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# Enhancing Oil Palm Plantation Resilience through Climate-Smart Agriculture under Climate Change

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A B S T R A C T

Climate change poses challenges to oil palm plantations through temperature variability, extreme weather, water stress, and decreased productivity. This study uses a systematic literature review to examine the role of Climate-Smart Agriculture (CSA) in strengthening the resilience of plantations to climate change, with a focus on adaptation, sustainable cultivation, resource management, and technological innovation. The results show that CSA improves resilience through optimization of water and nutrient management, climate-resilient planting practices, precision agriculture, soil improvement, and monitoring systems. This approach maintains productivity, reduces environmental impact, and increases adaptation capacity. However, its implementation is constrained by limited technology, financing, and farmers' knowledge. CSA is a path to resilient and sustainable oil palm plantations. Strengthening technology adoption, farmer capacity, institutional support, and collaborative governance are necessary for long-term productivity and environmental sustainability.

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## INTRODUCTION

Palm oil (Elaeis guineensis Jacq.) is a global strategic commodity that supplies about 40% of the world's traded vegetable oils and is consumed by more than three billion people. Despite having relatively high land productivity, crop production cycles that exceed 25 years cause oil palm plantations to be cumulatively exposed to rising temperatures, changes in rainfall patterns, droughts, floods, and the development of plant pest organisms (Murphy et al., 2021). This problem is particularly relevant for Indonesia as the world's largest palm oil producer because climate instability can affect plantation productivity, farmers' incomes, and supply chain sustainability. A review of 58 studies showed that temperature and rainfall were the most dominant climatic factors in influencing the physical condition and productivity of palm oil, accounting for 40% and 36% of the main factors analyzed respectively (Wulandari et al., 2025). This condition underscores the urgency of developing plantation systems that are able to maintain productivity while adapting to climate risks and reducing environmental pressures.

Climate-Smart Agriculture (CSA) offers an agricultural development framework that integrates three goals, namely increasing productivity sustainably, strengthening adaptation and resilience capacity, and reducing greenhouse gas emissions where possible. The CSA literature shows that these three goals cannot be achieved through a single technology, but requires a combination of practices adapted to local agroecological and socioeconomic conditions (Okolie et al., 2023). From an agricultural engineering perspective, CSA can be operationalized through water and nutrient management engineering, soil conservation, the use of stress-resistant planting materials, appropriate mechanization, environmental sensors, remote sensing, precision agriculture, and data-driven decision support systems. Such integration is important because the resilience of plantations is determined not only by the physiological tolerance of plants, but also by the ability of production systems to detect changes in environmental conditions and adjust the use of resources in a timely manner.

Empirical evidence suggests that water is one of the most decisive factors in the stability of oil palm yields. Based on 136 block-year observations on plantations in Indonesia, Monzon et al. (2022) found that water stress was the main factor explaining the spatial and temporal variations in the production of fresh fruit bunches, while the increase in vapor pressure deficit was negatively related to water use yield and efficiency (Monzon et al., 2022). Research by Delgado et al. (2024) also shows that the determination of water needs based on soil conditions and growth phases is necessary to improve irrigation efficiency and reduce plant susceptibility to climate variability (Delgado et al., 2024). On the other hand, the use of predictive technology is increasingly important. Khan et al. (2022), using weather data, root zone moisture, and yield records for 420 months, found that rainfall frequency, temperature, and soil moisture are important variables in machine learning-based prediction of oil palm yields (Khan et al., 2022). The findings show that combining resource management with digital monitoring has the potential to support adaptive decision-making.

The effectiveness of CSAs, however, is not only determined by the availability of technology. Smallholders face limited capital, access to information, technical assistance, certainty of land tenure, and institutional support. A review by Peprah Agyekum et al. (2024) shows that high technology costs, credit limitations, weak counseling services, and intervention incompatibility with local conditions are the main obstacles to CSA adoption (Peprah Agyekum et al., 2024). In the Indonesian context, a study of 1,280 independent oil palm smallholders found structural barriers in the fulfillment of sustainability practices and certifications, especially for smallholders who did not receive support from previous development programs (Watts et al., 2021). Hendrawan et al. (2024) further identified five groups of oil palm smallholders with different levels of livelihood resilience; more resilient groups generally have stronger access to government support, skills, and productive resources (Hendrawan et al., 2024). Thus, the implementation of CSA requires integration between engineering innovation, farmer capacity, financing, institutional, and collaborative governance.

