frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 06 August 2025
DOI 10.3389/fsufs.2025.1621217

Check for updates

OPEN ACCESS

EDITED BY
Shaowu Hu,
Yangzhou University, China

REVIEWED BY
Chalermpon Jatuporn,
Sukhothai Thammathirat Open University, Thailand
Iput Pradiko,
Indonesian Oil Palm Research Institute (IOPRI), Indonesia

*CORRESPONDENCE
Azlan Abas
✉ azlanabas@ukm.edu.my

RECEIVED 30 April 2025
ACCEPTED 25 July 2025
PUBLISHED 06 August 2025

CITATION
Wulandari R, Abas A and Abdullah A (2025) Understanding the impact of climate change on oil palm plantation: a systematic literature review.
Front. Sustain. Food Syst. 9:1621217.
doi: 10.3389/fsufs.2025.1621217

Understanding the impact of climate change on oil palm plantation: a systematic literature review

Rina Wulandari[1], Azlan Abas[1]* and Abdullah Abdullah[2]

[1]Centre for Research in Development, Social and Environment (SEEDS), Faculty of Social Sciences and Humanities, Universiti Kebangsaan Malaysia, Bangi, Malaysia, [2]Department of Biology Education, Syiah Kuala University, Banda Aceh, Indonesia

The impact of climate change on oil palm plantations has become a critical concern due to its effects on productivity and the physical conditions of oil palm trees. Unstable temperature and rainfall patterns contribute to plant stress, soil moisture fluctuations, and an increased frequency of extreme weather events, all of which affect oil palm growth and yield. This study aims to systematically review and analyze how climate change influences the productivity and physical conditions of oil palm. The present study integrates multiple research projects designs and follows the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) as the guideline for conducting systematic reviews. Web of Science (WoS) and Scopus were used as the primary databases to search for relevant articles. Through thematic analysis, this study categorizes the findings into four key themes: (a) economic and productivity aspects, (b) policies and adaptation strategies, (c) environmental and oil palm health, and (d) social and community wellbeing. The findings provide insights into how academics, practitioners, and policymakers can develop effective adaptation strategies to mitigate the impacts of climate change on oil palm plantations. This study recommends strengthening research on the physical effects of climate change on oil palm, developing climate-resilient oil palm varieties, and implementing advanced mitigation technologies to sustain oil palm productivity and industry resilience.

KEYWORDS

climate change, environmental impact, environmental management, palm oil production, oil palm

1 Introduction

Climate change is a significant global issue that affects various sectors and industries worldwide (Mendelsohn, 2009; Thornton et al., 2014). The impacts of climate change may vary across continents, countries, and regions. Some countries are likely to experience more severe impacts than others, while certain countries may even benefit from climate change (EPA, 2016). As a result, climate change can have both positive and negative effects on agricultural production at different spatial levels. However, research indicates that the negative impacts of climate change tend to outweigh the positive ones (Lavell et al., 2012). Studies on the economics of climate change suggest that while global crop production may see a slight increase due to global warming in the short term (before 2030), the long-term effects could ultimately be negative (IPOC Change, 2001; Bruinsma, 2003). One sector that is particularly affected by climate change is oil palm cultivation (Ahmed et al., 2021). Climate change is causing extreme weather events to become more frequent and intense, significantly impacting agricultural production. As temperatures rise, weather patterns become increasingly erratic, and ecosystems undergo significant changes. The impact of climate change on oil palm cultivation is becoming extensive and complex (Abubakar et al., 2022).

Oil palm (*Elaeis guineensis* Jacq.) is one of the most profitable and widely cultivated commercial tree crops in the tropical world. Over the last decade, the palm oil sector has experienced extraordinary expansion, particularly in Southeast Asia, including Indonesia and Malaysia (Luke et al., 2020; Said et al., 2021). Due to the trade-off between the economic benefits and environmental impacts of oil palm plantations, it is crucial to thoroughly understand the factors that determine palm oil yields, including efforts to find an optimal balance amid changing climate and weather conditions. By increasing oil palm productivity, the need for expanding additional plantations can be reduced (De Pinto et al., 2017), thus preserving valuable land resources. Conversely, low productivity in oil palm cultivation can present significant challenges in promoting sustainable practices within this sector (Kamil et al., 2024).

However, although efforts to increase productivity aim to reduce pressure on new land clearing, palm oil plantation management practices still face significant challenges. The ever-increasing global demand for palm oil is driving the expansion of plantations into sensitive natural areas, creating a dilemma between economic needs and environmental protection. This development has led to pressure to convert natural areas into plantations, resulting in deforestation and the loss of ecosystem functions (Savilaakso et al., 2014; Vijay et al., 2016). Sustainability certifications such as the Indonesian Sustainable Palm Oil (ISPO), Roundtable on Sustainable Palm Oil (RSPO), and Malaysian Sustainable Palm Oil (MSPO) play a crucial role in ensuring that oil palm cultivation practices not only meet environmental, social, and economic standards but also support sustainability amidst the challenges of climate change. While ISPO and MSPO are more focused on national frameworks aligned with local regulations, RSPO adopts a broader multi-stakeholder approach globally, providing flexibility in addressing issues such as deforestation, biodiversity, and greenhouse gas emissions (Nusli et al., 2024).

Although sustainability certifications aim to promote environmentally friendly practices, the palm oil industry continues to face sharp criticism regarding its environmental impacts. Palm oil products are often criticized for causing deforestation, land-use changes, peatland conversion, species extinction, greenhouse gas emissions, biomass waste, violations of indigenous rights, and limited local employment opportunities (Lim and Biswas, 2019). Additionally, the palm oil supply chain raises environmental concerns, as the sector's expansion often leads to land degradation and biodiversity loss (Gatti et al., 2019). Climate change exacerbates these challenges by reducing areas suitable for new oil palm plantations, limiting options for replacing losses from existing plantations, and increasing pressure on natural frontier areas (Descals et al., 2020; Runtuboi et al., 2021). The impact is particularly severe for smallholder farmers in regions like southern Sumatra and Kalimantan, who struggle to adapt to changing climatic conditions. Expansion into frontier areas also harms local communities by stripping them of land rights and reducing their livelihoods and welfare (Runtuboi et al., 2021; Andrianto et al., 2019).

Climate change has also resulted in rising temperatures, shifting rainfall patterns, and recurring extreme weather events like droughts and floods (Tang, 2019). These changes directly affect the quality and quantity of palm oil and fresh fruit bunches produced per tree (Shanmuganathan and Narayanan, 2012). Ahmad and Hossain (2015) and Paterson and Lima (2018) explained that climate change negatively affects oil palm agronomy, including reduced yields and lower production quality due to temperature stress and disrupted rainfall patterns. Chizari et al. (2017) used the autoregressive distributed lag (ARDL) economic model to examine the impact of climate change on palm oil production in Malaysia. The study predicts that unstable changes in temperature and rainfall will lead to a decline in yields. The significant impact of this climate change is reflected in the 3.3% reduction in palm oil production, from 17 million tons to 16.99 million tons in 2009 (Zainal et al., 2012). Paterson (2019a, 2019b) estimated that palm oil production could decline sharply after 2050 due to increasingly unsuitable climatic conditions, and that the crop's resilience to climate change may deteriorate between 2070 and 2,100, threatening long-term sustainability. Climate change may significantly affect production through rising temperatures, land degradation, and increased vulnerability to pests and diseases (Sarkar et al., 2020).

The impact of climate change on palm oil production has become a major concern, with declining yields and increasingly evident challenges (Fitzherbert et al., 2008). Unstable temperature and rainfall patterns have affected production, particularly in regions that rely on palm oil as a main commodity (Paterson and Lima, 2018). In addition to environmental and economic impacts, the social effects are also significant. Smallholder farmers face difficulties in maintaining their livelihoods due to declining yields and unpredictable weather conditions (Ahmad et al., 2022). Productivity instability can lead to income uncertainty, weakened food security, and increased competition for land and resources, potentially exacerbating social conflicts (Gomiero, 2016). Therefore, a deeper understanding of the impact of climate change on palm oil is needed to formulate more effective adaptation strategies (Sheil et al., 2009).

To address research gaps, this study aims to systematically review the impact of climate change on palm oil production. To achieve this objective, three key aspects will be examined: (1) to explore the spatial and temporal patterns of research on the impact of climate change on palm oil within the 2015–2025 timeframe; (2) to analyze the contextual issues discussed in studies related to climate change and its implications for palm oil productivity and physical conditions; and (3) to discover the methods or approaches used in research to understand and address the impact of climate change on the palm oil sector.

2 Research methodology

2.1 PRISMA (preferred reporting items for systematic reviews and meta-analyses)

This research employs a systematic review method called Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which includes materials from trusted sources. PRISMA involves four processes: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. We constructed a PRISMA flowchart to illustrate the data collection and screening process, as this method is commonly used in literature reviews and is effective in reducing bias (Knobloch et al., 2011; Prisma, 2015; Selçuk, 2019). PRISMA was used as a guide for the systematic review in this research and is frequently applied in the health and environmental sectors to conduct systematic reviews and meta-analyses (Nor Diana et al., 2022). In this research, PRISMA was used as a guide for a four-step systematic review to assess the impact of climate change on oil palm plantations. Additionally, PRISMA enables comprehensive searches for terms related to climate change and its effects on palm oil plantations.

2.2 Formulation of the research question

The research questions in this study were formulated based on the PICo framework, which helped the authors develop relevant questions for the literature review. PICo focuses on three main elements: Population or Problem, Interest, and Context (Abas et al., 2022). Based on these concepts, this study examines three main aspects in the review: oil palm plantations (population/problem), climate change factors (interest), and their impact on productivity and plant health (context). Against this background, this systematic review seeks to answer the following questions: (1) How does climate change affect the economy, productivity, and environmental health of oil palm plantations?; (2) What are the social impacts of climate change on the oil palm industry, such as on farmers and surrounding communities?; (3) What strategies and policies have been implemented to address the impacts of climate change, and how effective are these strategies in ensuring the long-term sustainability of oil palm plantations?

2.3 Resources

This research relies heavily on two leading scientific journal databases, namely Scopus and WOS, which are accessible to the authors through their institutional library subscriptions. These two databases provide access to a wide range of recent publications, including those from Wiley, ScienceDirect, Emerald, and Springer, facilitating the synthesis of relevant literature (Munodawafa and Johl, 2019; Shaffril et al., 2018). One of the largest and most comprehensive databases for abstracts and citations of scientific journals, peer-reviewed books, and conference proceedings is SCOPUS (Abas et al., 2021). This database covers more than 5,000 publishers worldwide and includes journals in the fields of science, technology, medicine, and social sciences, with over 22,000 titles. Meanwhile, Web of Science, managed by Clarivate Analytics, includes articles from 256 disciplines, including natural sciences, social sciences, arts, and humanities. WoS provides a variety of materials, such as full-text articles, reviews, editorials, abstracts, conference proceedings, and book chapters, with more than 33,000 journals published from 1900 to 2020 (Nor Diana et al., 2022).

2.4 Systematic searching strategies

The three main steps involved in a systematic search strategy are identification, screening, and eligibility, as illustrated in Figure 1.

2.4.1 Identification

The initial stage involved identifying keywords, which was then followed by searching for related and similar terms using resources such as thesauruses, dictionaries, encyclopedias, and previous studies (Arifin et al., 2023). Mohamed Shaffril et al. (2021) emphasize the need to refine primary keywords to obtain more relevant articles for systematic literature reviews (SLR). To broaden the search, several synonyms, related terms, and variations of the main keywords must be explored. The use of appropriate keywords significantly influences the quality and relevance of the articles found. In this case, the keywords used include terms related to climate change and palm oil, such as "climate change," "palm oil," and "impact," as well as variations like "climate variability," "climate extremes," "climate extremes," and "consequence." This literature search leverages the combination of these keywords to ensure that relevant articles are comprehensively identified.

