the degree to which adaptive strategies are effectively implemented.

Recent scientific literature has increasingly documented how climate-related variables such as temperature increases, rainfall variability, and altered hydrological regimes influence oil palm growth, yield formation, and harvesting stability. Empirical studies and modeling assessments have reported that prolonged dry periods, shifts in seasonal rainfall distribution, and rising mean temperatures can affect phenological development, fresh fruit bunch formation, and yield consistency over time [5]. At the same time, these impacts are rarely uniform across regions or production systems, as local environmental conditions and management practices mediate productivity outcomes. This heterogeneity underscores the importance of moving beyond generalized narratives toward more nuanced, evidence-based understandings of climate–productivity relationships.

In parallel with impact assessments, a growing body of literature has emphasized the role of adaptation strategies in moderating climate-related risks to oil palm productivity. Adaptation measures documented in previous studies range from water and soil management interventions to crop improvement, plantation design optimization, and adjustments in agronomic practices [6]. Rather than framing climate change solely as a threat, this body of work highlights the capacity of oil palm systems to respond dynamically through incremental and management-driven adaptations. Such perspectives align with broader resilience frameworks that emphasize adaptive capacity, learning, and system flexibility as critical components of long-term sustainability.

Beyond physical adaptation measures, knowledge systems have been increasingly recognized as a central element in shaping adaptive responses to climate change. Knowledge systems encompass formal scientific research, extension services, climate information services, technological tools, and accumulated operational experience within production systems [7]. In the context of oil palm cultivation, effective knowledge integration supports informed decision-making related to planting material selection, water management, nutrient application, and harvesting schedules under variable climatic conditions. The interaction between climate information and management knowledge thus plays a pivotal role in translating climate awareness into practical productivity outcomes.

Despite the growing volume of research addressing climate change impacts, adaptation strategies, and knowledge systems in oil palm production, the existing literature remains fragmented across disciplines, regions, and methodological approaches. Many studies focus on specific climatic variables or localized case studies, while others emphasize modeling projections without systematically integrating management and knowledge dimensions [8,9]. This fragmentation limits the ability to derive comprehensive insights into how climate change, adaptation strategies, and knowledge systems collectively shape oil palm productivity resilience. Consequently, there is a need for integrative synthesis that consolidates existing evidence, identifies dominant patterns, and clarifies areas of convergence and divergence across studies.

Systematic Literature Review (SLR) offers a rigorous methodological framework to address this need by enabling transparent, reproducible, and comprehensive synthesis of peer-reviewed research. Unlike narrative reviews, SLR applies structured search strategies, explicit inclusion criteria, and systematic analysis procedures to minimize bias and enhance analytical clarity. In the context of climate change and agricultural productivity, SLR has been widely adopted to map research trends, assess the consistency of evidence, and identify knowledge gaps warranting further investigation. Importantly, SLR relies exclusively on secondary data and does not involve field observations, interviews, or participatory methods, ensuring that findings are grounded entirely in verifiable scientific literature.

Building on this methodological foundation, this review focuses specifically on oil palm productivity as influenced by climate change, with an emphasis on adaptation strategies and knowledge systems that contribute to resilience. Rather than assessing sustainability outcomes in a normative or evaluative manner, the review adopts a neutral analytical stance that examines documented evidence on how productivity responses are shaped by climatic and management factors. By synthesizing studies published between 2020 and 2026, the review captures recent scientific advancements and reflects evolving research priorities in climate adaptation and agricultural resilience.

The objective of this study is to systematically synthesize and analyze peer-reviewed literature on the impacts of climate change on oil palm productivity, with particular attention to documented adaptation strategies and the role of knowledge systems in enhancing resilience. Through a structured SLR approach, the study aims to identify dominant climate-related stressors, quantify reported productivity impacts, examine adaptation measures at different production scales, and assess how knowledge systems support adaptive capacity within oil palm systems.

Based on this objective, the study addresses the following research question:
RQ: How do climate change impacts on oil palm productivity interact with adaptation strategies and knowledge systems to shape resilience across different production contexts?

This research question guides the analytical focus of the review and provides a coherent framework for the discussion and conclusion sections, where synthesized evidence is interpreted to clarify adaptation effectiveness, resilience pathways, and implications for future research.

Literature Review

The literature on climate change and oil palm productivity has expanded substantially over the past decade, reflecting growing scholarly attention to the interactions between climatic variability, agronomic performance, and adaptive capacity in perennial crop systems. Rather than treating climate change as a singular or deterministic driver of productivity outcomes, recent studies increasingly adopt integrative perspectives that account for biophysical processes, management practices, and knowledge-based interventions. This literature review synthesizes key thematic strands emerging from peer-reviewed research, focusing on climatic sensitivity in perennial crops, quantified productivity responses in oil palm systems, adaptation strategies at multiple scales, plantation-level management mechanisms, and the role of knowledge systems in enhancing resilience. By structuring the review around these interconnected themes, the section provides a conceptual and empirical foundation for understanding how oil palm productivity responds to climate change within diverse environmental and management contexts.

Climate Change and Agricultural Productivity in Perennial Crop Systems

Climate change has been widely recognized as a key driver influencing agricultural productivity, particularly in tropical regions where perennial crops dominate production systems. In contrast to annual crops, perennial commodities such as oil palm exhibit long biological cycles, delayed yield responses, and cumulative sensitivity to climatic variability [10]. Existing literature emphasizes that climate-related impacts on perennial crops are rarely immediate, instead manifesting through complex interactions between temperature, rainfall, soil moisture, and long-term management practices [11]. This temporal dimension complicates productivity assessment and necessitates longitudinal and systems-based analytical approaches.

Within agricultural climate studies, temperature increase and rainfall variability are consistently identified as the most influential climatic factors affecting crop growth and yield formation [12]. However, the magnitude and direction of productivity responses depend on crop physiology, local environmental conditions, and adaptive capacity. Several reviews highlight that productivity outcomes cannot be attributed solely to climatic variables, as management intensity and institutional support play equally significant roles [13]. This perspective provides an important conceptual foundation for examining oil palm productivity under changing climatic conditions.

Oil Palm Productivity and Climatic Sensitivity

Oil palm productivity is shaped by a combination of climatic suitability, agronomic management, and the age structure of the plantation. Optimal oil palm growth has traditionally been associated with relatively stable temperature ranges, evenly distributed rainfall, and adequate solar radiation [14]. Deviations from these conditions, particularly prolonged droughts or excessive rainfall events, have been shown to influence fresh fruit bunch (FFB) development, oil extraction efficiency, and harvest regularity. Empirical studies consistently report lagged productivity effects, with climatic stress events influencing yields 12–24 months after occurrence due to the crop's perennial growth cycle [15].

Temperature sensitivity has received increasing attention in recent oil palm research. Several modeling and observational studies suggest that sustained increases in mean daily temperature may alter flowering patterns, sex ratios, and assimilate allocation, with potential implications for long-term yield stability [16]. Nevertheless, the literature does not present a uniformly negative outlook. Instead, productivity responses vary considerably across regions and production systems, indicating that climate sensitivity is mediated by management practices and site-specific conditions.

Rainfall variability represents another critical climatic factor affecting oil palm productivity. Studies focusing on Southeast Asia and Africa highlight that both rainfall deficits and excesses can disrupt physiological processes, water availability, and nutrient uptake [17]. Importantly, moderate climatic variability does not necessarily lead to a decline in productivity when appropriate management strategies are in place. This reinforces the need to interpret climate impacts within broader agronomic and institutional contexts rather than as isolated stressors.