Although research on climate change and palm oil continues to grow, there are still clear scientific gaps. Abubakar et al. (2021) have identified the impacts of climate change and adaptation choices on oil palm plantations in Malaysia, but the study is region-specific and has not placed these practices within an integrated CSA framework (Abubakar et al., 2021). Monzon et al. (2022) and Delgado et al. (2024) focus more on the relationship between water, climate, and yields, while Khan et al. (2022) emphasize predictive modeling. The studies provide strong technical evidence, but still analyze interventions separately and have not yet explained the relationship between water, nutrient, soil, planting material, precision agriculture, and institutional factors. Meanwhile, Wulandari et al. (2025) map the impact of climate change on productivity, environment, economy, and community welfare, but have not specifically evaluated the effectiveness of CSA's portfolio of practices in strengthening the resilience of plantation systems. Therefore, a systematic synthesis is needed that connects the technical, ecological, digital, social, and institutional dimensions of CSA in the context of palm oil.

Based on these gaps, this study explicitly aims to identify, evaluate, and synthesize the role of Climate-Smart Agriculture practices in strengthening the resilience of oil palm plantations to climate change through a systematic literature review approach. The analysis focused on climate adaptation strategies, sustainable cultivation practices, water and nutrient management, soil quality improvement, use of climate-resilient planting materials, precision agriculture, and monitoring and decision-making innovations. Theoretically, this research is expected to produce an integrative framework that explains the relationship between climate risk, CSA interventions, plant biophysical responses, productivity, and plantation resilience. In practical terms, the results of the research can serve as a basis for plantation managers, smallholders, extension workers, and policymakers in determining appropriate technology combinations, strengthening smallholder capacity, increasing financing and institutional support, and building collaborative governance to achieve long-term productivity and environmental sustainability of the palm oil sector.

## THEORETICAL FRAMEWORK

### Climate-Smart Agriculture and Plantation Resilience

Climate-Smart Agriculture (CSA) is a multidimensional approach that integrates productivity improvement, adaptation to climate change, and environmental impact mitigation. Resilience within the CSA framework means not only the ability of plants to withstand stress, but also the ability of plantation systems to absorb disturbances, adjust management practices, and carry out technological and institutional transformations. Jamil et al. (2021) show that the use of a combination of CSA practices can increase farmers' adaptation capacity, productivity, and resilience to climate risks (Jamil et al., 2021). Meta-analysis of Kichamu-Wachira et al. (2021) also showed that the integrated implementation of CSA practices contributes to increased yields, soil organic carbon, and nitrogen reserves (Kichamu-Wachira et al., 2021). In oil palm plantations, the concept places the management of water, soil, nutrients, planting materials, and monitoring technology as interconnected components.

### Climate change and palm oil productivity response

Oil palm is an annual crop whose productivity is affected by the interaction between temperature, rainfall, soil moisture, radiation, and the physiological characteristics of the plant. Benezoli et al. (2021) developed an oil palm plant model based on Brazilian climatic conditions and showed that growth process modeling can be used to project energy, carbon, and yield balances in different production environments (Benezoli et al., 2021). However, plant responses to climate change are not always uniform as they are influenced by genotype and developmental phases. Hermanto et al. (2023) found that the number of bunches and stages of flower development, especially sex determination and flower abortion, are sensitive to rainfall variations. The study also showed that there were differences in responses between oil palm descendants to low rainfall conditions (Hermanto et al., 2023). Thus, strengthening resilience requires a combination of climate prediction, site-specific management, and adaptive planting material selection.