As shown in Table 1, this study enriches a series of keyword strings using the WoS and Scopus databases to search for the required articles. WoS and Scopus are websites that offer subscription-based access to various databases, as well as detailed citation data for a wide range of academic topics (Abas, 2023). Scopus and Web of Science were chosen because both offer several advantages, such as advanced search capabilities, broader subject coverage, and access to more comprehensive content, including journals discussing climate change (Shaffril et al., 2021; Gusenbauer and Haddaway, 2020).

2.4.2 Screening

A total of 494 articles were initially screened to identify and remove duplicates. This process eliminated 125 duplicate articles, leaving 369 articles for further review. Subsequently, these articles were re-evaluated to ensure the quality of the review, retaining only those that met specific criteria: containing empirical data, published in journals, dated between 2015 and 2025, and written in English. Other types of publications, such as books, annual reports, short reviews, and so on, were not included (Abas, 2021). This time frame was chosen because it reflects the most recent developments related to climate change and its impact on the palm oil sector. Over the past decade, attention to this issue has increased, with many relevant policies and new studies emerging. By limiting the time frame to this period, the study can include more up-to-date and relevant information in line with current conditions. This selection process excluded 180 articles that did not meet the inclusion criteria. Consequently, 189 articles qualified for the next stage, which involved an eligibility evaluation.

2.4.3 Eligibility

The third step, eligibility, involves the writers personally reviewing the articles that were obtained to make sure that, following the screening procedure, every last article met the requirements. Reading the paper titles and abstracts was how this procedure was completed (Abas et al., 2022). A total of 92 articles were excluded for various reasons, such as being unrelated to climate change and palm oil. For example, articles that discussed palm oil but were not related to climate change, or vice versa, as well as articles lacking empirical data. Articles that did not provide a clear methodology or were published in formats other than journals, such as book chapters, books, proceedings, or conference papers, were also excluded. As a result, only 97 articles remained and were accepted for the next stage.

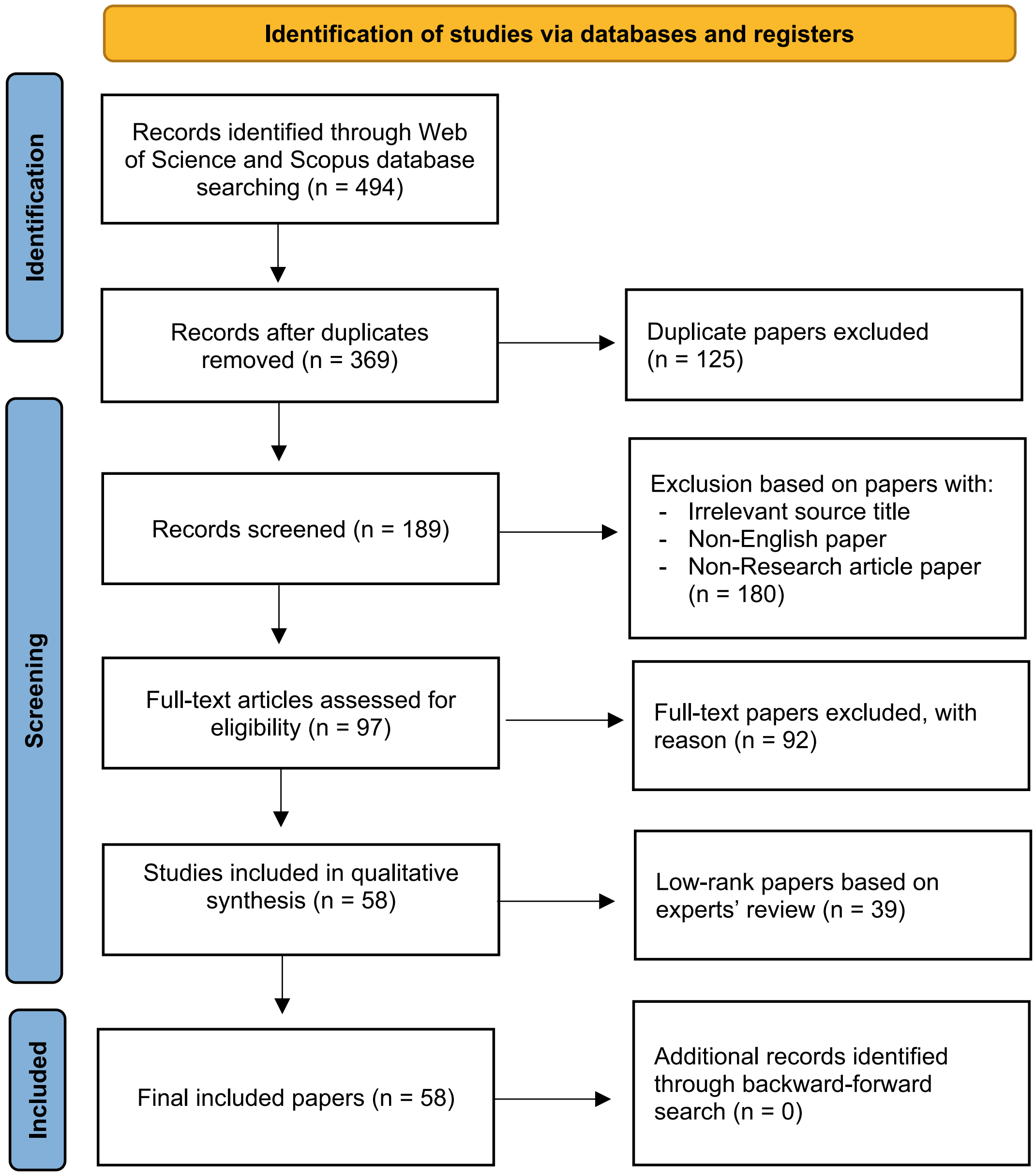


FIGURE 1
Flowchart of the process.

2.4.4 Quality appraisal

Quality appraisal procedures are typically conducted to ensure the quality of the article's content. The remaining articles from the eligibility method must be examined to ensure technical accuracy and that they are free from bias (Mohamed Shaffril et al., 2021). The remaining articles were divided into three quality categories: high, moderate, and low based on a qualitative assessment using three parameters: clarity of research objectives, methodological rigor (e.g., data collection and analysis), and relevance to the review topic. Only articles categorized as high and moderate were selected for further review (Azmi et al., 2023). In this study, two reviewers were chosen for quality assessment. Of the 97 remaining articles, 48 were rated as high quality, 14 as moderate quality, and 39 were classified as low quality. Only high and moderate-quality articles were eligible for further review, so 58 articles proceeded, while the remaining 58 were excluded due to not meeting the expected quality standards.

2.4.5 Data abstraction and analysis

In this study, thematic analysis was used to generate themes and subthemes relevant to the research topic (Abas et al., 2022). According to Braun and Clarke (2006), thematic analysis aims to identify patterns and themes through processes of grouping, counting, and recording similarities and relationships within the filtered data. Related data are then grouped into relevant categories. This process involves data synthesis, which refers to a set of techniques used to summarize, integrate, and combine findings from various studies on a specific topic or research question. After conducting thematic analysis, the final step of the systematic literature review (SLR) is to report the results through analysis and

TABLE 1 The search strings.

Database	Search strings
Web of science	TS = ("climate change" OR "global warming" OR "climate variability" OR "climate extremes") AND TS = ("oil palm" OR "palm oil" OR "oil palm plantation" OR "palm oil industry") AND TS = ("productivity" OR "yield" OR "growth" OR "physical condition" OR "growth performance" OR "crop yield") AND TS = ("impact" OR "effect" OR "influence" OR "consequence" OR "damage" OR "change")
Scopus	TITLE-ABS-KEY("climate change" OR "global warming" OR "climate variability" OR "climate extremes") AND TITLE-ABS-KEY("oil palm" OR "palm oil" OR "oil palm plantation" OR "palm oil industry") AND TITLE-ABS-KEY("productivity" OR "yield" OR "growth" OR "physical condition" OR "growth performance" OR "crop yield") AND TITLE-ABS-KEY("impact" OR "effect" OR "influence" OR "consequence" OR "damage" OR "change")

discussion (Salmah et al., 2017). Thematic analysis enables the identification of main themes and the structuring of literature, providing reviewers with the flexibility to adapt this method, and facilitating the integration of evidence from qualitative, quantitative, and mixed methods research (Dixon-Woods et al., 2005). In this study, after a thorough analysis, four themes were identified: (1) environmental health, (2) economy and productivity, (3) social or community wellbeing and (4) strategies or policies.

3 Results

3.1 Spatial and temporal analysis of selected articles

The distribution of articles by country highlights a broad geographical focus on climate change and its impact on oil palm plantations. Based on Figure 2a, Malaysia contributed the highest number of articles, with 19 articles, followed by Indonesia with 12 articles, reflecting their dominant roles in the palm oil industry. Thailand appears in 5 articles, while Colombia is represented in 4 articles. Nigeria is included in 3 articles, and Brazil appears in 2 articles. Other countries, such as Cameroon, Ghana, and Costa Rica, each contribute 1 article, indicating some level of research interest in these regions.

Additionally, several articles cover multiple countries simultaneously. Six articles focus on both Malaysia and Indonesia, emphasizing their shared significance in palm oil production. One article discusses a broader set of countries, including Colombia, Ecuador, Brazil, Malaysia, and Indonesia, while another examines various countries in Africa, suggesting a regional perspective rather than a country-specific analysis. Moreover, one article covers multiple Southeast Asian nations, including Indonesia, Malaysia, the Philippines, Cambodia, Laos, and Thailand, highlighting the interconnectedness of the palm oil industry in the region. Finally, one article does not specify a particular location, indicating a more global approach to the topic. This distribution, as illustrated in Figure 2a, underscores the extensive and worldwide scope of research on climate change and its impact on oil palm plantations.

Based on the analysis conducted, the 58 articles examined are distributed from 2015 to 2024. The highest number of articles were published in 2021 and 2024, with 10 articles each. This is followed by 2022 with 9 articles and 2023 with 8 articles. The year 2020 recorded 6 articles, while 2017 had 4 articles. The years 2015, 2018, and 2019 each had 3 articles. Finally, 2016 had 2 articles. This trend indicates a significant increase in the publication of articles on climate change, with a clear surge observed from 2020 to 2024. It reflects the growing attention and research interest in the impact of climate change on oil palm, as shown in Figure 2b.

3.2 Impact of climate change on oil palm production—contextual issues

The methodological approaches used in the analyzed articles are summarized in Figure 3a. A total of 28 articles employed Document Analysis, making it the most frequently used method (48%). This is followed by Experiments, which were utilized in 16 articles (27%), indicating a strong reliance on controlled studies to assess the impacts of climate change. Surveys and Interviews were each used in 5 articles (9%), highlighting the importance of stakeholder perspectives in understanding climate-related challenges. Lastly, Observations were conducted in 4 articles (7%), providing direct field assessments of climate change impacts on oil palm plantations.