Adaptation Strategies in Oil Palm Production Systems

Adaptation strategies form a central theme in the literature examining climate change impacts on oil palm productivity. Rather than advocating structural transformation of production systems, most studies emphasize incremental, management-oriented adaptation measures that enhance system resilience [18]. Water management interventions are among the most frequently documented strategies, including drainage optimization, water table regulation in peatlands, and supplemental irrigation during extended dry periods. These measures are consistently associated with reduced yield variability under climatic stress.

Soil and nutrient management practices are also highlighted as key adaptive responses. Adjustments in fertilizer timing, nutrient formulation, and organic matter application are reported to improve nutrient use efficiency under variable rainfall conditions [19]. The use of mulching materials, such as empty fruit bunches, is frequently cited for improving soil moisture retention and moderating surface temperatures, thereby buffering crops against heat and drought stress. Such practices illustrate how adaptation often builds upon existing agronomic techniques rather than introducing entirely new systems.

Crop-level adaptation strategies have gained prominence in more recent literature. The development and deployment of climate-resilient planting materials, including drought-tolerant or heat-adapted varieties, are increasingly discussed as medium- to long-term adaptation pathways [20]. While large-scale adoption remains uneven, modeling studies suggest that improved planting material can contribute significantly to yield stability under projected climate scenarios. Importantly, these strategies are typically framed as complementary to, rather than substitutes for, improved management practices.

Plantation Management and Microclimatic Regulation

Beyond individual adaptation measures, the literature increasingly emphasizes plantation-scale management as a determinant of climate resilience. Canopy management, planting density adjustments, and harvest scheduling are identified as mechanisms for regulating microclimatic conditions within plantations [21]. By influencing light interception, evapotranspiration rates, and soil temperature, these practices can moderate the impacts of external climatic variability on oil palm physiology.

Several studies argue that management intensity explains a substantial proportion of observed yield variability, often exceeding the explanatory power of climatic variables alone [22]. This finding challenges simplified narratives that attribute productivity outcomes primarily to climate change, instead highlighting the role of adaptive management in shaping resilience. Such insights support a balanced interpretation of climate impacts that recognizes both environmental constraints and human agency.

Knowledge Systems and Adaptive Capacity

Knowledge systems constitute a critical, though sometimes underexplored, dimension of climate adaptation in oil palm production. The literature distinguishes between formal knowledge systems, such as research institutions, extension services, and decision-support tools, and informal systems based on experiential learning and operational knowledge [23]. Effective adaptation depends on integrating these knowledge forms, enabling producers to translate climate information into context-specific management decisions.

Formal knowledge systems are frequently associated with improved access to climate data, seasonal forecasts, and best-practice guidelines. Studies report that timely climate information supports proactive planning for fertilization, harvesting, and water management, thereby contributing to yield stabilization under variable conditions [24]. Technological advancements, including remote sensing and digital monitoring platforms, further enhance the capacity to detect early stress signals and implement targeted interventions.

At the same time, several reviews caution that knowledge dissemination alone is insufficient without institutional support and access to resources. Adaptive capacity is shaped by the interaction between information availability, management flexibility, and economic feasibility. This integrated perspective reinforces the importance of knowledge systems as enablers of adaptation rather than standalone solutions.

Collectively, the reviewed literature presents a nuanced understanding of climate change impacts on oil palm productivity. Rather than depicting oil palm systems as uniformly vulnerable, existing studies highlight significant variability in productivity responses driven by management practices, adaptation strategies, and knowledge integration. Climate change acts as a modifying force that interacts with existing system characteristics, amplifying or attenuating productivity outcomes depending on adaptive capacity.

Despite these insights, several conceptual and empirical gaps remain. First, adaptation strategies are often assessed in isolation, with limited synthesis of how multiple measures interact synergistically. Second, knowledge systems are frequently discussed descriptively rather than analytically, limiting understanding of their quantitative contribution to resilience. Third, spatial unevenness persists in the evidence base, with disproportionate focus on certain regions and production contexts.

Addressing these gaps requires an integrative synthesis that consolidates fragmented findings into coherent analytical frameworks. By systematically reviewing recent peer-reviewed literature, this study contributes to a more comprehensive understanding of how climate change, adaptation strategies, and knowledge systems collectively shape oil palm productivity resilience. This synthesis provides a critical foundation for subsequent discussion on adaptation effectiveness, research priorities, and policy relevance.

Method

This study adopts the Systematic Literature Review (SLR) methodology, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to synthesize and critically assess scholarly evidence on the impacts of climate change on oil palm productivity, with a particular focus on adaptation strategies and knowledge systems that contribute to resilience. Oil palm is a strategic agricultural commodity with significant socioeconomic importance in tropical regions, and its productivity is increasingly influenced by climate-related factors, including temperature variability, altered rainfall patterns, and extreme weather events. Within this context, adaptation and management responses have become central to sustaining productivity while maintaining environmental and operational balance. By systematically consolidating peer-reviewed studies, this review provides an evidence-based overview of how climate change impacts oil palm productivity and how adaptation strategies and knowledge systems have been conceptualized and applied across different production settings.

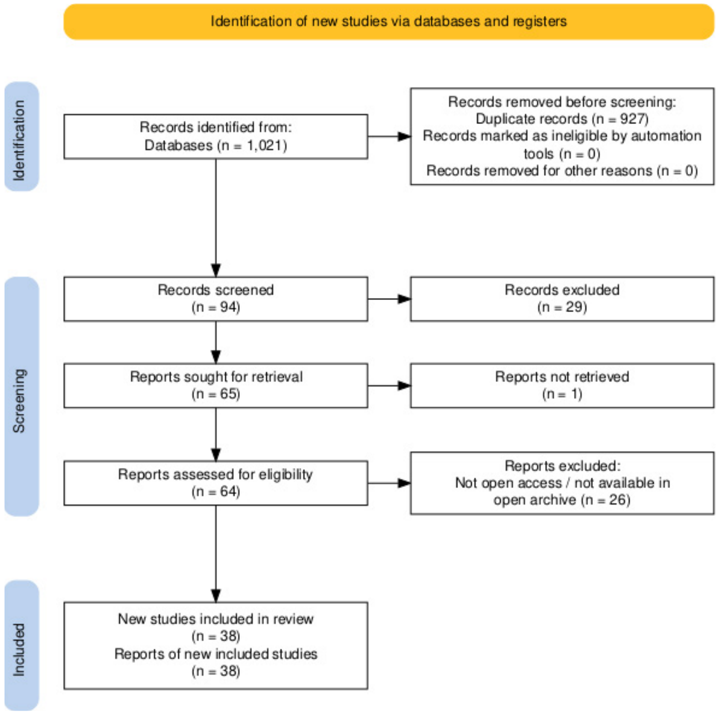

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 illustrates the identification, screening, and selection process of articles conducted in accordance with the PRISMA protocol. The initial literature search was performed using the Scopus database with the broad keyword combination Oil Palm AND Climate Change, which yielded 1,021 records. To enhance thematic focus and relevance, the search was refined using a targeted Boolean string: ("oil palm" OR "palm oil" OR "Elaeis guineensis") AND ("climate change" OR "climate variability") AND ("productivity" OR "yield" OR "growth") AND ("adaptation" OR "management" OR "farming practices"). This refinement resulted in the exclusion of 927 records that did not align with the scope of the review, leaving 94 articles for further screening. A publication year filter was subsequently applied to include studies published between 2020 and 2026, which led to the removal of 29 articles and reduced the dataset to 65 records. Language screening excluded one non-English publication, resulting in 64 eligible English-language articles. Further screening based on accessibility criteria eliminated 26 articles that were not available through Open Access or Open Archive sources. At the conclusion of the selection process, 38 peer-reviewed articles met all inclusion criteria and were retained for full-text analysis and qualitative synthesis.