### Water management engineering

Water management is a key element of agricultural engineering in CSA because lack and excess water can reduce growth and productivity. Brum et al. (2021) showed that irrigation increases soil moisture and maintains oil palm transpiration during droughts due to ENSO in the eastern Amazon. Sprinkler irrigation and drip irrigation increased fruit production by about 35% and 26% respectively compared to unirrigated crops (Brum et al., 2021). Meanwhile, the simulation of Akram et al. (2022) confirms that the water needs of oil palm on marginal land must be taken into account based on growth phases, soil characteristics, effective rainfall, and irrigation system efficiency (Akram et al., 2022). Therefore, CSA does not encourage uniform irrigation, but prioritizes data-driven scheduling, root zone humidity monitoring, water conservation, adaptive drainage, and the selection of irrigation technologies that are appropriate to resource availability.

**Management of plantation soil, nutrients, and biomass**

The resilience of plantations also depends on the ability of the soil to store water, provide nutrients, maintain biological activity, and reduce loss of elements due to erosion or leaching In the context of oil palm plantations, empty fruit bunches (EFB) have the potential to be mulch, compost, and biochar. A meta-analysis of 19 studies showed that the use of EFB as a soil improverent increased plant growth and yield by 49.2% compared to soil without a fertilizer, although the benefits depended on the treatment method, dosage, soil type, and fertilizer combination (Adu et al., 2022). Mahmud and Chong (2021) also explained that the combination of EFB with growth-boosting microorganisms can be developed as biological fertilizers to increase nutrient availability while reducing dependence on synthetic fertilizers (Mahmud & Chong, 2021). The circular approach supports adaptation through improving water retention and soil fertility and supports mitigation through waste utilization and soil carbon increase.

**Adaptive planting materials and precision agriculture**

The selection of climate-resilient planting material is a form of long-term adaptation because palm oil productivity lasts for decades. Wei et al. (2021) explain that the resistance of oil palm to drought, salinity, extreme temperatures, inundation, and pathogens involves complex physiological and molecular mechanisms. The development of resilient varieties therefore requires the integration of conventional selection, physiology, molecular markers, and genomic analysis (Wei et al., 2021). At the operational level, precision farming allows the condition of crops to be monitored spatially and temporally. Watson-Hernández et al. (2022) showed that vegetation and moisture indices from Landsat imagery combined with machine learning can estimate oil palm yields, with the plant-related water content index being an important predictor (Watson-Hernández et al., 2022). The integration of soil sensors, weather stations, satellite imagery and prediction models allows plantation managers to determine irrigation, fertilization, maintenance and harvest times more efficiently.

**Technology adoption, smallholder and institutional support**

The technical success of CSAs does not automatically result in adoption at the plantation level. A review of 100 articles shows that smallholder oil palm farmers still face limited capital, information, land security, market access, technical support, and evidence of the economic benefits of sustainability practices (Ogahara et al., 2022). Pramudya et al. (2022) emphasized that financial incentives, simplification of requirements, land legality, strengthening of farmer groups, and technical assistance are needed so that farmers are able to meet sustainable management standards (Pramudya et al., 2022). Based on this synthesis, the resilience of oil palm plantations can be understood as the result of the interaction between climate pressures, CSA technical interventions, plant and soil biophysical responses, and institutional social conditions. Freshwater management, soil improvement, adaptive planting materials, and precision agriculture are direct mechanisms for increasing resilience, while financing, knowledge, farmer capacity, institutional support, and collaborative governance are factors that determine the sustainability of their implementation.

## METHODS

### Types of Research

This study uses a systematic literature review (SLR) to examine the role of Climate-Smart Agriculture (CSA) in increasing the resilience of oil palm plantations to climate change. The study focused on temperature variability, extreme weather, water stress, decreased productivity, adaptation strategies, sustainable cultivation, resource management, and technological innovation. The process of identifying, filtering, eligibility, and selecting articles follows the PRISMA 2020 guidelines (Page et al., 2021) and the reporting of search strategies follows PRISMA-S (Rethlefsen et al., 2021).