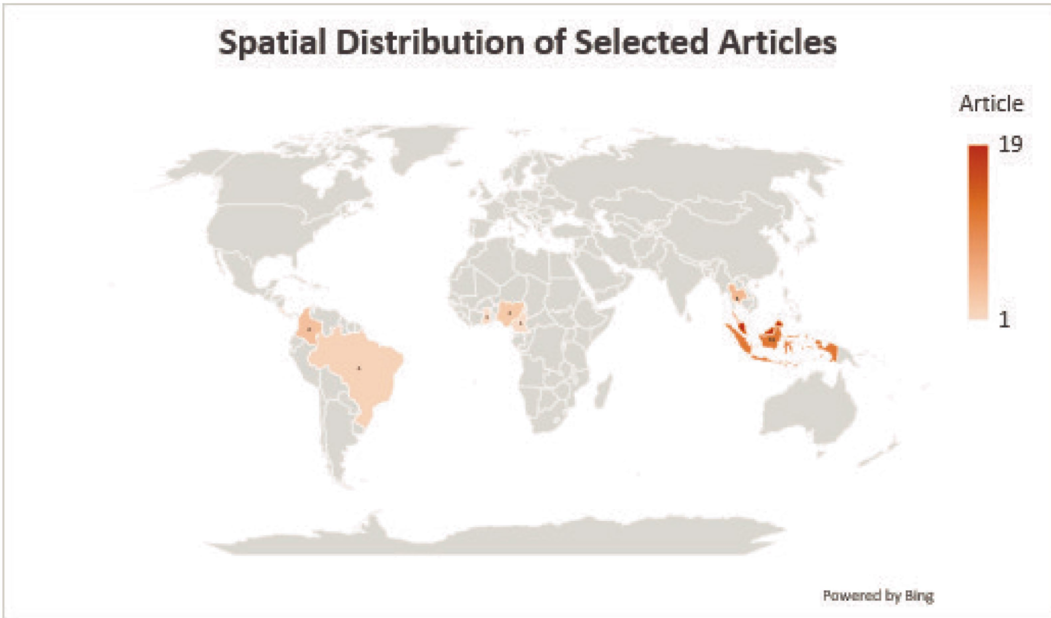
Based on Figure 3b, the analysis of 58 articles shows that climate change factors affecting oil palm plantations are highly diverse. The most dominant factor is temperature, which appears 32 times (40%), indicating that temperature changes have a significant impact on the productivity and physical condition of oil palm. Other frequently mentioned factors include rainfall, which appears 29 times (36%), followed by humidity at 12 times (15%) and Drought which appears 7 times (9%). These findings indicate that temperature and rainfall are the primary factors influencing the impact of climate change on oil palm, affecting growth, productivity, and the plant's resilience to changing environmental conditions.

3.3 Impact of climate change on oil palm production—thematic analysis

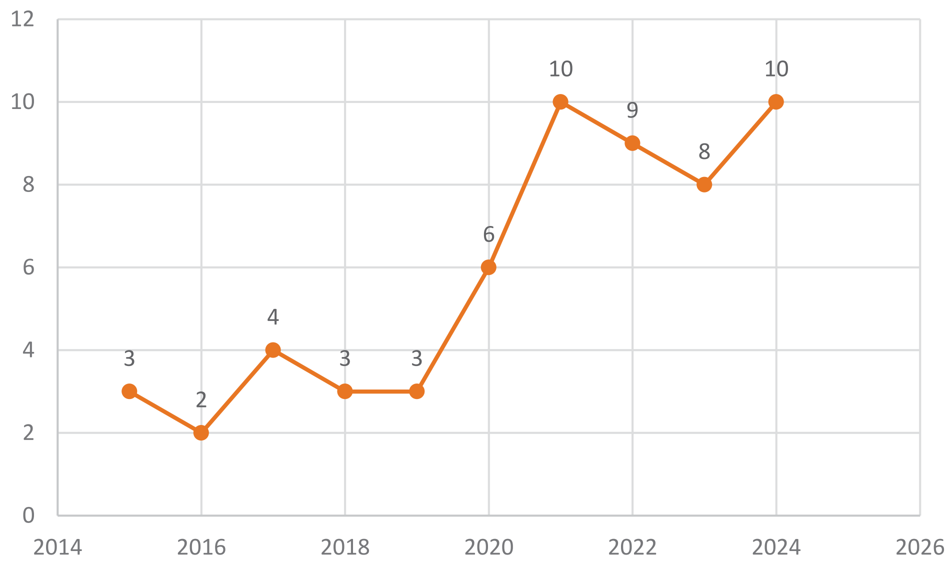
Four main themes related to the impact of climate change on oil palm plantations were identified: (a) environmental health, (b) economy, (c) community wellbeing, and (d) Strategies and Policies. Among these, Environmental Health emerged as the most frequently discussed theme, representing 55% of the total references (32 papers). This was followed by Economy at 22% (13 papers), Strategies and Policies at 14% (8 papers), and Community Wellbeing at 9% (5 papers) (Figure 4).

These four themes were driven by various climate-related environmental factors frequently reported across the reviewed literature. Table 1 categorizes the climate change variables found in the studies, which underpin the discussions across all thematic areas.

Table 2 presents a categorization of climate change factors commonly reported in the selected studies. The factors are grouped into thematic categories based on their environmental characteristics



(a)



(b)

FIGURE 2
(a) The spatial distribution of selected articles. **(b)** The temporal distribution of selected articles.

and frequency of occurrence. Temperature and heat stress emerged as the most frequently mentioned variables, followed by rainfall variability and drought-related stress.

a. Environmental health

Climate change has a significant impact on oil palm (*Elaeis guineensis*) plantations, particularly in terms of water availability, soil fertility, and pest and disease dynamics. Rising temperatures and unstable rainfall patterns induce physiological stress, reduce productivity, and increase pest infestations, leading to greater dependence on pesticides (Rival, 2017). Additionally, changes in temperature and CO_2 levels affect soil microbial communities, reducing nitrogen and phosphorus availability and lowering nutrient uptake efficiency. Climate change also accelerates weed growth, increasing management costs and potentially reducing yields by up to 20% (Dilipkumar et al., 2017). Beyond its effects on nutrient dynamics and weed competition, climate change also heightens the risk of disease infections in oil palm. Paterson (2019b, 2020a, 2020b, 2020c) highlighted the increasing incidence of Basal

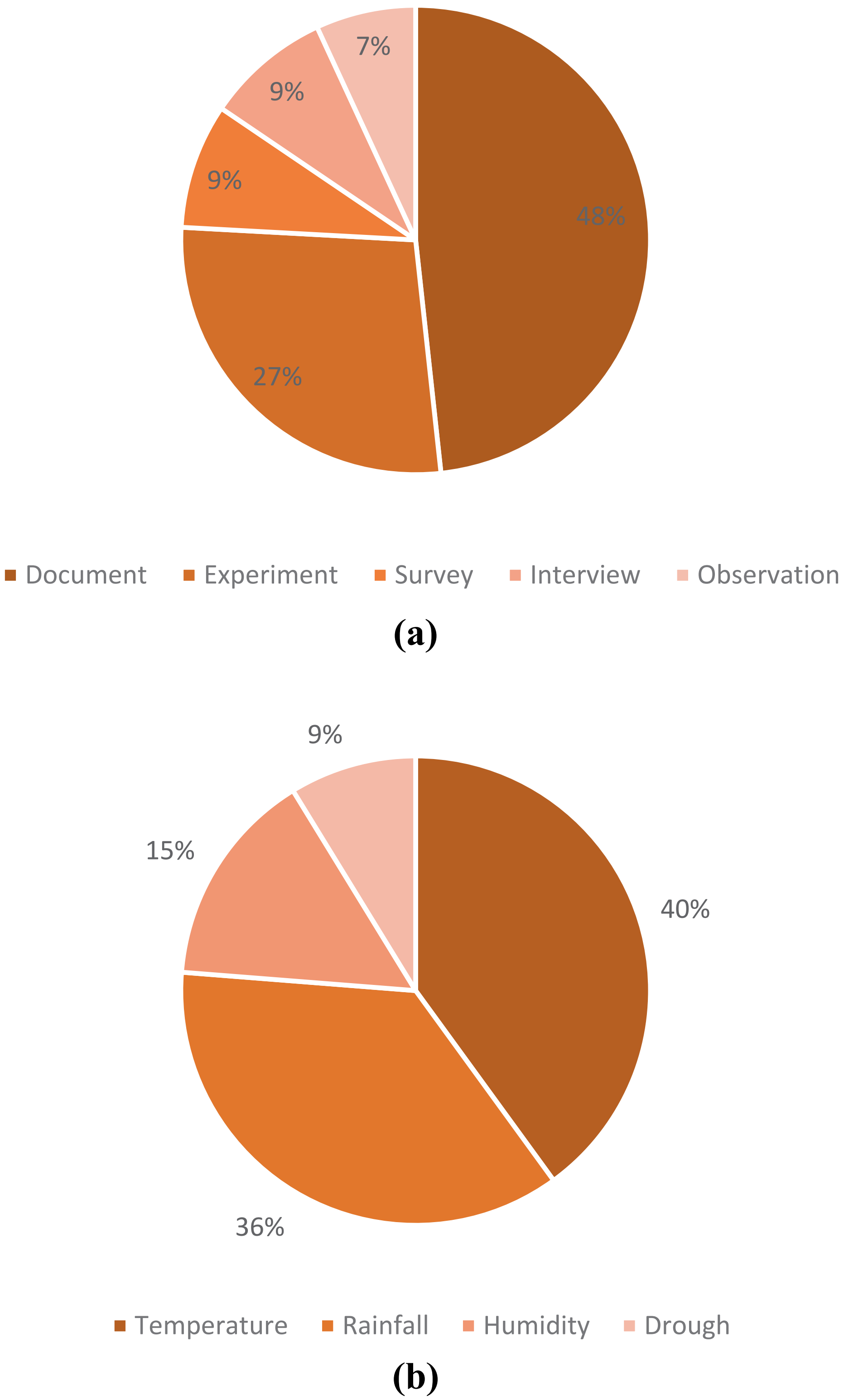


FIGURE 3
(a) Method used in selected articles. **(b)** Type of climate change factor.

Stem Rot (BSR) caused by *Ganoderma boninense*, exacerbated by temperature fluctuations, irregular rainfall, and replanting practices. Currently, 50% of oil palm plantations in Peninsular Malaysia are infected, and by 2,100, it is projected that all plantations will be affected. The total area suitable for oil palm cultivation in Malaysia is also expected to decline from 93 to 42%, although *Sabah* and *Sarawak* demonstrate greater resilience. Additionally, climate change increases the prevalence of

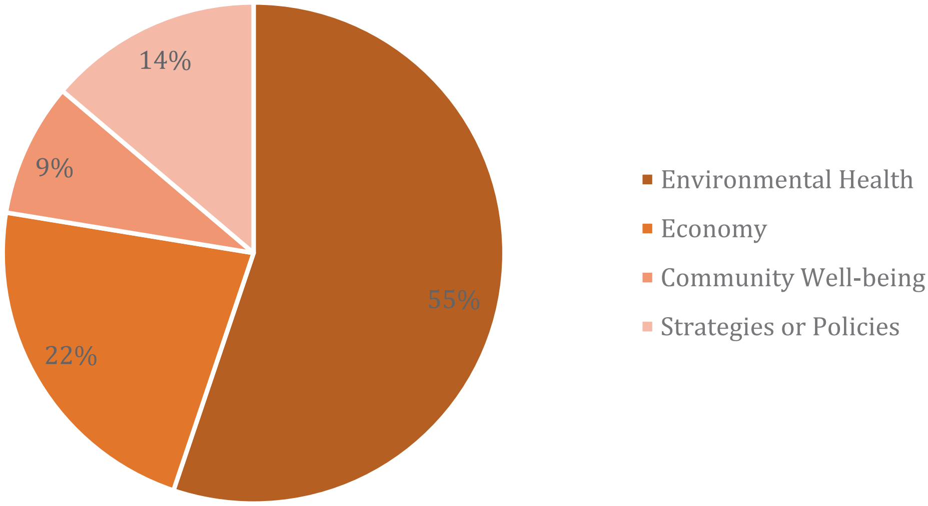


FIGURE 4
The impact of climate change on oil palm plantations.

TABLE 2 Categorization of climate change factors identified in the reviewed studies.