All bibliographic records were systematically managed in Mendeley Desktop to support reference organization, duplicate detection, and consistent citation formatting throughout the review process. This study is based entirely on secondary data from peer-reviewed scientific literature; no field observations, interviews, or focus group discussions were conducted. The findings and interpretations presented in this review are therefore grounded exclusively in the critical synthesis of the selected 38 studies. Through this systematic consolidation, the review aims to provide a comprehensive understanding of climate change impacts on oil palm productivity and to map documented adaptation strategies and knowledge systems that support resilience, while also identifying areas where further research is required.

Results

This systematic literature review identified five key thematic clusters that collectively characterize how recent peer-reviewed studies examine the impacts of climate change on oil palm productivity and the roles of adaptation strategies and knowledge systems in shaping resilience. These themes emerged from an in-depth analysis of 38 peer-reviewed articles published between 2020 and 2026 and reflect the dominant analytical emphases within the contemporary literature.

The Identified Thematic Domains are:

- Climate-induced biophysical stressors in oil palm systems,
- Quantified impacts of climate variability and extremes on productivity and yield,
- Farm-level and plantation-scale adaptation strategies,
- Institutional, technological, and management-based knowledge systems supporting resilience,
- Cross-cutting synthesis of patterns, contextual variation, and remaining research gaps.

The most frequently addressed theme was climate-induced biophysical stressors, which appeared in 31 of the 38 studies (approximately 82%). This dominance reflects the strong agronomic and climatological orientation of oil palm research, where temperature dynamics, rainfall variability, and hydrological conditions are commonly treated as foundational determinants of crop growth and physiological performance. Closely following this, quantified impacts of climate variability on productivity and yield were examined in 28 studies (around 74%), highlighting the extensive use of statistical analyses, climate–yield modeling, and long-term plantation datasets to translate climatic signals into measurable production outcomes.

Adaptation strategies at farm and plantation scales constituted the third most prevalent theme, documented in 25 studies (approximately 66%). The prominence of this theme indicates a growing recognition that climate-related productivity outcomes are strongly mediated by management responses, including water regulation, soil and nutrient management, and crop-level adjustments. The literature within this cluster largely frames adaptation as incremental and management-driven, emphasizing optimization of existing production systems rather than structural transformation.

In contrast, knowledge systems supporting climate resilience were explicitly analyzed in 18 studies (approximately 47%). These studies addressed the roles of extension services, climate advisory tools, digital monitoring technologies, and experiential management knowledge in enabling adaptive decision-making. Although increasingly acknowledged as critical enablers of resilience, knowledge systems remain less consistently integrated into climate–productivity analyses, reflecting methodological challenges in capturing institutional capacity, information flows, and learning processes.

The least represented thematic cluster was cross-cutting synthesis of patterns, contextual variation, and research gaps, which appeared explicitly in 11 studies (approximately 29%). This relatively low representation suggests that while individual components of climate impacts and adaptation are well documented, fewer studies adopt fully integrative or systems-oriented perspectives that link biophysical stressors, adaptation strategies, and knowledge systems across diverse production contexts.

The predominance of biophysical and yield-focused themes indicates that the literature has largely mirrored broader global debates on climate change impacts and productivity risk assessment. Meanwhile, the comparatively lower emphasis on knowledge systems and integrative synthesis reflects structural gaps in connecting climate exposure with adaptive capacity and decision-making processes. This imbalance implies that resilience is often inferred indirectly through productivity metrics rather than explicitly conceptualized as an emergent outcome of interacting climatic, managerial, and institutional factors. The following sections elaborate each thematic cluster in detail, drawing on quantitative and qualitative evidence from the reviewed studies.

Climate-Induced Biophysical Stressors in Oil Palm Systems

Across the reviewed literature, climate change was consistently conceptualized as a modifier of biophysical growing conditions rather than as a deterministic driver of productivity decline. Temperature increases, rainfall variability, and hydrological alterations were identified as the most influential climate-related stressors affecting oil palm growth dynamics [25-27]. Reported increases in mean annual temperature ranged from 0.8 to 1.5 °C across major oil palm-producing regions over the past three decades, with climate projections suggesting potential increases of up to 2.0 °C by 2050 under intermediate emission scenarios [28,29]. Several studies linked these temperature changes to accelerated phenological development, including shortened leaf emergence intervals and reduced durations of inflorescence differentiation, which in turn influenced bunch formation processes [30].

Rainfall variability emerged as a critical stressor, particularly in regions characterized by pronounced dry and wet seasons. Multiple studies reported that deviations exceeding ±15% from the long-term mean annual rainfall significantly affected the initiation and filling stages of fresh fruit bunch (FFB) development [31,32]. Prolonged dry periods lasting more than 3 consecutive months were frequently associated with physiological stress responses, such as reduced stomatal conductance and lower photosynthetic efficiency, with yield impacts evident 12–18 months after the initial drought event [33,34]. In contrast, excessive rainfall events were associated with increased cloud cover, reduced solar radiation interception, and heightened disease pressure, indirectly constraining productivity [35,36].

Hydrological stress was particularly pronounced in lowland and peat-based production systems. Studies focusing on peatland plantations documented fluctuations in groundwater table depth ranging from approximately −40 cm during extended droughts to +10 cm during extreme rainfall events [37,38]. Both conditions were shown to impair root development and nutrient uptake efficiency, with waterlogging increasing anaerobic stress and drought conditions limiting nutrient mobility [39]. These findings collectively indicate that climate-induced biophysical stressors affect oil palm productivity through multiple, interacting physiological and environmental pathways rather than through isolated mechanisms.

Quantified Impacts of Climate Variability on Productivity and Yield

A substantial proportion of the reviewed studies employed statistical analyses, process-based crop models, or hybrid modeling approaches to quantify the impacts of climate variability on oil palm productivity. Yield responses were commonly reported in terms of percentage changes in FFB yield and, to a lesser extent, oil extraction rate (OER). Across Southeast Asian case studies, drought-related yield reductions ranged from approximately 5% to 25%, depending on drought severity, duration, soil characteristics, and management intensity [40-42]. A multi-country comparative analysis reported average yield declines of 10–12% following El Niño-associated dry events, with recovery periods extending up to 24 months in some locations [43,44].

Temperature sensitivity analyses indicated that sustained mean daily temperatures exceeding 29–30 °C during critical growth stages were associated with yield declines of approximately 3–6% per 1 °C increase, particularly in rainfed systems with limited adaptive capacity [45,46]. However, yield sensitivity varied significantly across production systems. Studies comparing management regimes found that plantations with optimized fertilization schedules and canopy management exhibited yield losses that were 30–40% lower than those observed in less intensively managed systems under similar climatic conditions [47].

Rainfall extremes produced asymmetric yield responses. Moderate increases in rainfall during typically dry periods were associated with yield stabilization or marginal gains of 2–4%, particularly in moisture-limited environments [48]. In contrast, excessive rainfall during peak production phases resulted in yield reductions of up to 8%, primarily due to waterlogging, reduced radiation availability, and increased pest and disease incidence [49]. Importantly, several studies emphasized that climate variables alone accounted for only part of observed yield variability, with agronomic management factors explaining between 30% and 50% of productivity differences across sites [50].