### Population and Sample

The research population includes international journal articles that discuss CSAs, climate change, and oil palm plantation resilience. Articles are searched through Scopus, Web of Science, and Dimensions, while Google Scholar and reference lists are used as additional sources. Publication is limited to the period 2021–2025.

Samples were selected using purposive sampling. Articles are included when they have been peer reviewed, available in English and full text, discuss oil palm plantations, and report on CSA practices and their impact on productivity, adaptation, or the environment. Articles on downstream industries, biofuels, palm oil trade, and research without a clear method are issued. Based on the selection process, as many as 39 articles were determined as the final sample.

### Research Instruments

The research instrument consists of a screening sheet, a data extraction form, and a quality assessment sheet. The extracted data included authors, year, country, research design, type of climate threat, CSA practices, technologies used, impacts on productivity and the environment, and implementation constraints.

The extraction form is structured based on four main focuses of the abstract, namely: (1) climate change adaptation; (2) sustainable cultivation; (3) water, nutrient, and soil management; and (4) technological innovation, precision agriculture, and monitoring systems. In addition, information on technological limitations, financing, farmer knowledge, institutional support, and collaborative governance was also collected.

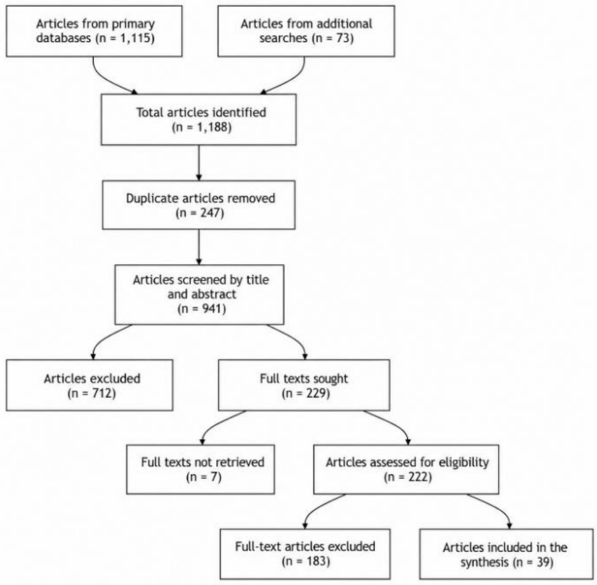
The quality of the articles was assessed using Quality Assessment with Diverse Studies or QuADS (Harrison et al., 2021). Screening was conducted independently by two reviewers, with a Cohen's kappa score of 0.84 at the title and abstract stage and 0.81 at the full-text stage. The results show a strong level of agreement between reviewers.

### Data Collection Procedure

The procedure began with the preparation of keywords that combined the terms climate-smart agriculture, oil palm, climate change, water stress, nutrient management, soil management, precision agriculture, remote sensing, and plantation resilience. The articles found were managed using Zotero, while the screening was done with Rayyan.

The search yielded 1,188 articles. After 247 duplicate articles were removed, a total of 941 articles were filtered by title and abstract. A total of 712 articles were issued and 229 articles were searched in full text. Seven full texts were not obtained, while 183 articles did not meet the eligibility criteria. Thus, a total of 39 articles were included in the final synthesis.

**Figure 1. PRISMA 2020 Flowchart.**




Source: Adapted from Page et al. (2021).

**Data Analysis Techniques**

The data were analyzed descriptively and thematically. Descriptive analysis used Microsoft Excel and R/RStudio to map articles by year, country, climate threat, CSA practices, and plantation type. Thematic synthesis is carried out using NVivo 14 through the coding stage, theme development, theme review, and interpretation (Byrne, 2022).

The themes of the analysis include: (1) water and nutrient management; (2) climate-resilient planting practices; (3) soil improvement and conservation; (4) precision agriculture and monitoring systems; (5) the effect of CSA on productivity, environment, and adaptation capacity; and (6) barriers to technology, financing, farmer knowledge, institutions, and governance. Because there are differences in design, location, and outcome indicators between articles, the findings are synthesized narratively and not followed by meta-analysis.