Factor category	Frequency	Example terms	Percentage*
Temperature and heat stress	68	Temperature increase; heat stress; cold stress	30.6%
Rainfall and precipitation	48	Rainfall variability; precipitation; heavy rains	21.6%
Drought and water stress	22	Drought conditions; water deficit; dry periods	9.9%
Extreme weather events	15	Flooding; storms; extreme weather events	6.8%
Humidity	13	Humidity levels; humidity	5.9%
Carbon dioxide	12	CO_2 concentration; carbon dioxide levels	5.4%
Soil moisture	7	Soil moisture dynamics; soil moisture	3.1%
Pests and diseases	7	Pests and diseases; fusarium wilt	3.1%
Soil quality	7	Soil fertility deterioration; soil quality	3.1%
… (other categories)	…	…	…

*Percentage is based on the total number of mentions across all reviewed studies.

Phytophthora palmivora, which spreads more extensively due to rising humidity and drought stress. Predictive models for 2050 and 2,100 indicate a significant risk to plant health and a substantial decline in oil palm productivity.

Climate change triggers fluctuations in soil moisture, shifts in monsoon patterns, and extreme weather events, leading to plant stress and reduced oil palm (*Elaeis guineensis*) productivity. Adaptation strategies such as soil moisture management, agroforestry, and the development of climate-resilient varieties are essential to mitigate these impacts (Abubakar et al., 2023). In Borneo, forest fragmentation caused by oil palm expansion during the *El Niño* event of 2015–2016 accelerated leaf loss, reduced productivity, and increased tree mortality, particularly in forests adjacent to plantations (Nunes et al., 2021). Conversely, the conversion of savanna into oil palm plantations can enhance ecosystem carbon storage by up to 40 ± 13 *Mg C per hectare*, provided that organic matter management maintains soil microbial activity at levels comparable to natural ecosystems (Carlos et al., 2021). Additionally, rising temperatures and changing rainfall patterns reduce water availability for oil palm, affecting growth and yields (Gunawan et al., 2020). The application of organic materials, such as *Empty Fruit Bunches (EFB)* and *Nephrolepis biserrata* vegetation, has been shown to improve soil quality and water retention capacity, mitigating the adverse effects of climate change. The *CLIMEX* model predicts that climate suitability for oil palm cultivation in Africa will decline by 2,100, although certain regions, such as Uganda, may still offer viable conditions for oil palm farming (Paterson, 2021a). Furthermore, a temperature increase of 1–4°C could reduce yields by up to 41%, accelerate water stress, and enhance the spread of *Basal Stem Rot (BSR)* caused by *Ganoderma boninense*, with infection rates projected to reach 100% in certain regions, such as Sumatra, by 2,100 (Abubakar et al., 2022).

RNA sequencing studies have identified 1,087 genes involved in oil palm (*Elaeis guineensis*) responses to heat stress, with 64 genes showing significant changes. Among these, 12.5% are heat shock proteins (HSPs), which play a crucial role in high-temperature tolerance (Maryanto et al., 2021). These findings support the development of heat-stress-tolerant oil palm varieties. Temperature fluctuations also affect the life cycle of *Metisa plana*, a major oil palm pest that thrives in temperatures ranging from 20–36°C. Climate change-induced temperature variations may lead to increased pest populations and reduced yields (Enting and Latip, 2021). Other climatic factors, such as vapor pressure deficit (VPD) and water availability, also impact productivity. High temperatures and elevated *VPD* hinder photosynthesis due to stomatal closure, while hydrological stress disrupts vegetation growth (Benezoli et al., 2021). Meanwhile, increased atmospheric CO_2 levels have the potential to boost yields, but temperature and rainfall remain limiting factors. The LPJmL4 model projects production increases under various climate scenarios, highlighting the need to optimize the fertilization effect of CO_2 while mitigating its adverse impacts (Beringer et al., 2023; Beringer et al., 2023). However, environmental influences vary regionally. In Malaysia, yield variations are more strongly influenced by plantation-specific differences rather than climatic factors, which account for <1% of total variation (Fleiss et al., 2022). In Colombia, water availability of 450–600 L per day supports oil palm growth, whereas water deficits reduce productivity (Delgado et al., 2024). In Costa Rica, climate change is predicted to cause an 18.06% decline in rainfall and a 3.31°C temperature increase, leading to higher irrigation demands (Watson-hern et al., 2023). Meanwhile, southern Nigeria is expected to remain suitable for oil palm cultivation until 2050, whereas northern regions will experience reduced suitability due to high temperatures and an increased risk of *Fusarium wilt* (Paterson and Chidi, 2023).

Soil moisture fluctuations, monsoon pattern shifts, and increased extreme weather events driven by climate change exert significant pressure on oil palm (*Elaeis guineensis*) ecosystems. In Thailand, predictive models indicate a rise in plant mortality due to climate-induced stress, whereas the impact in Indonesia and Malaysia is comparatively lower (Pater Ruson, 2023). To address this issue, modified oil palm (*mOP*) varieties are being developed, although further research is required. Additionally, the interaction between plant physiology and environmental factors influences oil palm adaptation. Full defoliation in *pisifera* palms has been found to increase male inflorescence production by 104% in response to mechanical stress and water deficits, demonstrating an acclimatization mechanism (Ajambang et al., 2015). In Sumatra, forest-to-plantation conversion disrupts carbon and nutrient cycles, increasing environmental vulnerability to climate change (Kotowska et al., 2016). Genotype-environment interactions also affect yields, with certain progenies exhibiting greater tolerance to climatic variability (Bueraheng et al., 2018). Innovations such as Self-Purging Microwave Pyrolysis (SPMP) have proven effective in converting oil palm shells into environmentally friendly biochar (Kong et al., 2018). Furthermore, the concentration of non-structural carbohydrates in oil palm stems plays a crucial role in reproductive growth, influenced by temperature and rainfall, suggesting opportunities for optimization to enhance production.

The conversion of forests into oil palm (*Elaeis guineensis*) plantations disrupts the hydrological balance, with forests in Sabah exhibiting better water availability compared to mature plantations. Consequently, forest conservation proves to be more effective in maintaining hydrological stability amid climate change (Nainar et al., 2022). Additionally, land conversion accelerates environmental degradation, as seen in Kepau Jaya, where deforestation occurs at a rate of 23.15 ha/year, while oil palm expansion increases by 40.10 ha/year, leading to reduced carbon storage and peatland ecosystem degradation. This highlights the critical need for rehabilitation through agroforestry (Frianto and Sutrisno, 2024). Forest conversion also increases carbon emissions, though its long-term impact can be mitigated through sustainable policies (Nurhayati et al., 2022). The rising incidence of diseases in oil palm further exacerbates ecosystem degradation, affecting forest health, carbon balance, and landscape dynamics. Oil palm productivity varies due to climate change; however, adaptive strategies such as adjusting planting dates and irrigation can mitigate negative effects (Okoro et al., 2017). Drought responses among oil palm cultivars also differ, with some varieties exhibiting higher resistance (Bayona-Rodriguez and Romero, 2019). Furthermore, the concentration of non-structural carbohydrates in oil palm stems, influenced by temperature and rainfall, plays a crucial role in reproductive growth and optimizing oil palm production (Tani et al., 2020).

b. Economy

Climate change has significantly impacted the productivity and economic viability of the oil palm (*Elaeis guineensis*) sector across various countries. Paterson et al. (2015) reported that climate change substantially reduces land suitability for oil palm cultivation in Malaysia and Indonesia, with a potential shrinkage of over 220,000 km^2 by 2030 and even greater impacts projected by 2,100. This decline implies reduced productivity and economic profitability while simultaneously increasing environmental pressure due to potential land-use shifts to alternative commodities. A similar trend was observed by Rhebergen et al. (2016), who noted that rainfall variability in Ghana has led to decreased oil palm productivity, increasing reliance on palm oil imports and negatively affecting the local economy. Meanwhile, Noor et al. (2024) found that in Malaysia, fertilizer use, palm oil prices, and plantation area positively contribute to long-term production, whereas rainfall has a short-term negative impact but enhances yields over the long run. Predictive models indicate that under a minimal climate change scenario, production could increase by 5% by 2030, whereas in an extreme scenario, yields could decline by up to 16.41 tons/ha. These findings underscore the need for adaptation strategies to ensure the sustainability of production and economic stability in the oil palm industry.

Climate change can have both positive and negative effects on agricultural productivity, depending on crop type and regional conditions. Corte's-Cataño et al. (2024) found that in Colombia, rising average temperatures negatively impact major crops such as coffee, rice, and sugarcane, whereas oil palm (*Elaeis guineensis*) and maize exhibit increased productivity. This suggests that climate change effects on agriculture are highly crop-specific. Similarly, Jatuporn and Takeuchi (2024) reported that in Thailand, a rise in average temperature could boost oil palm productivity by 17.987% per 1% temperature increase. However, variations in minimum temperature reduce productivity by 8.707%, while higher rainfall enhances yields by 0.345%. Water management plays a crucial role in mitigating climate risks, with irrigation systems improving oil palm productivity by up to 35% during El Niño-induced droughts (Brum et al., 2021). The impacts of El Niño and La Niña on oil palm yields were further confirmed by Kamil et al. (2024), who found that extreme *ENSO* (El Niño-Southern Oscillation) events significantly reduce fresh fruit bunch (FFB) yields and oil extraction rates, particularly in plantations with low investment in fertilizers and labor. These findings highlight the importance of adaptive strategies to sustain productivity under increasing climate variability.

However, Khong et al. (2023) found that while temperature increases up to 27.01°C can enhance oil palm (*Elaeis guineensis*) yields, further warming beyond this threshold leads to a decline in productivity. In Malaysia, extreme drought conditions reduce yields due to a decrease in male flower production (Musa et al., 2019). These climatic shifts influence farmers' decisions, such as the shift from rubber to oil palm cultivation in Ketapang to ensure income stability (Widayati et al., 2021). Samsuddin et al. (2024) highlighted that temperature and rainfall variability could reduce land suitability for oil palm cultivation, increasing operational costs and reducing economic output. For example, the opportunity cost of preventing deforestation caused by oil palm expansion in Indonesia is estimated at 24.42 USD/tCO_2 eq, significantly higher than the carbon market price in 2011 (Li et al., 2021). One potential solution to mitigate these challenges is the implementation of sustainability standards such as the Malaysian Sustainable Palm Oil (MSPO) certification. Hamid et al. (2024) found that MSPO adoption not only enhances sustainable production but also improves market access and economic wellbeing for Malaysian oil palm farmers.

c. Community wellbeing

Climate change impacts environmental health and oil palm (*Elaeis guineensis*) productivity by altering temperature and rainfall patterns, affecting soil fertility, biodiversity, and water availability. Increased rainfall leads to nutrient leaching, reducing soil fertility, while excessive fertilizer use exacerbates water pollution and threatens aquatic ecosystems (Somboonsuke et al., 2018). The conversion of forests into oil palm plantations reduces biodiversity and the ecosystem's carbon storage capacity, with an average carbon loss of 157 tons per hectare and up to an 80% decline in ecosystem functions due to deforestation (Qaim et al., 2020; Paterson, 2021b). The loss of forests also affects communities reliant on natural resources by limiting access to food, medicinal plants, and other livelihoods. Regarding hydrological balance, deforestation lowers river baseflow, exacerbates clean water shortages, and heightens the risk of conflicts over water resources (Nainar et al., 2022). Additionally, shifting rainfall and temperature patterns may reduce land suitability for oil palm cultivation, triggering expansion into new areas, increasing deforestation, and intensifying tenure conflicts between communities and corporations (Appelt et al., 2023).

d. Strategies or policies

Mitigation and adaptation strategies in the palm oil industry involve environmental regulations, incentives for sustainable practices, and investments in climate-friendly technology. Austin et al. (2015) found that a moratorium on the conversion of primary forests and peatlands can reduce greenhouse gas (/GHG/) emissions by up to 10%, while restricting expansion into all peatlands and forests can lower emissions by up to 35%. However, the implementation of these policies faces challenges, including industry resistance and social conflicts. Additionally, the effectiveness of mitigation strategies, as examined by Alisjahbana and Busch (2017), remains limited due to weak government coordination and law enforcement. Nevertheless, several strategies have been implemented to manage palm oil plantations in Indonesia, including a moratorium on land conversion, zoning for forest protection, and improving productivity on existing land. Beyond policies and regulations, technological innovation plays a crucial role in enhancing the sector's resilience. Rajakal et al. (2021) reported that changes in rainfall patterns and rising temperatures have led to a decrease in fresh fruit bunch (/FFB/) yields by up to 33.31%, highlighting the need for predictive models that consider plant age and climatic conditions to manage risks. Ang et al. (2022) developed a deep learning-based yield prediction model, which has proven to be highly accurate in forecasting production based on climate and vegetation data. In the energy sector, Wattana et al. (2022) demonstrated that palm oil-based biofuel use can reduce CO_2 emissions, supporting a transition to sustainable energy. Usapein et al. (2022) emphasized the importance of advancing production technology research and utilizing biomass to enhance the industry's value-added potential. In terms of land suitability, Paterson and Chidi (2023) predicted that climate change could reduce the suitability of palm oil cultivation in Nigeria, particularly in the northern region, making land zoning and varietal diversification essential adaptation strategies. Lau et al. (2024) also identified that compost derived from palm oil waste can enhance plant growth and reduce dependence on chemical fertilizers, supporting a circular farming approach. Thus, the integration of policies, technology, and adaptation strategies is key to ensuring the sustainability of the palm oil industry amid the challenges of climate change.