Adaptation Strategies at Farm and Plantation Scales

Adaptation strategies identified in the reviewed literature were diverse and strongly context-dependent, reflecting differences in climatic exposure, soil conditions, and production scale. Water management interventions were among the most frequently documented adaptation measures. These included enhanced drainage infrastructure, controlled water table management in peatlands, and supplemental irrigation during prolonged dry spells [51,52]. Quantitative evaluations indicated that improved water management reduced drought-related yield losses by approximately 20–40% compared to non-adapted systems [53].

Soil and nutrient management practices were also widely reported as effective adaptation measures. Adjustments in fertilizer timing to align with rainfall patterns improved nutrient use efficiency and contributed to yield stabilization of around 5–10% during climatically adverse years [54]. The application of organic residues, particularly empty fruit bunch mulching, was associated with increased soil moisture retention, improved soil organic carbon content, and reductions in surface soil temperature of up to 2 °C, thereby mitigating heat stress effects [55].

Genetic and crop management strategies gained increasing attention in recent studies. The use of climate-resilient or drought-tolerant planting materials was associated with modeled yield gains of 8% to 15% under future climate scenarios [56]. Additionally, modifications to planting density, pruning regimes, and canopy structure improved microclimatic conditions within plantations, enhancing radiation use efficiency and reducing evapotranspiration losses [57]. Overall, adaptation was predominantly framed as incremental and management-driven, emphasizing optimization of existing practices rather than radical system transformation [58].

Knowledge Systems Supporting Climate Resilience

The reviewed studies underscored the importance of knowledge systems in facilitating effective climate adaptation in oil palm production. Formal knowledge systems, including agricultural extension services, climate advisory platforms, and decision-support tools, were frequently cited as mechanisms for translating climate information into operational management decisions [59]. Access to seasonal climate forecasts was reported to improve the timing of fertilization, harvesting, and water management interventions, contributing to yield stability gains of approximately 3–7% in several plantation contexts [60].

Technological knowledge systems were increasingly integrated into adaptive management strategies. Remote sensing technologies and digital monitoring platforms were used to track rainfall patterns, vegetation indices, and soil moisture conditions, enabling early detection of stress and timely management responses [61]. These tools were particularly effective in large-scale plantations, where spatial heterogeneity in climate impacts could be systematically monitored and addressed.

Experiential and operational knowledge also played a complementary role. While not always quantified numerically, several studies emphasized that accumulated management experience informed localized adaptive responses, such as drainage adjustments and harvest scheduling [62]. The integration of scientific, technological, and experiential knowledge was consistently identified as a key factor enhancing adaptive capacity and resilience.

Synthesis of Patterns and Emerging Evidence

Synthesis across the 38 reviewed studies revealed a consistent pattern in which climate change impacts on oil palm productivity were strongly mediated by management intensity and adaptive capacity rather than driven solely by climatic variables. Yield responses varied widely across regions and production systems, highlighting the importance of context-specific adaptation strategies. Although climate stressors such as drought and elevated temperatures posed measurable challenges, the evidence demonstrated that targeted adaptation measures substantially mitigated negative impacts and supported productivity resilience.

The reviewed literature increasingly emphasized proactive adaptation supported by evolving knowledge systems and technological innovation. Rather than depicting oil palm systems as uniformly vulnerable, the studies collectively identified practical pathways to enhance resilience through improved management, informed decision-making, and the strategic use of climate information. These synthesized findings provide a robust empirical basis for the subsequent discussion on adaptation effectiveness, resilience frameworks, and implications for sustainable oil palm production under changing climatic conditions.

Discussion

This discussion addresses the research question: How do climate change impacts on oil palm productivity interact with adaptation strategies and knowledge systems to shape resilience across different production contexts? By synthesizing evidence from 38 peer-reviewed studies published between 2020 and 2026, this section interprets how climate stressors, management responses, and knowledge infrastructures jointly influence productivity outcomes in oil palm systems. Rather than treating climate change impacts as isolated biophysical phenomena, the reviewed literature collectively demonstrates that productivity responses emerge from dynamic interactions between environmental pressures, adaptive practices, and the capacity to access and apply relevant knowledge.

Interactions Between Climate Stressors and Productivity Responses

The reviewed studies consistently indicate that climate change influences oil palm productivity through cumulative and often delayed pathways rather than immediate yield shocks. Temperature increases, rainfall variability, and hydrological disturbances interact with the perennial growth cycle of oil palm, producing lagged effects on yield formation and harvest outcomes [63,64]. This temporal lag commonly ranging from 12 to 24 months means that productivity outcomes observed in a given year often reflect climatic conditions experienced in previous growth stages [65,66].

Importantly, the literature does not present a uniform relationship between climate stressors and productivity decline. Instead, yield responses vary substantially across regions, soil types, and management regimes. For example, drought-related yield reductions reported in Southeast Asia were generally lower in plantations with well-developed drainage and soil moisture management systems compared to less intensively managed sites under similar climatic conditions [67,68]. This variability suggests that climate change acts as a modifying force whose impacts are mediated by system characteristics rather than as a deterministic driver of productivity loss.

Temperature-related stress exhibits similar interaction effects. While sustained increases in mean daily temperature above optimal thresholds were associated with reduced bunch formation efficiency and altered phenological patterns, several studies demonstrated that these effects were attenuated in systems with optimized canopy management and nutrient supply [69]. These findings reinforce the interpretation that climate impacts on oil palm productivity cannot be understood independently of management context.

Adaptation Strategies as Mediators of Climate Impacts

Adaptation strategies emerge in the reviewed literature as critical mediators shaping how climate stressors translate into productivity outcomes. Rather than emphasizing radical transformation of oil palm systems, most studies highlight incremental, management-oriented adaptations that enhance resilience within existing production frameworks [70]. Water management interventions, including drainage optimization, water table regulation in peatlands, and supplemental irrigation during extended dry periods, were among the most frequently cited strategies [71].

Quantitative evidence indicates that such interventions can substantially reduce climate-induced yield variability. Several studies reported reductions in drought-related yield losses of approximately 20–40% following the implementation of improved water management practices [72]. These findings illustrate that adaptation strategies not only buffer productivity against climatic extremes but also stabilize production over time, contributing to resilience rather than short-term yield maximization.

Soil and nutrient management adaptations further illustrate the interactive nature of climate impacts and management responses. Adjustments in fertilizer timing to align with rainfall patterns were consistently associated with improved nutrient use efficiency and reduced yield variability under fluctuating climatic conditions [73]. Organic amendments, particularly empty fruit bunch mulching, were reported to enhance soil moisture retention and moderate soil temperature, thereby mitigating both heat and drought stress. These practices exemplify how adaptation strategies operate by modifying the microenvironment in which climatic stressors are expressed.

Crop-level adaptation strategies, including the use of climate-resilient planting materials, also contribute to mediating climate impacts. Modeling studies suggest that drought-tolerant or heat-adapted varieties can improve yield stability by 8–15% under projected climate scenarios [74]. However, the literature emphasizes that genetic adaptation alone is insufficient; its effectiveness depends on complementary management practices and suitable environmental conditions.

Knowledge Systems and Adaptive Capacity

Knowledge systems play a central role in shaping the effectiveness of adaptation strategies and, by extension, productivity resilience. The reviewed literature distinguishes between formal knowledge systems, such as research institutions, extension services, climate advisory platforms, and decision-support tools, and informal systems grounded in experiential and operational knowledge [75]. Resilience emerges most strongly in contexts where these knowledge forms are integrated rather than operating in isolation.