## RESULTS

**Characteristics of Selected Studies**

The literature selection process based on PRISMA resulted in 39 articles that met the inclusion criteria. Based on the year of publication, the most articles were published in 2022, namely 10 articles (25.6%), followed by 2021 with nine articles (23.1%), 2024 with eight articles (20.5%), 2023 with seven articles (17.9%), and 2025 with five articles (12.8%).

Based on the research area, a total of 13 articles (33.3%) were conducted in Indonesia, eight articles (20.5%) in Malaysia, five articles (12.8%) in Brazil, three articles (7.7%) in other Latin American countries, five articles (12.8%) in Africa, and five articles (12.8%) were multi-country or global-scale research. Based on the assessment using QuADS, as many as 24 articles (61.5%) were in the high-quality category and 15 articles (38.5%) were in the medium quality category.

**Table 1. Characteristics of the articles analyzed**

| Features | Category | Quantity (n) | Percentage |
|---|---|---|---|
| Year of publication | 2021 | 9 | 23,1% |
| | 2022 | 10 | 25,6% |
| | 2023 | 7 | 17,9% |
| | 2024 | 8 | 20,5% |
| | 2025 | 5 | 12,8% |
| Research area | Indonesia | 13 | 33,3% |
| | Malaysia | 8 | 20,5% |
| | Brazil | 5 | 12,8% |
| | Other Latin America | 3 | 7,7% |
| | Africa | 5 | 12,8% |
| | Multinegara/global | 5 | 12,8% |
| Research design | Field experiments/observations | 14 | 35,9% |
| | Modeling, remote sensing and *machine learning* | 9 | 23,1% |
| | Socio-economic and adoption | 7 | 17,9% |
| | Plant physiology and genetics | 4 | 10,3% |
| | Systematic review/meta-analysis | 5 | 12,8% |
| Methodological quality | High | 24 | 61,5% |
| | Medium | 15 | 38,5% |

**Climate Risks to Oil Palm Plantations**

A total of 28 articles (71.8%) reported a relationship between climate variability and changes in palm oil productivity or physiological conditions. Water stress and changes in rainfall distribution were found in 24 articles (61.5%), increased temperature or *vapor pressure deficit* in 17 articles (43.6%), extreme weather events in 13 articles (33.3%), and soil degradation and nutrient loss in 11 articles (28.2%). A single article can cover more than one climate risk factor.

An analysis of 136 *block-year observations* in Indonesia noted that water stress is related to spatial and temporal variations in the yield of fresh fruit bunches. The increase *in vapor pressure deficit* was also recorded to have a negative relationship with the yield and efficiency of water use (Monzon et al., 2022).

The study of 11 plant materials noted that the number of bunches was the most sensitive component of yield to changes in rainfall. Differences in responses were found between progeni, especially in the phase of determining the sex of flowers and flower abortion (Hermanto et al., 2023). The review by Wulandari et al. (2025) also noted changes in temperature, rainfall, soil moisture, and extreme weather frequency as climate variables that affect crop conditions and oil palm productivity.

**Water and Nutrient Management**

Water and nutrient management was found in 22 articles (56.4%). Practices identified include scheduled irrigation, soil moisture conservation, monitoring of root zone moisture content, fertilization based on plant needs, and reuse of plantation biomass as a source of nutrients.

Field research in the eastern Amazon noted that irrigation maintained soil moisture and crop transpiration during periods of drought due to ENSO. Compared to unirrigated land, fruit production increased by 35% in sprinkler irrigation systems and 26% in drip irrigation systems (Brum et al., 2021).

Studies on nutrient management reported the use of site-specific fertilization, dosage adjustments based on plant age, soil and leaf analysis, and integration of organic and mineral fertilizers. The results recorded included increased nutrient availability, fertilization efficiency, plant growth, and production stability.

**Soil Conservation and Improvement**

Soil conservation and improvement were reported in 17 articles (43.6%). Practices found include the use of mulch, compost, biochar, empty oil palm bunches, ground cover crops, and reduction of mechanical disturbances to the soil surface.