4 Discussion

The impact of climate change on oil palm plantations is influenced by various environmental factors that affect plant growth and productivity. Factors such as temperature, rainfall, humidity, and extreme weather events play a crucial role in assessing the effects of climate change. Among the 58 studies analyzed, most employed document analysis, experiments, and field observations, while only a few utilized surveys and interviews. Among these factors, temperature, rainfall, and humidity were the most frequently cited as the primary influences on oil palm productivity. Research on the impact of climate change on oil palm plantations has increased annually (Paterson and Lima, 2018), in line with growing global awareness of climate change and its effects on the agricultural sector, particularly in 2021 and 2024. The selection of the 2015–2025 period for studying the impact of climate change on oil palm is based on the relevance of this timeframe to global environmental and policy issues. Over this decade, climate change has intensified, affecting temperature, rainfall patterns, and environmental conditions that directly influence oil palm productivity. In terms of spatial distribution, most research on the impact of climate change on oil palm plantations has been conducted in Southeast Asia, particularly in Malaysia and Indonesia, which are the world's two largest palm oil-producing countries. Thailand has also been a focus of research, although to a lesser extent compared to Malaysia and Indonesia. The dominance of studies in Southeast Asia reflects the region's significance in the global palm oil industry and the challenges it faces concerning climate change and environmental sustainability (Agus et al., 2013; Mukherjee and Sovacool, 2014). On the other hand, research from African and South American countries, such as Ghana, Cameroon, Nigeria, Costa Rica, and Brazil, remains limited. This is due to the relatively smaller extent of oil palm plantations in these countries, resulting in fewer studies on the impact of climate change on oil palm. While regional studies provide valuable information, most rely on secondary data and modeling. The lack of long-term field research, particularly in Africa and South America, makes it difficult to generalize findings globally.

Oil palm plantations face numerous challenges, including threats arising from climate change and the potential emergence of new pests and diseases (Murphy et al., 2021). Changes in rainfall patterns and rising temperatures can affect crop productivity, reduce harvest quality, and increase vulnerability to pests and diseases. According to Rival (2017), rising temperatures and rainfall variability can exacerbate plant stress and decrease productivity by influencing soil nutrient availability, particularly nitrogen and phosphorus, as well as increasing the risk of pathogen infections, including fungal diseases. A study conducted by Maryanto et al. (2021) revealed that oil palm (*Elaeis guineensis*) responds to heat stress through changes in gene expression. RNA sequencing analysis identified 1,087 genes involved in adaptation mechanisms to high temperatures, with 64 genes exhibiting significant changes in expression levels. Among these, 12.5% belong to the heat shock protein (HSP) family, which plays a crucial role in protecting plants from extreme temperature effects. Meanwhile, Abubakar et al. (2022) reported that climate change could reduce oil palm productivity by up to 41% due to temperature increases of 1 to 4°C and water stress. Additionally, *Ganoderma boninense* infections are predicted to rise sharply, with potential infection rates reaching 100% in Sumatra by 2,100. Several studies suggest that the impact of climate change on oil palm is highly contextual. A study in Thailand found a significant correlation between maximum and minimum temperatures and variations in oil palm yields, although the magnitude of the effect depended on the region and temperature range of the study (Chiarawipa et al., 2020). A study in Colombia also found that for every 1°C rise in average temperature, oil palm yield increased by 2.55%, although hydrological factors had no significant effect (Corte's-Cataño et al., 2024). These findings highlight that crop responses are strongly influenced by local conditions, genotype, and management practices.

The impact of climate change on oil palm health and productivity underscores the need for effective adaptation strategies. One of the primary approaches is the development and deployment of climate-resilient cultivars that can tolerate temperature extremes, variable rainfall, and associated environmental stressors. Various studies have identified specific varieties with enhanced tolerance, enabling oil palm to remain productive despite increasingly extreme environmental challenges. Based on research by Sujadi et al. (2020), varieties such as Dumpy, Avros, and PPKS 540 are predicted to adapt more effectively to rising air temperatures. For instance, the Dumpy variety is better suited for regions with high rainfall due to its slow vertical growth and shorter fronds, allowing better adaptation to humid conditions. Avros shows rapid bunch development and strong tolerance to heat stress and temperature fluctuations. PPKS 540, with its robust morphology, performs well in both wet and dry climates, showing high productivity and resilience to environmental stress. Additionally, the Lame, Langkat, and Simalungun varieties are more adaptive to drier areas. Lame is drought-tolerant and ideal for low and erratic rainfall zones; Langkat maintains productivity under dry conditions; and Simalungun is suitable for dry and fluctuating climates due to its high resistance to environmental stress. These findings suggest that site-specific cultivar selection, guided by regional climatic profiles, can significantly improve oil palm resilience under climate stress. Incorporating local knowledge and agroecological conditions into breeding programs will be essential to maintaining long-term productivity.

Oil palm plays a crucial role in the economies of several countries, particularly Indonesia and Malaysia, which export large quantities of various palm oil products, including crude palm oil, palm kernel meal, and its derivatives (Murphy, 2018). Climate change exerts significant economic pressure on oil palm plantations, leading to fluctuations in productivity. Changes in temperature and rainfall also affect the export of different agricultural commodities in varying ways. An annual temperature increase of 1 % is estimated to reduce coffee bean exports by 0.56%, as warmer temperatures can trigger the emergence of plant diseases that negatively impact coffee production. Conversely, rising temperatures have a positive effect on palm oil exports, with a 1 % increase in temperature potentially boosting exports by 0.59%, as warmer conditions support oil palm production (Purbantoro et al., 2024). However, this effect is likely valid only within the optimal temperature range of 24–33°C (Paterson et al., 2015), as temperatures above 34°C may negatively impact growth and productivity. Meanwhile, rainfall has a positive impact on cocoa bean exports, where a 1 % increase in rainfall can enhance exports by 0.047% (Purbantoro et al., 2024). These findings align with those of Jatuporn and Takeuchi (2024), who reported that in Thailand, an increase in average temperature could enhance oil palm productivity by up to 17.987%, although variations in minimum temperature had a negative effect, reducing productivity by 8.707%. Additionally, higher average rainfall positively influenced productivity, with increased rainfall contributing to a 0.345% rise in output. Similar trends were observed in a study conducted in Colombia by Corte's-Cataño et al. (2024), which found that rising average temperatures negatively affected the production of coffee, rice, and sugarcane but led to increased production of oil palm and maize. These mixed findings emphasize the need for climate-based trade models that take into account crop-specific thresholds and regional differences.

Climate change affects the production and export of palm oil, impacting farmers' livelihoods and community wellbeing. A study conducted in Langgikima District revealed that oil palm plantations contribute positively to the local economy and society by increasing income, creating employment opportunities, and supporting empowerment programs and environmental management (Rela et al., 2023). Another study found that the presence of oil palm plantations enhances social interactions, living conditions, and public awareness of the importance of community participation programs. A high social index indicates an improvement in quality of life, particularly in meeting basic needs such as education and healthcare, supported by stable income from the sector. However, challenges such as potential social tensions related to land disputes must be addressed through inclusive dialogue between companies and local communities (Ramadhan et al., 2024). On the other hand, the expansion of oil palm plantations has significant ecological consequences. Research in Jambi Province found that converting tropical rainforests into oil palm plantations leads to biodiversity loss and a reduction in carbon stocks of up to 157 tons per hectare, contributing to greenhouse gas emissions and disrupting ecosystem functions such as carbon storage and nutrient cycling (Qaim et al., 2020). Additionally, a study in Sabah, Malaysia, indicated that land-use changes lower baseflow and exacerbate water availability issues, particularly amid climate change (Nainar et al., 2022). These ecological impacts not only degrade the environment but also harm surrounding communities that rely on natural resources for their daily needs. The decline in water availability and biodiversity loss can threaten their livelihoods and overall quality of life in the long run.

In addressing the impacts of climate change on oil palm, various strategies and policies have been implemented to ensure the sustainability of the industry. Research by Austin et al. (2015) indicates that policies such as a moratorium on concessions in primary forests and peatlands, as well as restrictions on expansion in low-carbon stock areas, could reduce greenhouse gas (GHG) emissions by up to 60%. Additionally, the promotion of palm oil-based biofuels in diesel blends has the potential to reduce dependence on fossil fuels while lowering CO_2 and PM2.5 emissions, contributing to environmental health. An analysis using the LEAP model suggests that renewable energy policies must balance environmental sustainability, food security, and land management (Wattana et al., 2022). However, sustainability efforts in the palm oil industry do not rely solely on national policies and biofuel technology but also on the implementation of global certification standards.

Global strategies and policies to mitigate the impact of climate change on oil palm production include certification frameworks such as the Roundtable on Sustainable Palm Oil (RSPO), Malaysia Sustainable Palm Oil (MSPO), and Indonesia Sustainable Palm Oil (ISPO). The RSPO mandates the protection of High Conservation Value (HCV) and High Carbon Stock (HCS) forests, prohibits cultivation on peatlands, and aims to reduce emissions by up to 35% compared to non-certified palm oil (Kumaran, 2019; Brandi et al., 2015; Hidayat et al., 2018). The MSPO emphasizes the utilization of biogas, biomass energy, and zero-burning practices to limit emissions (0.38 MT CO_2 eq/ton), while the ISPO requires certification for all plantations to support Indonesia's emission reduction targets under the *Paris Agreement*. Collectively, these frameworks focus on preventing deforestation, promoting sustainable land management, and mitigating emissions (Mohd Hanafiah et al., 2022; Tropenbos Indonesia, 2020). A high-impact study by Sarkar et al. (2020) published in *Environmental Science and Pollution Research* underscores the urgency of these policies, projecting a 10–41% decline in palm oil yields in Malaysia due to a temperature increase of 1–4°C, along with production losses resulting from rising sea levels.