Formal knowledge systems enhance adaptive capacity by translating climate information into actionable guidance. Access to seasonal climate forecasts, for example, enables producers to adjust fertilization schedules, harvesting plans, and water management practices in anticipation of climatic variability. Several studies reported yield stability improvements of approximately 3–7% in plantations using climate advisory services compared with those relying solely on historical management practices [76].

Technological knowledge systems further strengthen adaptation by enabling real-time monitoring of climatic and biophysical conditions. Remote sensing tools and digital plantation management platforms were increasingly reported as mechanisms for detecting early signs of water stress, nutrient imbalance, or disease pressure [77]. These technologies are particularly effective in large-scale production contexts, where spatial heterogeneity in climate impacts can be systematically identified and managed.

At the same time, experiential knowledge remains a crucial component of adaptive capacity. While often less formally documented, localized management experience informs practical adjustments such as drainage regulation, harvest timing, and labor allocation during periods of climatic stress [78]. The literature suggests that resilience is greatest when formal scientific knowledge complements rather than replaces operational expertise.

Contextual Variation Across Production Systems

The interaction between climate impacts, adaptation strategies, and knowledge systems varies markedly across production contexts. Studies focusing on industrial plantations often emphasize technological and institutional mechanisms, including digital monitoring systems and structured extension services [79]. In these contexts, adaptive capacity is closely linked to access to capital, infrastructure, and technical expertise.

Conversely, studies examining smaller-scale or resource-constrained systems highlight the importance of low-cost, management-based adaptations and localized knowledge. While these systems may be more exposed to climate variability, the literature indicates that targeted support through extension services and knowledge-sharing platforms can significantly enhance resilience [80]. This variation underscores that resilience is not solely a function of scale but of the alignment between climatic exposure, adaptation strategies, and knowledge accessibility.

Importantly, the reviewed literature avoids portraying any single production context as inherently unsustainable or resilient. Instead, resilience emerges as a dynamic property shaped by adaptive capacity and learning processes over time. This perspective aligns with broader sustainability frameworks that emphasize continuous improvement and adaptive management rather than fixed benchmarks [81].

Synthesis: Answering the Research Question

In response to the research question, the synthesis indicates that climate change impacts on oil palm productivity interact with adaptation strategies and knowledge systems in complex, mutually reinforcing ways. Climate stressors impose biophysical pressures that influence growth and yield, but their ultimate effects on productivity are mediated by the presence and effectiveness of adaptive practices. Adaptation strategies, in turn, derive their effectiveness from knowledge systems that enable timely, context-specific decision-making.

Resilience thus emerges not from any single factor but from the alignment of climatic conditions, adaptive management, and knowledge integration. Systems characterized by proactive adaptation and robust knowledge exchange consistently demonstrate lower yield variability and faster recovery following climatic stress events. This finding supports a resilience-oriented interpretation of climate impacts that recognizes both environmental constraints and management agency.

The findings of this systematic review have several important implications. First, they underscore the need for climate impact assessments to move beyond deterministic narratives and incorporate management and knowledge dimensions when evaluating productivity outcomes. Second, they highlight the value of incremental adaptation strategies that build on existing practices, offering practical pathways for enhancing resilience without necessitating fundamental system transformation.

From a policy and management perspective, strengthening knowledge systems, particularly extension services and climate advisory platforms, emerges as a key lever for enhancing adaptive capacity. Investments in digital monitoring tools and decision-support systems can further enable timely, targeted adaptation, especially in large, heterogeneous production landscapes.

For future research, several gaps warrant attention. There remains limited empirical synthesis on the synergistic effects of multiple adaptation strategies applied concurrently. Additionally, the contribution of knowledge systems to resilience is often discussed qualitatively, indicating a need for more quantitative assessment of knowledge-driven productivity outcomes. Addressing these gaps will require integrative, cross-regional studies that combine climatic, agronomic, and institutional perspectives.

Overall, this review demonstrates that oil palm productivity under climate change is shaped by interactive processes rather than linear cause–and–effect relationships. By consolidating evidence on climate impacts, adaptation strategies, and knowledge systems, the study contributes to a more balanced and evidence-based understanding of resilience in oil palm production systems, providing a foundation for informed discussion and future research.

Conclusion

This systematic literature review synthesizes recent evidence on how climate change impacts oil palm productivity through complex interactions with adaptation strategies and knowledge systems across diverse production contexts. The reviewed literature demonstrates that climate-related stressors such as temperature increases, rainfall variability, and hydrological extremes do not operate as isolated determinants of productivity outcomes. Instead, their effects are mediated by management practices and by production systems' capacity to anticipate, absorb, and respond to climatic variability.

The synthesis reveals that adaptation strategies play a central role in shaping productivity resilience. Incremental, management-oriented adaptations, particularly those related to water regulation, soil and nutrient management, and agronomic timing, consistently reduce yield variability and buffer oil palm systems against climate-induced stress. These strategies are most effective when applied in a context-specific manner, reflecting local environmental conditions, plantation characteristics, and operational constraints. As such, resilience emerges not from a single intervention, but from the cumulative and coordinated application of adaptive practices over time.

Knowledge systems are identified as a critical enabling factor that determines how effectively adaptation strategies are implemented and sustained. Formal knowledge infrastructures, including research outputs, extension services, climate advisory tools, and digital monitoring platforms, enhance adaptive capacity by translating climate information into actionable management decisions. At the same time, experiential and operational knowledge remains essential for contextualizing scientific guidance and facilitating practical responses at the field level. The integration of formal and informal knowledge systems is consistently associated with greater productivity, stability, and adaptive responsiveness.

Across different production contexts, resilience is shaped by the alignment between climatic exposure, available adaptation options, and access to knowledge. Large-scale plantation systems tend to leverage technological and institutional resources, while smaller or resource-constrained systems rely more heavily on low-cost adaptations and localized knowledge. Importantly, the literature does not support a binary distinction between resilient and non-resilient production systems. Instead, resilience is portrayed as a dynamic and evolving property that reflects learning processes, management flexibility, and continuous adjustment to changing climatic conditions.

Overall, the findings indicate that climate change impacts on oil palm productivity are best understood through an integrative framework that accounts for biophysical stressors, adaptive management, and knowledge exchange. Productivity resilience is not solely determined by climate trends, but by the extent to which production systems are equipped to interpret climatic signals and translate them into timely, informed, and context-appropriate responses. This review therefore contributes a balanced, evidence-based perspective on resilience in oil palm production, emphasizing adaptive capacity and knowledge integration as key determinants of sustained productivity under a changing climate