A meta-analysis of 19 studies on empty oil palm bunches recorded an average increase in growth or yield of 49.2% compared to soil without amelioration. Joint application of mineral fertilizers increased yields by 16.4%. Based on the form of the material, the increase recorded was 78.4% in biochar, 33.8% in raw empty bunches, 30.9% in compost, and 21.0% in ash (Adu et al., 2022).

The use of empty bunches with plant growth-boosting microorganisms has been reported to increase nutrient availability and soil biological activity (Mahmud & Chong, 2021). Soil indicators used in the selected study included organic matter content, water retention capacity, nitrogen, phosphorus and potassium availability, microorganism activity, and soil moisture.

**Climate-Resilient Planting Practices**

A total of 12 articles (30.8%) discussed planting materials or planting practices related to resilience to climatic conditions. Indicators used include the stability of the number of bunches, tolerance to low rainfall, tolerance to high temperatures and inundation, water use efficiency, vegetative growth, and the ability to maintain yields under stressful conditions.

The extraction results showed a difference in response between progeny to low rainfall conditions. The number of bunches, the weight of the bunches, the abortion of flowers, and the ratio of female flowers are the most widely used variables to identify the response of planting materials to climate stress. Some studies also use physiological indicators, such as the rate of photosynthesis, stomata conductance, chlorophylll content, root growth, and relative water content of the leaves.

**Precision Agriculture and Monitoring Systems**

Precision agriculture and monitoring systems were found in 16 articles (41.0%). The technologies used include soil moisture sensors, automatic weather stations, satellite imagery, vegetation index, humidity index, geographic information systems, unmanned aerial vehicles, and *machine learning* algorithms.

Research in Costa Rica noted that a combination of vegetation and moisture indexes from Landsat imagery with *machine learning* algorithms could be used to predict oil palm yields one year in advance. Variables related to plant water content are noted as important predictors (Watson-Hernández et al., 2022).

Another study used 420 months of actual yield data, 12 weather parameters, and three soil moisture parameters. *The Extra Trees* and *AdaBoost models* generate predictions of results after the preprocessing and feature selection stages. Minimum temperatures, root zone humidity, and solar radiation are noted as important features in yield prediction (Khan et al., 2022).

**The Impact of CSA on Plantation Resilience**

Of the 39 articles analyzed, 31 articles (79.5%) reported positive results on at least one dimension of plantation resilience. Six articles (15.4%) reported different outcomes by location, soil type, planting material, planting scale, or form of intervention. Two articles (5.1%) did not record consistent changes in productivity.

A total of 25 articles (64.1%) reported maintenance or increased productivity, 28 articles (71.8%) recorded an increase in adaptation capacity, 21 articles (53.8%) reported an increase in the efficiency of water or nutrient use, and 17 articles (43.6%) recorded improvements in environmental indicators. A total of 14 articles (35.9%) reported an increase in the ability to monitor, predict results, or early detection of plant stress.

**Table 2. Mapping of findings based on CSA dimensions**

| Dimensions of findings | Number of studies | Percentage | Reported results |
|---|---|---|---|
| Climate and productivity risks | 28 | 71,8% | Changes in yields, flower formation, number of bunches, and physiological conditions |
| Water and nutrient management | 22 | 56,4% | Moisture stability, input efficiency, and production maintenance |
| Soil conservation and improvement | 17 | 43,6% | Organic matter improvement, water retention, and nutrient availability |
| Precision farming and monitoring | 16 | 41,0% | Yield prediction, crop condition mapping, and stress detection |

| | | | |
|---|---|---|---|
| Climate-resilient planting | 12 | 30,8% | Differences in tolerance to drought, temperature, and inundation |
| Barriers to CSA implementation | 14 | 35,9% | Technological, financing, knowledge, and institutional barriers |

**Barriers to CSA Implementation**

Barriers to CSA implementation were found in 14 articles (35.9%). Limitations of technology and infrastructure were found in 11 articles (28.2%), limitations of financing or access to credit in 10 articles (25.6%), limitations of knowledge and extension services in nine articles (23.1%), and institutional constraints, legality of land, markets, and governance in eight articles (20.5%).