The Climate-Smart Agriculture (CSA) approach aims to transform agricultural systems toward environmentally friendly and climate-resilient practices through three main objectives: sustainably increasing productivity and income, building resilience to climate change (*climate-smart resilience*), and reducing greenhouse gas emissions. In the context of oil palm, CSA is relevant to support sustainable intensification through practices such as efficient water management, the use of drought-tolerant varieties, and agroforestry. CSA also aligns with the *FAO Strategic Framework 2022–2031*, which focuses on better production, better nutrition, a better environment, and a better life. Its implementation is context-specific and guided by five key actions, including strengthening policies and institutions, as well as field-level application. Integrating CSA principles into oil palm management can enhance resilience to climate stress and maintain yield stability (FAO, 2010). However, while CSA provides a strategic framework for climate adaptation in agriculture, addressing specific and localized challenges such as human-wildlife conflict in oil palm landscapes requires more targeted and integrated policy interventions.

Adaptation policies to address climate change in the oil palm plantation sector must holistically encompass economic, social, and ecological aspects. One of the increasing challenges driven by climate change is human-wildlife conflict. Habitat fragmentation caused by plantation expansion, environmental degradation, and the depletion of natural resources forces wildlife to move beyond their original habitats, leading to increased interactions with humans and posing risks to both community safety and wildlife population sustainability. Although various policies have been implemented to reduce deforestation and enhance plantation sustainability, a more comprehensive approach is still required to address human-wildlife conflict, which is exacerbated by climate change. Future studies should explore the relationship between climate variability, changes in wildlife movement patterns, and conflict risks in oil palm plantation landscapes. A spatial and temporal data-driven approach is needed to identify high-risk areas and analyze environmental factors contributing to conflict escalation. Additionally, evaluating the effectiveness of existing policies such as the development of wildlife corridors, the implementation of mitigation technologies, and compensation schemes for affected communities is crucial. Research that actively involves local communities can provide more contextually relevant insights for designing solutions grounded in social and ecological realities. By integrating wildlife conservation strategies, climate change adaptation, and sustainable development, more responsive and evidence-based policies can be developed to support the long-term sustainability of the oil palm plantation sector.

5 Conclusion

Climate change has significant impacts on oil palm plantations, with temperature, rainfall, and humidity being the key factors affecting plant growth and productivity. The analyzed studies indicate that research is predominantly concentrated in Southeast Asia, particularly in Malaysia and Indonesia, while studies in Africa and South America remain limited. Four main themes were identified in this study: environmental health, economy and productivity, social aspects and community wellbeing, and strategies and policies. In terms of environmental health, changing rainfall patterns and extreme temperatures contribute to increased risks of crop diseases and land degradation. From an economic perspective, climate change threatens to reduce yields and raise production costs, especially for smallholder farmers who have limited access to adaptive technologies. Socially, climate change exacerbates human-wildlife conflict (HWC) as shifts in natural habitats and declining natural resources drive wildlife into plantation areas, increasing the risk of negative interactions with humans. In the policy domain, various strategies have been implemented, such as a moratorium on expansion in high-carbon stock lands and the promotion of palm oil-based biofuel, though their long-term effectiveness remains challenged by economic sustainability concerns.

However, several research gaps need to be addressed, including the limited studies on smallholder farmers' adoption of water management technologies, the risks of soil erosion due to extreme rainfall, the long-term effectiveness of sustainability and biofuel policies, and the relationship between climate variability, wildlife movement, and human-wildlife conflict patterns in plantation areas. Addressing these gaps will provide a strong basis for policymakers to develop targeted support schemes, such as subsidies for irrigation technologies and training programs to increase adaptive capacity among smallholders. Additionally, mapping the link between climate-driven wildlife movement and conflict patterns can guide conservation agencies in designing proactive mitigation strategies.

To overcome these challenges, future research should focus on more inclusive adaptation strategies, particularly by enhancing smallholder resilience through broader access to sustainable technology and infrastructure. Multidisciplinary approaches that integrate artificial intelligence-based technologies, agroforestry practices, and ecosystem-based landscape management should also be developed to improve the sector's overall resilience. For instance, early warning systems powered by AI and remote sensing could be deployed to detect drought stress or pest outbreaks in real time, enabling both smallholders and large-scale producers to respond more rapidly and efficiently. Additionally, spatial and temporal data-driven approaches can be utilized to map high-risk human-wildlife conflict areas and identify environmental factors influencing wildlife movements. Further studies should evaluate the effectiveness of policies such as wildlife corridors, technology-based mitigation systems, and compensation mechanisms for affected communities.

From a policy perspective, governments need to strengthen regulations on environmental protection and provide incentives for the adoption of eco-friendly technologies in oil palm plantations. Meanwhile, NGOs and the industry should enhance collaboration to promote sustainable plantation practices and support research on climate change impacts on local communities. Furthermore, increasing investment in water resource management infrastructure and developing climate-resilient oil palm varieties are crucial steps to ensure the sector remains productive and sustainable amid the challenges posed by climate change. This review offers a conceptual basis for policymakers and industry stakeholders to design environmentally oriented incentives, strengthen public–private collaboration, and direct investments toward climate-adaptive technologies. The findings are expected to inform strategies that balance climate risk reduction with long-term productivity.

Author contributions

RW: Data curation, Investigation, Methodology, Writing – original draft. AzA: Funding acquisition, Supervision, Writing – review & editing. AbA: Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study has been funded by Universiti Kebangsaan Malaysia and Malaysia Palm Oil Green Conservation Foundation through research grant SK-2023-034.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

References

Abas, A. (2021). A systematic review on biomonitoring using lichen as the biological indicator: a decade of practices, progress and challenges. *Ecol. Indic.* 121:107197. doi: 10.1016/j.ecolind.2020.107197

Abas, A. (2023). A systematic literature review on the forest health biomonitoring technique: a decade of practice, progress, and challenge. *Front. Environ. Sci.* 11:970730. doi: 10.3389/fenvs.2023.970730

Abas, A., Aiyub, K., and Idris, N. A. (2021). Systematic review on ecosystem services (Es) of ecotourism in south-east asia (asean). *Probl. Ekorozw.* 16, 113–121. doi: 10.35784/pe.2021.1.12

Abas, A., Aziz, A., and Awang, A. (2022). A systematic review on the local wisdom of indigenous people in nature conservation. *Sustainability* 14:3415. doi: 10.3390/su14063415

Abas, A., Er, A. C., Tambi, N., and Yusoff, N. H. (2022). A systematic review on sustainable agricultural practices among oil palm farmers. *Outlook Agric.* 51, 155–163. doi: 10.1177/00307270211021875

Abubakar, A., Gambo, J., and Ishak, M. Y. (2023). Navigating climate challenges: change on oil palm cultivation and adaptation strategies. *Adv. Food Secur. Sustain* 8, 95–116. doi: 10.1016/bs.af2s.2023.07.002

Abubakar, A., Ishak, M. Y., and Makmom, A. A. (2022). Nexus between climate change and oil palm production in Malaysia: a review. *Environ. Monit. Assess.* 194:262. doi: 10.1007/s10661-022-09915-8

Abubakar, A., Yusoff, M., Aisyah, I., Bakar, A., and Kamal, M. (2022). *Ganoderma boninense* basal stem rot induced by climate change and its effect on oil palm. *Environ. Sustain.* 5, 289–303. doi: 10.1007/s42398-022-00244-7

Agus, F., Gunarso, P., Sahardjo, B. H., Harris, N., Noordwijk, M., and Killeen, T. J. (2013). Historical CO2 emissions from land use and land use change from the oil palm industry in Indonesia, Malaysia and Papua New Guinea. Roundtable sustain. *Palm Oil* 22, 65–88.

Ahmad, N. N. N., and Hossain, D. M. (2015). Climate change and global warming discourses and disclosures in the corporate annual reports: a study on the Malaysian companies. *Procedia-social Behav. Sci.* 172, 246–253. doi: 10.1016/j.sbspro.2015.01.361

Ahmad, M. M., Yaseen, M., and Saqib, S. E. (2022). Climate change impacts of drought on the livelihood of dryland smallholders: implications of adaptation challenges. *Int. J. Disaster Risk Reduct.* 80:103210. doi: 10.1016/j.ijdrr.2022.103210

Ahmed, A., Mohd, Y. B. I., and Abdullah, A. M. (2021). Oil palm in the face of climate change: a review of recommendations. *IOP Conf. Ser. Earth Environ. Sci.* 646:12065. doi: 10.1088/1755-1315/646/1/012065

Ajambang, W., Ardie, S. W., Volkaert, H., Galdima, M., and Sudarsono, S. (2015). Huge carbohydrate assimilates delay response to complete defoliation stress in oil palm (*Elaeis guineensis* Jacq.). *Emirates J. Food Agric.* 27, 127–138. doi: 10.9755/ejfa.v27i1.18734

Alisjahbana, A. S., and Busch, J. M. (2017). Forestry, Forest fires, and climate change in Indonesia. *Bull. Indones. Econ. Stud.* 53, 111–136. doi: 10.1080/00074918.2017.1365404

Andrianto, A., Komarudin, H., and Pacheco, P. (2019). Expansion of oil palm plantations in Indonesia's frontier: problems of externalities and the future of local and indigenous communities. *Land* 8:56. doi: 10.3390/land8040056

Ang, Y., Shafri, H. Z. M., Lee, Y. P., Bakar, S. A., Abidin, H., Mohd Junaidi, M. U. U., et al. (2022). Oil palm yield prediction across blocks from multi-source data using machine learning and deep learning. *Earth Sci. Informatics* 15, 2349–2367. doi: 10.1007/s12145-022-00882-9

Appelt, J. L., Saphangthong, T., Malek, Ž., Verburg, P. H., and van Vliet, J. (2023). Climate change impacts on tree crop suitability in Southeast Asia. *Reg. Environ. Chang.* 23:117. doi: 10.1007/s10113-023-02111-5

Arifin, K., Ahmad, M. A., Abas, A., and Ali, M. X. M. (2023). Systematic literature review: characteristics of confined space hazards in the construction sector. *Results Eng.* 18:101188. doi: 10.1016/j.rineng.2023.101188

Austin, K. G., Kasibhatla, P. S., Urban, D. L., Stolle, F., and Vincent, J. (2015). Reconciling oil palm expansion and climate change mitigation in Kalimantan, Indonesia. *PLoS One* 10:e0127963. doi: 10.1371/journal.pone.0127963

Azmi, E., Che Rose, R. A., Awang, A., and Abas, A. (2023). Innovative and competitive: a systematic literature review on new tourism destinations and products for tourism supply. *Sustainability* 15:1187. doi: 10.3390/su15021187

Bayona-Rodriguez, C. J., and Romero, H. M. (2019). Physiological and agronomic behavior of commercial cultivars of oil palm (*Elaeis guineensis*) and OxG hybrids (*Elaeis oleifera* x *Elaeis guineensis*) at rainy and dry seasons. *Aust. J. Crop. Sci.* 13, 424–432. doi: 10.21475/ajcs.19.13.03.p1354

Benezoli, V. H., Imbuzeiro, H. M. A., Cuadra, S. V., Colmanetti, M. A. A., deAraújo, A. C., Stiegler, C., et al. (2021). Modeling oil palm crop for Brazilian climate conditions. *Agricultural Systems*, 190. doi: 10.1016/j.agsy.2021.103130

Beringer, T., Müller, C., Chatterton, J., Kulak, M., and Schaphoff, S. (2023). CO2 fertilization effect may balance climate change impacts on oil palm cultivation. *Environ. Res. Lett.* 18:054019. doi: 10.1088/1748-9326/accbd5

Brandi, C., Cabani, T., Hosang, C., Schirmbeck, S., Westermann, L., and Wiese, H. (2015). Sustainability standards for palm oil: challenges for smallholder certification under the RSPO. *J. Environ. Dev.* 24, 292–314. doi: 10.1177/1070496515593775

Braun, V., and Clarke, V. (2006). Using thematic analysis in psychology. *Qual. Res. Psychol.* 3, 77–101. doi: 10.1191/1478088706qp063oa

Bruinsma, J. (2003). World agriculture: Towards 201572030: An FAO perspective. London: Earthscan.