References

1. Enting, C. E., & Latip, S. N. H. M. (2021). Life cycle of oil palm bagworm, Metisa plana Walker (Lepidoptera: Psychidae) at different temperatures under controlled environment.
2. Rosa Silva, A. A., da Silva Brito, G. F., Araruna, T., Gambetta, R., & Machado, F. (2026). Thermochemical conversion of oil palm empty fruit bunch into fuel gas in a fluidized bed gasifier. *Bioresource Technology, 440.*
3. Muhamad, N. A. S., Mohd Mokhtar, N., Naim, R., Lau, W. J., & Ismail, N. H. (2024). Treatment of wastewater from oil palm industry in Malaysia using polyvinylidene fluoride-bentonite hollow fiber membranes via membrane distillation system. *Environmental Pollution, 361.*
4. Mendonça, D. P., Brito, M. L. B., Dias, J. T., da Silva, V. D. P. P., Pacheco, M. J. B., da Cruz Ferreira, T., Rodrigues, M. C. S. F., da Silva Junior, D. D., Silva, G. B., & de Castro, G. L. S. (2025). Amazonian Microorganism Strains Improve Physiological Performance to Oil Palm Seedlings Growth Promote. *Journal of Plant Growth Regulation, 44*(12), 7175–7185.
5. Abubakar, A., Ishak, M. Y., Aisyah, A. B., Uddin, M. K., & Ahmad, M. H. (2022). Assessing the Suitability of Oil Palm (Elaeis guineensis) Production in Peninsular Malaysia based on Soil, Climate and Land Use. *Nature Environment and Pollution Technology, 21*(5), 2141–2163.
6. Isa, N. M., Sivapathy, A., & Kamarruddin, N. N. A. (2021). Malaysia on the Way to Sustainable Development: Circular Economy and Green Technologies. *In Modeling Economic Growth in Contemporary Malaysia* (pp. 91–115).
7. Wandri, R., Monzon, J. P., Carciochi, W. D., Hairiah, K., Suprayogo, D., van Noordwijk, M., Asmono, D., & Grassini, P. (2025). Can improved plant nutrition buffer against water-related yield losses in oil palm? *Agricultural Water Management, 322.*
8. Corning, S. N., Boere, E., Krasovskiy, A., Lessa Derci Augustynczik, A., Shepherd, T., Ghosh, R., Kraxner, F., & Havlík, P. (2024). Flammable futures—storylines of climatic impacts on wildfire events and palm oil plantations in Indonesia. *Environmental Research Letters , 19*(11).

9. Cutz, L., Maldonado, H., Zambrano, G., Al-Naji, M., & de Jong, W. (2023). Hydrothermal liquefaction of Elaeis guineensis trunks: Lessons learned from a case study in Guatemala. *Industrial Crops and Products, 206.*
10. Fung, K. F., Huang, Y. F., Koo, C. H., & Mirzaei, M. (2020). Improved svr machine learning models for agricultural drought prediction at downstream of langat river basin, Malaysia. *Journal of Water and Climate Change, 11*(4), 1383–1398.
11. Thongbunrod, N., & Chaiprasert, P. (2024). Efficient methane production from agro-industrial residues using anaerobic fungal-rich consortia. *World Journal of Microbiology and Biotechnology, 40*(8).
12. Go, Y.-H., Tan, Y.-L., & Yiew, T.-H. (2024). Sensitivity of oil palm yield in Indonesia to climate change: evidence from threshold cointegration models. *Environment, Development and Sustainability.*
13. Gellert, P. K., & D'Onofrio, S. (2024). Flex commodities and intertwining world-ecologies: Indonesian palm waste as an environmental fix in the New Zealand dairy industry. *Political Geography, 108,* 103038.
14. Kayondo, B., Jalloh, M. B., Nur Aainaa, N. A., IImas, A., & Selliah, P. (2023). Influence of Agronomic Practices on the Yield of Oil Palm (Elaeis Guineensis Jacq.) Grown on Various Soil Management Groups. Malaysian Journal of Soil Science, 27.
15. Kolathayar, S., Sreekeshava, K. S., Vinod Chandra Menon, N., Shekhawat, P., & Bhargavi, C. (2024). Recent Advances in Building Materials and Technologies–An Introduction. *Lecture Notes in Civil Engineering, 456 LNCE,* 1–8.
16. Okafor, C. C., Nzekwe, C. A., Ajaero, C. C., Ibekwe, J. C., & Otunomo, F. A. (2022). Biomass utilization for energy production in Nigeria: A review. *Cleaner Energy Systems, 3,* 100043.
17. Purnama, I., Mutamima, A., Sunarno, S., Nasution, I. A. U., Syaputra, E., & Aziz, M. (2025). Scalable biochar production from oil palm fronds and waste cooking oil: Techno-economic and policy-oriented evaluation for rural deployment. *Journal of Cleaner Production, 527.*
18. Song, Y., John Martin, J. J., Liu, X., Li, X., Hou, M., Zhang, R., Xu, W., Li, W., & Cao, H. (2025). Unraveling the response of secondary metabolites to cold tolerance in oil palm by integration of physiology and metabolomic analyses. *BMC Plant Biology, 25*(1).
19. Rajakal, J. P., Andiappan, V., & Wan, Y. K. (2021). Mathematical approach to forecast oil palm plantation yield under climate change uncertainties. *Chemical Engineering Transactions, 83*, 115–120.
20. Okoro, S. U., Schickhoff, U., Boehner, J., Schneider, U. A., & Huth, N. I. (2017). Climate impacts on palm oil yields in the Nigerian Niger Delta. *European Journal of Agronomy, 85,* 38–50.
21. Benezoli, V. H., Imbuzeiro, H. M. A., Cuadra, S. V, Colmanetti, M. A. A., de Araújo, A. C., Stiegler, C., & Motoike, S. Y. (2021). Modeling oil palm crop for Brazilian climate conditions. *Agricultural Systems, 190.*
22. Promraksa, A., Seekao, N., Mueanmas, C., Chungsiriporn, J., & Rakmak, N. (2025). Synergistic Co-Pyrolysis of biomass for renewable energy: Enhanced energy recovery and heat integration from non-condensable gases. *Energy Conversion and Management, 343,* 120260.
23. Susilawati, A., Maftuah, E., & Fahmi, A. (2020). The utilization of agricultural waste as biochar for optimizing swampland: a review. *IOP Conference Series: Materials Science and Engineering, 980*(1).
24. de Souza, P. R., de Lima, H. V, da Silva, G. B., & dos Santos Moura, A. (2023). Limiting Water Content for Compaction Induced by Mechanized Operations in the Soil with Oil Palm in the Eastern Amazon. *Journal of Soil Science and Plant Nutrition, 23*(4), 6167–6182.
25. Ahmad, M., Waraich, E. A., Skalicky, M., Hussain, S., Zulfiqar, U., Anjum, M. Z., Habib ur Rahman, M., Brestic, M., Ratnasekera, D., Lamilla-Tamayo, L., Al-Ashkar, I., & EL Sabagh, A. (2021). Adaptation Strategies to Improve the Resistance of Oilseed Crops to Heat Stress Under a Changing Climate: An Overview. *Frontiers in Plant Science, 12.*
26. Murphy, D. J., Goggin, K., & Paterson, R. R. M. (2021). Oil palm in the 2020s and beyond: challenges and solutions. *CABI Agriculture and Bioscience, 2,* 1–22.
27. Safitri, L., Galdos, M. V, Pradiko, I., Comber, A., & Challinor, A. (2026). Assessing climate-smartness of agronomic practices in oil palm production under changing climate conditions. *European Journal of Agronomy, 174.*
28. Estefan, A., Ordoñez, R., Parilli, C., & Winters, P. (2025). Hybrid agricultural extension and the adoption of climate-resilient varieties: Evidence from oil palm in the Amazon. *Food Policy, 136.*
29. Naito, C., & Takeuchi, W. (2024). Projections of oil palm area in Malaysia and Indonesia to assess the relationship between plant growth and water consumption. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 48*(3), 365–370.
30. Asubonteng, K. O., Ros-Tonen, M. A. F., Baud, I., & Pfeffer, K. (2021). Envisioning the Future of Mosaic Landscapes: Actor Perceptions in a Mixed Cocoa/Oil-Palm Area in Ghana. *Environmental Management,* 68(5), 701–719.
31. Konyai, S., Khuanmar, K., & Kanarkard, W. (2025). A Geoanalytical and AI-Driven Approach for Optimising Biomass Energy Generation from Key Economic Crops in Northeastern Thailand. *E3S Web of Conferences, 629.*
32. Malahayati, M. (2023). INDONESIA'S FOREST MANAGEMENT PROGRESS: EMPIRICAL ANALYSIS OF ENVIRONMENTAL KUZNETS CURVE. *Agricultural and Resource Economics, 9*(3), 216–249.
33. Abubakar, A., Kasim, S., Ishak, M. Y., & Uddin, M. K. (2025). Oil Palm in the Face of Climate Change: The Role of Extension Services in Malaysia. *Research on World Agricultural Economy, 6*(2), 446–466.
34. Widayati, A., Louman, B., Mulyoutami, E., Purwanto, E., Kusters, K., & Zagt, R. (2021). Communities' adaptation and vulnerability to climate change: Implications for achieving a climate-smart landscape. *Land, 10*(8).
35. Azeez, A. A., Esiegbuya, D. O., Jaber, E., Ren, W., Lateef, A. A., Ojieabu, A., & Asiegbu, F. O. (2023). Thermal Tolerance Data and Molecular Identification Are Useful for the Diagnosis, Control and Modeling of Diseases Caused