Brum, M., Oliveira, R. S., López, J. G., Licata, J., Pypker, T., Chia, G. S., et al. (2021). Effects of irrigation on oil palm transpiration during ENSO-induced drought in the Brazilian eastern Amazon. *Agric. Water Manag.* 245:106569. doi: 10.1016/j.agwat.2020.106569

Bueraheng, N., Sdoodee, S., Anothai, J., and Eksomtramage, T. (2018). Stability of oil palm (*Elaeis guineensis* Jacq.) progenies on yield and yield components across environments using AMMI analysis. *Aust. J. Crop. Sci.* 12, 1259–1264. doi: 10.21475/ajcs.18.12.08.PNE964

Carlos, J., Thomas, Q., Poeplau, C., Ghazoul, J., and Buttler, A. (2021). Deforestation-free land-use change and organic matter-centered management improve the C footprint of oil palm expansion. *Glob. Chang. Biol.* 22, 2476–2490. doi: 10.1111/gcb.16069

Chiarawipa, R., Thongna, K., and Sdoodee, S. (2020). Assessing impact of weather variability and changing climate on oil-palm yield in major growing regions of southern Thailand. *J. Agrometeorol.* 22, 274–284. doi: 10.54386/jam.v22i3.189

Chizari, A., Mohamed, Z., Shamsudin, M. N., and Seng, K. W. K. (2017). Economic climate model of the oil palm production in Malaysia. *Int. J. Horticulture Agric. Food Sci.* 1, 27–32. doi: 10.22161/ijhaf.1.3.6

Corte's-Cataño, C. F., Foronda-tobo, Y., Paez-Ricardo, J. A., Parra-Herrera, J. E., and Cañon-Ayala, M. J. (2024). The effect of environmental variations on the production of the principal agricultural products in Colombia. *PLoS One* 19, 1–14. doi: 10.1371/journal.pone.0304035

De Pinto, A., Wiebe, K., and Pacheco, P. (2017). Help bigger palm oil yields to save land. *Nature* 544:416. doi: 10.1038/544416d

Delgado, T., Ladino, G., and 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* 14:976. doi: 10.3390/agronomy14091976

Descals, A., Wich, S., Meijaard, E., Gaveau, D. L. A., Peedell, S., and Szantoi, Z. (2020). High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. *Earth Syst. Sci. Data Discuss.* 2020, 1–22. doi: 10.5194/essd-13-1211-2021

Dilipkumar, M., Seng, T., Sheng, S., and Sahid, I. (2017). Weed management issues, challenges, and opportunities in Malaysia. *Crop Prot.*, 1–9. doi: 10.1016/j.cropro.2017.08.027

Dixon-Woods, M., Agarwal, S., Jones, D., Young, B., and Sutton, A. (2005). Synthesising qualitative and quantitative evidence: a review of possible methods. *J. Health Serv. Res. Policy* 10, 45–53. doi: 10.1177/135581960501000110

Enting, C. E., and Latip, S. N. H. M. (2021). Life cycle of oil palm bagworm, metisa plana walker (Lepidoptera: Psychidae) at different temperatures under controlled environment. *Serangga* 26, 151–165.

EPA (2016). Climate impacts on global issues. Washington, DC: U.S. Environmental Protection Agency.

FAO (2010). Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation. Rome: Food and Agriculture Organization of the United Nations (FAO).

Fitzherbert, E. B., Struebig, M. J., Morel, A., Danielsen, F., Brühl, C. A., Donald, P. F., et al. (2008). How will oil palm expansion affect biodiversity? *Trends Ecol. Evol.* 23, 538–545. doi: 10.1016/j.tree.2008.06.012

Fleiss, S., McClean, C. J., King, H., and Hill, J. K. (2022). Limited impacts of climatic conditions on commercial oil palm yields in Malaysian plantations. *CABI Agric. Biosci.* 3:127. doi: 10.1186/s43170-022-00127-1

Frianto, D., and Sutrisno, E. (2024). Carbon stock dynamics of forest to oil palm plantation conversion for ecosystem rehabilita-tion planning. *Glob. J. Environ. Sci. Manag.* 10:2034. doi: 10.22034/gjesm

Gatti, R. C., Liang, J., Velichevskaya, A., and Zhou, M. (2019). Sustainable palm oil may not be so sustainable. *Sci. Total Environ.* 652, 48–51. doi: 10.1016/j.scitotenv.2018.10.222

Gomiero, T. (2016). Soil degradation, land scarcity and food security: reviewing a complex challenge. *Sustainability* 8:281. doi: 10.3390/su8030281

Gunawan, S., Budiastuti, M. T. S., Sutrisno, J., and Wirianata, H. (2020). Effects of organic materials and rainfall intensity on the productivity of oil palm grown under sandy soil condition. *Int. J. Adv. Sci. Eng. Inf. Technol.* 10, 356–361. doi: 10.18517/ijaseit.10.1.11001

Gusenbauer, M., and Haddaway, N. R. (2020). Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google scholar, PubMed, and 26 other resources. *Res. Synth. Methods* 11, 181–217. doi: 10.1002/jrsm.1378

Hamid, S. R., Arzaman, A. F. M., Razali, M. A., Yasin, N. I., Masrom, N. R., Sabri, N. A. A., et al. (2024). The deployment of the Malaysian sustainable palm oil standard in the agriculture sector. *Multidiscip. Sci. J.* 6:2024115. doi: 10.31893/multiscience.2024115

Hidayat, N. K., Offermans, A., and Glasbergen, P. (2018). Sustainable palm oil as a public responsibility? On the governance capacity of Indonesian standard for sustainable palm oil (ISPO). *Agric. Human Values* 35, 223–242. doi: 10.1007/s10460-017-9816-6

IPOC Change (2001). Climate change 2007: Impacts, adaptation and vulnerability. Genebra: IPOC.

Jatuporn, C., and Takeuchi, K. (2024). Estimating the potential impact of climate change on energy crop productivity in Thailand: an empirical study of sugarcane, cassava, and oil palm using panel data analysis. *Environ. Dev. Sustain.* 26, 14205–14222. doi: 10.1007/s10668-023-03188-y

Kamil, N. N., Xiao, S., Salleh, S. N. S., Xu, H., and Zhuang, C. C. (2024). Nonlinear impacts of climate anomalies on oil palm productivity. *Heliyon* 10:e35798. doi: 10.1016/j.heliyon.2024.e35798

Khong, R. W. L., Pek, C.-K., and Tan, H.-B. (2023). Non-linear effect of temperature on oil palm yield: a note based on panel threshold analysis. *Int. J. Bus. Soc.* 24, 1359–1368. doi: 10.33736/ijbs.6425.2023

Knobloch, K., Yoon, U., and Vogt, P. M. (2011). Preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement and publication bias. *J. Craniofac. Surg.* 39, 91–92. doi: 10.1016/j.jcms.2010.11.001

Kong, S., Lam, S., Yuh, N., and Liew, K. (2018). Self-purging microwave pyrolysis: an innovative approach to convert oil palm shell into carbon-rich biochar for methylene blue adsorption. *J. Chem. Technol. Biotechnol.* 94, 1397–1405. doi: 10.1002/jctb.5884

Kotowska, M. M., Leuschner, C., Triadiati, T., and Hertel, D. (2016). Conversion of tropical lowland forest reduces nutrient return through litterfall, and alters nutrient use efficiency and seasonality of net primary production. *Oecologia* 180, 601–618. doi: 10.1007/s00442-015-3481-5

Kumaran, S. (2019). The dynamics for mandatory MSPO certification scheme to be successfully implemented. *J. Oil Palm Environ. Health.* 10, 1–7. doi: 10.5366/jope.2019.01

Lau, G. W., King, P. J. H., Chubo, J. K., King, I. C., Ong, K. H., Ismail, Z., et al. (2024). The potential benefits of palm oil waste-derived compost in embracing the circular economy. *Agronomy* 14:517. doi: 10.3390/agronomy14112517

Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., et al. (2012). Managing the risks of extreme events and disasters to advance climate change adaptation. A spec. *Rep. Work. groups I II Intergov. panel Clim. Chang* 3, 25–64.

Li, X., Zhang, X., and Yang, H. (2021). Chinese journal of population, resources and environment estimating the opportunity costs of avoiding oil palm-based deforestation in Indonesia: implications for REDD þ. *Chinese J. Popul. Resour. Environ* 18, 9–15. doi: 10.1016/j.cjpre.2021.04.010

Lim, C. I., and Biswas, W. (2019). Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework. *Sustain. Dev.* 27, 253–269. doi: 10.1002/sd.1872

Luke, S. H., Advento, A. D., Aryawan, A. A. K., Adhy, D. N., Ashton-Butt, A., Barclay, H., et al. (2020). Managing oil palm plantations more sustainably: large-scale experiments within the biodiversity and ecosystem function in tropical agriculture (BEFTA) Programme. *Front. For. Glob. Chang.* 2:75. doi: 10.3389/ffgc.2019.00075

Maryanto, S. D., Roberdi, R., Tanjung, Z. A., Artutiningsih, W., Purba, O. S., Saputra, T. I., et al. (2021). Transcriptome profiling of *Elaeis guineensis* Jacq. Under heat stress condition. *Int. J. Adv. Sci. Eng. Inf. Technol.* 11:2016. doi: 10.18517/ijaseit.11.5.13457

Mendelsohn, R. (2009). The impact of climate change on agriculture in developing countries. *J. Nat. Resour. policy Res.* 1, 5–19. doi: 10.1080/19390450802495882

Mohamed Shaffril, H. A., Samsuddin, S. F., and Abu Samah, A. (2021). The ABC of systematic literature review: the basic methodological guidance for beginners. *Qual. Quant.* 55, 1319–1346. doi: 10.1007/s11135-020-01059-6

Mohd Hanafiah, K., Abd Mutalib, A. H., Miard, P., Goh, C. S., Mohd Sah, S. A., and Ruppert, N. (2022). Impact of Malaysian palm oil on sustainable development goals: co-benefits and trade-offs across mitigation strategies. *Sustain. Sci.* 17, 1639–1661. doi: 10.1007/s11625-021-01052-4

Mukherjee, I., and Sovacool, B. K. (2014). Palm oil-based biofuels and sustainability in Southeast Asia: a review of Indonesia, Malaysia, and Thailand. *Renew. Sust. Energ. Rev.* 37, 1–12. doi: 10.1016/j.rser.2014.05.001

Munodawafa, R. T., and Johl, S. K. (2019). A systematic review of eco-innovation and performance from the resource-based and stakeholder perspectives. *Sustainability* 11:6067. doi: 10.3390/su11216067

Murphy, D. (2018). Oil palm value chain management.

Murphy, D. J., Goggin, K., and Paterson, R. R. M. (2021). Oil palm in the 2020s and beyond: challenges and solutions. *CABI Agric. Biosci.* 2, 39–22. doi: 10.1186/s43170-021-00058-3

Musa, N. F., Razali, S. M., Ahmad, A. A., and Shafri, Z. M. S. M. (2019). Oil palm dry season analysis based on moderate-resolution imaging spectroradiometer (MODIS) satellite indices. *Int. J. Remote Sens.* 40:394. doi: 10.1080/01431161.2019.1608394

Nainar, A., Walsh, R. P. D., Bidin, K., Tanaka, N., Annammala, K. V., Letchumanan, U., et al. (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* 14:791. doi: 10.3390/w14223791

Nor Diana, M. I., Zulkepli, N. A., Siwar, C., and Zainol, M. R. (2022). Farmers' adaptation strategies to climate change in Southeast Asia: a systematic literature review. *Sustainability* 14:3639. doi: 10.3390/su14063639

Noor, W. N. W. M., Nawi, N. M., Buda, M., and Seng, K. W. K. (2024). Oil Palm Production in the 20th Century and Beyond: The Impact of Climate Change in Malaysia. *AGRARIS: Journal of Agribusiness and Rural Development Research*, 10, 55–69.