by Thielaviopsis paradoxa. *Pathogens, 12*(5).
36. Wenzel, A., Westphal, C., Ballauff, J., Berkelmann, D., Brambach, F., Buchori, D., ... & Grass, I. (2024). Balancing economic and ecological functions in smallholder and industrial oil palm plantations. *Proceedings of the National Academy of Sciences, 121*(17), e2307220121.
37. Panjapornpon, C., Satjeenphong, T., Bardeeniz, S., & Hussain, M. A. (2024). Enhancing sustainability in palm oil industry: reinforcement learning for renewable energy management considered climatic variability. *Discover Chemical Engineering, 4*(1).
38. Yamamoto, E. M. S., Sayama, T., & Yamamoto, K. (2021). Mapping of Mature and Young Oil Palm Distributions in a Humid Tropical River Basin for Flood Vulnerability Assessment. *IOP Conference Series: Earth and Environmental Science, 789*(1).
39. Muatho, M. I. (2025). Agroclimatic suitability analysis for oil palm under projected climate in North Aceh Regency, Indonesia. *Journal of Agrometeorology, 27*(2), 177–183.
40. Delgado, T., Ladino, G., & Arias, N. (2024). Evaluation of the Effect of Soil Water Conditions on the Development and Water Requirements of Adult Oil Palm (Elaeis guineensis Jacq.) in the Northern Region of Colombia. *Agronomy, 14*(9).
41. Nainar, A., Walsh, R. P. D., Bidin, K., Tanaka, N., Annammala, K. V, Letchumanan, U., Ewers, R. M., & Reynolds, G. (2022). Baseflow Persistence and Magnitude in Oil Palm, Logged and Primary Tropical Rainforest Catchments in Malaysian Borneo: Implications for Water Management under Climate Change. *Water (Switzerland), 14*(22).
42. Noor, W. N. W. M., Nawi, N. M., Seng, K. W. K., & Buda, M. (2021). Supply response analysis on the impact of climate change on oil palm production in Malaysia. *IOP Conference Series: Earth and Environmental Science, 757*(1).
43. Kamil, N. N., Xiao, S., Salleh, S. N. S., Xu, H., & Zhuang, C. C. (2024). Nonlinear impacts of climate anomalies on oil palm productivity. *Heliyon, 10*(15).
44. Zabel, F., Knüttel, M., & Poschlod, B. (2025). CropSuite v1.0 – a comprehensive open-source crop suitability model considering climate variability for climate impact assessment. *Geoscientific Model Development, 18*(4), 1067–1087.
45. Lau, G. W., King, P. J. H., Chubo, J. K., King, I. C., Ong, K. H., Ismail, Z., Robin, T., & Shamsi, I. H. (2024). The Potential Benefits of Palm Oil Waste-Derived Compost in Embracing the Circular Economy. *Agronomy, 14*(11).
46. Su, H., Willaarts, B., Luna-Gonzalez, D., Krol, M. S., & Hogeboom, R. J. (2022). Gridded 5 arcmin datasets for simultaneously farm-size-specific and crop-specific harvested areas in 56 countries. *Earth System Science Data, 14*(9), 4397–4418.
47. Tchonkouang, R. D., Onyeaka, H., & Nkoutchou, H. (2024). Assessing the vulnerability of food supply chains to climate change-induced disruptions. *Science of The Total Environment, 920*, 171047.
48. Wulandari, R., Abas, A., & Abdullah, A. (2025). Understanding the impact of climate change on oil palm plantation: a systematic literature review. *Frontiers in Sustainable Food Systems, 9.*
49. Wu, Q., Yang, X., Huang, Q., Li, R., Zeng, X., Li, Q., Li, Z., Fu, D., Cao, H., Li, X., Liu, X., & Zhou, L. (2025). Comparative transcriptomics reveals key regulatory networks underlying cold stress adaptation in oil palm (Elaeis guineensis). *Frontiers in Plant Science, 16.*
50. Nwaogu, C. (2021). Improving Food Security by Adapting and Mitigating Climate Change-Induced Crop Pest: The Novelty of Plant-Organic Sludge in Southern Nigeria. *In African Handbook of Climate Change Adaptation: With 610 Figures and 361 Tables* (pp. 1659–1684).
51. Cazier, E. A., Pham, T.-N., Cossus, L., Abla, M., Ilc, T., & Lawrence, P. (2024). Exploring industrial lignocellulosic waste: Sources, types, and potential as high-value molecules. *Waste Management, 188,* 11–38.
52. Couto, E. G. O., Chaves, S. F. S., Dias, K. O. G., Morales-Marroquín, J. A., Alves-Pereira, A., Motoike, S. Y., Colombo, C. A., & Zucchi, M. I. (2024). Training set optimization is a feasible alternative for perennial orphan crop domestication and germplasm management: an Acrocomia aculeata example. *Frontiers in Plant Science, 15.*
53. Gunawan, S., Budiastuti, M. T. S., Sutrisno, J., & Wirianata, H. (2020). Effects of organic materials and rainfall intensity on the productivity of oil palm grown under sandy soil condition. *International Journal on Advanced Science, Engineering and Information Technology, 1,* 356–361.
54. Salleh, S. F., Mohd Roslan, M. E., Abd Rahman, A., Shamsuddin, A. H., Tuan Abdullah, T. A. R., & Sovacool, B. K. (2020). Transitioning to a sustainable development framework for bioenergy in Malaysia: policy suggestions to catalyse the utilisation of palm oil mill residues. *Energy, Sustainability and Society, 10,* 1–20.
55. Kunert, N., & Brändle, J. (2022). How drought tolerant are tropical woody crop species - Turgor loss points for the five most common species in the emerging landscapes on the Malaysian Peninsular. *IOP Conference Series: Earth and Environmental Science, 1053*(1).
56. Najihah, T. S., Ibrahim, M. H., Zain, N. A. M., Nulit, R., & Wahab, P. E. M. (2020). Activity of the oil palm seedlings exposed to a different rate of potassium fertilizer under water stress condition. *AIMS Environmental Science, 7*(1), 46–68.
57. Hamid, S. R., Arzaman, A. F. M., Razali, M. A., Yasin, N. I., Masrom, N. R., Sabri, N. A. A., & Margono, M. (2024). The deployment of the Malaysian sustainable palm oil standard in the agriculture sector. *Multidisciplinary Science Journal, 6*(7), 2024115-2024115.
58. Tschora, H., & Cherubini, F. (2020). Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. *Global Ecology and Conservation, 22.*
59. Hegde, V., Babu, M., & Josephrajkumar, A. (2023). GLOBAL SCENARIO ON PHYTOPLASMAL DISEASES IN PALMS.