Nunes, M. H., et al. (2021). Recovery of logged forest fragments in a human-modi fi ed tropical landscape during the 2015-16 El Niño. *Nat. Commun.* 12, 1–11. doi: 10.1038/s41467-020-20811-y

Nurhayati, A., Aziz, R., Ekasari, K., and Beddu, H. (2022). Analysis of agronomy and environmental impacts of palm oil production: evidence from Indonesia. *AgBioforum* 24, 193–204.

Nusli, H., Muhamad, M. Z., Mustafa, M. M., Vaiapuri, S., Fatah, F. A., and Syahlan, S. (2024). "Sustainable Certification in the Oil Palm Industry: A Comparative Analysis of MSPO, RSPO, ISPO and ISCC Schemes," in Innov. Cent. Agritechnology Adv. *Bioprocess. Univ. Teknol. Malaysia Pagoh Campus Johor Darul Tak. Malaysia*, 26.

Okoro, S. U., Schickhoff, U., Boehner, J., Schneider, U. A., and Huth, N. I. (2017). Climate impacts on palm oil yields in the Nigerian Niger Delta. *Eur. J. Agron.* 85, 38–50. doi: 10.1016/j.eja.2017.02.002

Pater Ruson, R. R. M. (2023). Future climate effects on yield and mortality of conventional versus modified oil palm in SE Asia. *Plants* 12:236. doi: 10.3390/plants12122236

Paterson, R. R. M. (2019a). Ganoderma boninense disease of oil palm to significantly reduce production after 2050 in Sumatra if projected climate change occurs. *Microorganisms* 7:24. doi: 10.3390/microorganisms7010024

Paterson, R. R. M. (2019b). Ganoderma boninense disease deduced from simulation modelling with large data sets of future Malaysian oil palm climate. *Phytoparasitica* 47, 255–262. doi: 10.1007/s12600-019-00723-4

Paterson, R. R. M. (2020a). Oil palm survival under climate change in Malaysia with future basal stem rot assessments. *For. Pathol.* 50:12641. doi: 10.1111/efp.12641

Paterson, R. R. M. (2020b). Oil palm survival under climate change in Kalimantan and alternative SE Asian palm oil countries with future basal stem rot assessments. *For. Pathol.* 9, 1–8. doi: 10.1111/efp.12604

Paterson, R. R. M. (2020c). Future scenarios for oil palm mortality and infection by Phytophthora palmivora in Colombia, Ecuador and Brazil, extrapolated to Malaysia and Indonesia. *Phytoparasitica* 48, 513–523. doi: 10.1007/s12600-020-00815-6

Paterson, R. R. M. (2021a). Longitudinal trends of future climate change and oil palm growth: empirical evidence for tropical Africa. *Environ. Sci. Pollut. Res.* 28, 21193–21203. doi: 10.1007/s11356-020-12072-5

Paterson, R. R. M. (2021b). Optimised and systematic suitable climate modelling confirms future longitudinal-trends for growing oil palm in Africa. *J. Environ. Manag.* 300:113785. doi: 10.1016/j.jenvman.2021.113785

Paterson, R. R. M., and Chidi, N. I. (2023). Climate refuges in Nigeria for oil palm in response to future climate and Fusarium wilt stresses. *Plants* 12. doi: 10.3390/plants12040764

Paterson, R. R. M., Kumar, L., Taylor, S., and Lima, N. (2015). Future climate effects on suitability for growth of oil palms in Malaysia and Indonesia. *Sci. Rep.* 5:14457. doi: 10.1038/srep14457

Paterson, R. R. M., and Lima, N. (2018). Climate change affecting oil palm agronomy, and oil palm cultivation increasing climate change, require amelioration. *Ecol. Evol.* 8, 452–461. doi: 10.1002/ece3.3610

Prisma, P. C. (2015). Transparent reporting of systematic reviews and meta-analyses. Oxford: University of Oxford Ottawa, 41–58.

Purbantoro, B. A., Anggraeni, L., and Pasaribu, S. H. (2024). Impact of climate change on the export of palm oil, coffee beans, and cocoa beans. *J. Manaj. Agribisnis.* 21:25. doi: 10.17358/jma.21.1.25

Qaim, M., Sibhatu, K. T., Siregar, H., and Grass, I. (2020). Environmental, economic, and social consequences of the oil palm boom. *Annu. Rev. Resour. Econ.* 12:9422. doi: 10.1146/annurev-resource-110119-024922

Rajakal, J. P., Andiappan, V., and Wan, Y. K. (2021). Mathematical approach to forecast oil palm plantation yield under climate change uncertainties mathematical approach to forecast oil palm plantation yield under climate change uncertainties. *Chem. Eng. Trans.* 83:20. doi: 10.3303/CET2183020

Ramadhan, A., Rizal, Y., and Syarief, S. (2024). Social, environmental and economic impacts of oil palm plantation in Aceh, Indonesia. *Int. Rev. Econ. Financ. Issues* 1, 57–72. doi: 10.62941/irefi.v1i1.23

Rela, I. Z., Widayati, W., Fausayana, I., Agustina, D., Batoa, H., and Buana, T. (2023). The impact of palm oil plantation on the community well-being in Langgikima District Konawe Utara regency: structural equation modeling analysis partial least square (PLS) approach. *Bul. Penelit. Sos. Ekon. Pertan. Fak. Pertan. Univ. Haluoleo* 25, 103–111.

Rhebergen, T., Fairhurst, T., Zingore, S., Fisher, M., Oberthür, T., and Whitbread, A. (2016). Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. *Eur. J. Agron.* 81, 1–14. doi: 10.1016/j.eja.2016.08.004

Rival, A. (2017). Breeding the oil palm (*Elaeis guineensis* Jacq.) for climate change. *OCL-Oilseeds fats, Crop. Lipids* 24, 1–7. doi: 10.1051/ocl/2017001

Runtuboi, Y. Y., Permadi, D. B., Sahide, M. A. K., and Maryudi, A. (2021). Oil palm plantations, forest conservation and indigenous peoples in West Papua Province: what lies ahead? *For. Soc.* 5, 23–31. doi: 10.24259/fs.v5i1.11343

Said, F. F., Syed Roslan, S. N. A., Zaidi, M. A. S., and Yaakub, M. R. (2021). A probe into the status of the oil palm sector in the Malaysian value chain. *Economies* 9:106. doi: 10.3390/economies9030106

Salmah, M., Adam, N. A., Muhamad, R., Lau, W. H., and Ahmad, H. (2017). Research article special issue. *J. Fundam. Appl. Sci.* 9, 799–812.

Samsuddin, N. S., Aziz, N. F. A., Balachandran, B., and Ali, J. (2024). Economic climate model on the palm production: empirical evidence for Malaysia and Indonesia. *Malaysian J. Consum. Fam. Econ.* 33, 465–489. doi: 10.60016/majcafe.v33.17

Sarkar, M. S. K., Begum, R. A., and Pereira, J. J. (2020). Impacts of climate change on oil palm production in Malaysia. *Environ. Sci. Pollut. Res.* 27, 9760–9770. doi: 10.1007/s11356-020-07601-1

Savilaakso, S., Garcia, C., Garcia-Ulloa, J., Ghazoul, J., Groom, M., Guariguata, M. R., et al. (2014). Systematic review of effects on biodiversity from oil palm production. *Environ. Evid.* 3, 1–21. doi: 10.1186/2047-2382-3-4

Selçuk, A. A. (2019). A guide for systematic reviews: PRISMA. *Turkish Arch. Otorhinolaryngol.* 57, 57–58. doi: 10.5152/tao.2019.4058

Shaffril, H. A. M., Krauss, S. E., and Samsuddin, S. F. (2018). A systematic review on Asian's farmers' adaptation practices towards climate change. *Sci. Total Environ.* 644, 683–695. doi: 10.1016/j.scitotenv.2018.06.349

Shaffril, H. A. M., Samah, A. A., and Samsuddin, S. F. (2021). Guidelines for developing a systematic literature review for studies related to climate change adaptation. *Environ. Sci. Pollut. Res.* 28, 22265–22277. doi: 10.1007/s11356-021-13178-0

Shanmuganathan, S., and Narayanan, A. (2012). "Modelling the climate change effects on Malaysia's oil palm yield," in *2012 IEEE Symposium on E-Learning, E-Management and E-Services*, 1–6.

Sheil, D., Casson, A., Meijaard, E., van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., et al. (2009). The impacts and opportunities of oil palm in Southeast Asia: what do we know and what do we need to know? Bogor: Center for International Forestry Research.

Somboonsuke, B., Phitthayaphinant, P., Sdoodee, S., and Kongmanee, C. (2018). Farmers' perceptions of impacts of climate variability on agriculture and adaptation strategies in Songkhla Lake basin. *Kasetsart J. Soc. Sci.* 39, 277–283. doi: 10.1016/j.kjss.2018.05.006

Sujadi, S., Pradiko, I., Rahutomo, S., and Farrasati, R. (2020). Prediksi Kemampuan Adaptasi Delapan Varietas Kelapa Sawit pada Cekaman Abiotik Akibat Perubahan Iklim Global. *J. Tanah dan Iklim* 44, 129–139. doi: 10.21082/jti.v44n2.2020.129-139

Tang, K. H. D. (2019). Climate change in Malaysia: trends, contributors, impacts, mitigation and adaptations. *Sci. Total Environ.* 650, 1858–1871. doi: 10.1016/j.scitotenv.2018.09.316

Tani, N., Abdul Hamid, Z. A., Joseph, N., Sulaiman, O., Hashim, R., Arai, T., et al. (2020). Small temperature variations are a key regulator of reproductive growth and assimilate storage in oil palm (*Elaeis guineensis*). *Sci. Rep.* 10, 650–611. doi: 10.1038/s41598-019-57170-8

Thornton, P. K., Ericksen, P. J., Herrero, M., and Challinor, A. J. (2014). Climate variability and vulnerability to climate change: a review. *Glob. Chang. Biol.* 20, 3313–3328. doi: 10.1111/gcb.12581

Tropenbos Indonesia (2020). New ISPO: a New Hope to Strengthen Oil-Palm Governance? Bogor: Tropenbos Indonesia.

Usapein, P., Tuntiwiwattanapun, N., Polburee, P., Veerakul, P., Seekao, C., and Chavalparit, O. (2022). Transition pathway palm oil research framework toward a bio-circular-green economy model using SWOT analysis: a case study of Thailand. *Front. Environ. Sci.* 10:877329. doi: 10.3389/fenvs.2022.877329

Vijay, V., Pimm, S. L., Jenkins, C. N., and Smith, S. J. (2016). The impacts of oil palm on recent deforestation and biodiversity loss. *PLoS One* 11:e0159668. doi: 10.1371/journal.pone.0159668

Watson-hern, F., Serrano-n, V., and Natalia, G. (2023). Quantification and evaluation of water requirements of oil palm cultivation for different climate change scenarios in the Central Pacific of Costa Rica using APSIM. *Agronomy* 13:19. doi: 10.3390/agronomy13010019

Wattana, S., Wattana, B., and Purathanung, T. (2022). Impacts of palm oil-based biofuel utilization promotion policy in the Thai transport sector. *Environ. Res. Eng. Manag.* 78, 7–18. doi: 10.5755/j01.erem.78.2.30745

Widayati, A., Louman, B., Mulyoutami, E., Purwanto, E., Kusters, K., and Zagt, R. (2021). Communities' adaptation and vulnerability to climate change: implications for achieving a climate-smart landscape. *Land* 10:816. doi: 10.3390/land10080816

Zainal, Z., Shamsudin, M. N., Mohamed, Z. A., and Adam, S. U. (2012). Economic impact of climate change on the Malaysian palm oil production. *Trends Appl. Sci. Res.* 7:872.