Indian Journal of Entomology, 85(4), 1150–1164.
60. Meena, S., Manjaiah, K. M., Sharma, V. K., Purakayastha, T. J., Das, S., Bana, R. S., Gawdiya, S., Yadav, S., Saini, R., Kumar, A., El-Hendawy, S., Mattar, M. A., & Salem, A. (2025). Exploring soil organic carbon fractions, stocks, and carbon management index across land uses in subtropical ecosystems of Tripura, India. *Frontiers in Sustainable Food Systems, 9.*
61. Luanwuthi, S., Iamprasertkun, P., Akkharaamnuay, T., Kunyawut, C., Phukhrongthung, A., & Puchongkawarin, C. (2024). Techno-economic and Environmental Assessment of Activated Carbon Electrodes for Supercapacitors from Oil Palm Leaves. *ACS Sustainable Chemistry and Engineering, 12*(39), 14446–14458.
62. Paterson, R. R. M. (2020). Depletion of indonesian oil palm plantations implied from modeling oil palm mortality and ganoderma boninense rot under future climate. *AIMS Environmental Science, 7*(5), 366–379.
63. Hernawan, E., Rosmiati, M., Lastini, T., Mustari, E., & Kandar, M. (2025). System dynamics scenarios for sustainable oil palm management toward Indonesia's 2060 net zero target. *Asian Journal of Agriculture, 9*(2), 402–414.
64. Sunarta, S., Widiyatno, W., Deendarlianto, D., Fitriani, I., Fitriani, R., Yoga, C., Utami, M., Oh, W.-C., Pratika, R., & Wijaya, K. (2025). Distribution and Habitat Characterization of Non-Edible Plants with Potential as Biodiesel Feedstock on Java Island, Indonesia. *Journal of the Korean Wood Science and Technology, 53*(4), 389–400.
65. Nasir, N. M., Nordin, N., & Azmi, F. R. (2025). The Challenges of Return on Investment in the Malaysian Palm Oil Industry. *In The Palm Oil Export Market* (pp. 114–137). Routledge.
66. Zon, A. O., Kouassi, E. K., & Ouédraogo, A. (2021). Current knowledge and future directions on West African wild palms: an analytical review for its conservation and domestication in the context of climate change and human pressures. *Genetic Resources and Crop Evolution, 68*(5), 1731–1745.
67. Aziz, R., Ekasari, K., & Beddu, H. (2022). Analysis of agronomy and environmental impacts of palm oil production: evidence from Indonesia. AgBioForum, 24(1), 193-204.
68. Thoumi, G. (2018). Palm Oil: Mitigating Material Financial Risks via Sustainability. In *Palgrave Studies in Sustainable Business in Association with Future Earth: Vol. Part F1860* (pp. 289–326).
69. Mardiningsih, T. L., Indriati, G., Suneth, R. F., Lestari, P., Utama, I. W. E. K., & Millado, J. B. H. (2025). Pests of Coconut and Its Innovative Management Strategies: Brontispa longissima Gestro (Coleoptera: Chrysomelidae). *In Science-Based Pest Management for a Sustainable and Resilient Coconut Sector* (pp. 381–407).
70. Uttran, A., Loh, S. K., Ahmad, M., & Bachman, R. T. (2023). Soil Nutrient and Management in Oil Palm Plantations and Agronomic Potential of Biochar. *In Advanced Structured Materials* (Vol. 193, pp. 167–188).
71. Danso, I., Larbi, E., Andoh-Menash, E., Ribeiro, P. F., Anumu, S. K., Aboagye, G. A., Gyeabour, R., Brako, C. N., Dampare, F. A., Adjarko, I. K., & Agyarko-Mintah, E. (2020). Ceres-maize crop model for evaluating rates of nitrogen fertilizer on a short season maize (Zea mays L.) cultivar intercropped with oil palm in the semi-deciduous forest zone of Ghana. *Journal of the Ghana Science Association, 19*(1), 16–23.
72. Ang, Y., Shafri, H. Z. M., Lee, Y. P., Bakar, S. A., Abidin, H., Mohd Junaidi, M. U. U., Hashim, S. J., Che'Ya, N. N., Hassan, M. R., Lim, H. S., Abdullah, R., Yusup, Y., Muhammad, S. A., Teh, S. Y., & Samad, M. N. (2022). Oil palm yield prediction across blocks from multi-source data using machine learning and deep learning. *Earth Science Informatics, 15*(4), 2349–2367.
73. Nyasapoh, J. B. A., Danso, E. O., Kpodo, D. S., Amponsah, W., Arthur, E., Sabi, E. B., Obour, P. B., Akortey, W., Mensah, B. K. B., Ayayi, G. E., & Andersen, M. N. (2024). Irrigation and oil palm empty fruit bunch mulch enhance eggplant growth, radiation interception and dry matter yield. *European Journal of Agronomy, 160,* 127322.
74. Paterson, R. R. M. (2021). Optimised and systematic suitable climate modelling confirms future longitudinal-trends for growing oil palm in Africa. *Journal of Environmental Management, 300.*
75. Man, N., Hassim, H., Sehu, N. I., & Norasma, N. (2019). Drone services and application for paddy fertilizing and oil palm mapping for climate change. In Proc. 40th Asian Conf. Remote Sens.(ACRS) (pp. 1-7).
76. Abubakar, A., Gambo, J., & Ishak, M. Y. (2023). Navigating climate challenges: Unraveling the effects of climate change on oil palm cultivation and adaptation strategies. In Advances in Food Security and Sustainability (Vol. 8, pp. 95-116). Elsevier.
77. Xue, M., Dai, M., Li, H., Deng, H., Wang, S., Sun, M., & Wang, Y. (2024). Understanding the benefits and challenges of harvested wood products in response to climate change. *Resources, Conservation and Recycling, 209*, 107739.
78. Yatim, P., Lin, N. S., Lam, H. L., & Choy, E. A. (2017). Overview of the key risks in the pioneering stage of the Malaysian biomass industry. *Clean Technologies and Environmental Policy, 19*(7), 1825–1839.
79. Soh, A. C., Mayes, S., & Roberts, J. (2017). Oil palm breeding: Genetics and genomics. In *Oil Palm Breeding: Genetics and Genomics.*
80. Frianto, D., Sutrisno, E., Wahyudi, A., Novriyanti, E., Adinugroho, W. C., Yunianto, A. S., Kurniawan, H., Khotimah, H., Windyoningrum, A., Dharmawan, I. W. S., Tata, H. L., Suharti, S., Rachmat, H. H., & Lim, E. M. (2024). Carbon stock dynamics of forest to oil palm plantation conversion for ecosystem rehabilitation planning. *Global Journal of Environmental Science and Management, 10*(4), 1593–1614.
81. Olabi, A. G., Shehata, N., Sayed, E. T., Rodriguez, C., Anyanwu, R. C., Russell, C., & Abdelkareem, M. A. (2023). Role of microalgae in achieving sustainable development goals and circular economy. *Science of the Total Environment, 854.*