A study of 1,280 independent oil palm smallholders in Indonesia noted technical, administrative, and institutional obstacles in implementing sustainable practices and meeting certification requirements (Watts et al., 2021).

Research by Hendrawan et al. (2024) identified five groups of farmers based on their level of resilience, namely vulnerable groups, economically and socially constrained, low-skilled, semi-safe, and adaptive. Differences between groups were found in characteristics of age, skills, productive assets, access to information, and government support. The review by Ogahara et al. (2022) noted constraints in the form of low income and yields, tenure uncertainty, and limited access to financing, information, markets, and technical assistance.

**Main Study Data Extraction Table**

**Table 3. Extraction and mapping of representative studies**

| **Researcher** | **Location or data** | **CSA Focus** | **Extracted findings** | **Durability dimensions** |
|---|---|---|---|---|
| Wulandari et al. (2025) | Multinegara; SLR | Climate risks and adaptation | Temperature, rainfall, soil moisture, and extreme weather affect crop conditions and yields | Climate risks |
| Monzon et al. (2022) | Indonesia; 136 observasi *block-year* | Water management | Water stress and VPD are associated with changes in water yield and efficiency | Productivity and water |
| Brum et al. (2021) | Amazon Hour; Experiments | Irrigation | Production increased by 35% on sprinklers and | Water adaptation |

| | | | | |
|---|---|---|---|---|
| | | | 26% on drip irrigation | |
| Adu et al. (2022) | Meta-analysis of 19 studies | Soil improvement | Empty bunches increase growth or average yield by 49.2% | Soil and nutrients |
| Mahmud dan Chong (2021) | Tinjauan | Biofertilizer | Empty bunches and microorganisms increase nutrient availability | Nutrients and the environment |
| Hermanto et al. (2023) | Eleven plant materials | Climate-resistant planting materials | The response to the number of bunches and flower development differs between progeny | Genetic resistance |
| Watson-Hernández et al. (2022) | Costa Rica; citra Landsat | Remote sensing | The vegetation and moisture index is used to predict the outcome one year in advance | Monitoring |
| Khan et al. (2022) | 420 months of results data | *Machine learning* | Weather and soil moisture data are used to predict yields | Precision farming |
| Watts et al. (2021) | Indonesia; 1,280 farmers | Adoption of sustainable practices | Technical, administrative, and institutional barriers were found | Adoption capacity |
| Hendrawan et al. (2024) | Indonesian smallholder farmers | Livelihood resilience | Five groups of farmers with different levels of resilience were found | Socio-economic resilience |

| | | | | |
|---|---|---|---|---|
| Ogahara et al. (2022) | Smallholder survey | Sustainability | Found barriers to income, yield, tenure, capital, and technical assistance | Adoption and institutionalization |

**DISCUSSION**

The results of a systematic review of 39 articles showed that 31 articles (79.5%) reported the positive effect of the implementation of Climate-Smart Agriculture (CSA) on at least one dimension of oil palm plantation resilience. Six articles showed results that depended on local conditions, while two found no consistent changes in productivity. Because this study uses a systematic literature review design, the proposition that CSA strengthens plantation resilience is not tested through statistical hypotheses, but is assessed based on the consistency of evidence between publications. The dominance of positive findings shows that CSA is able to integrate productivity, climate change adaptation, and environmental sustainability. These results are in line with Satria et al. (2025) and Wulandari et al. (2025), who explain that oil palm resilience is influenced by the integration of climate management, natural resources, technology, and supporting policies.

Water and nutrient management was found in 22 articles (56.4%), while soil improvement was reported in 17 articles (43.6%). Adequate water availability can sustain stomata activity, photosynthesis, female flower formation, and bunch development. Monzon et al. (2022) affirm that water stress is one of the main factors explaining the spatial and temporal variation in oil palm yields. Research by Rao et al. (2024) also showed that irrigation increased the number of bunches by about 34% and the yield of fresh fruit bunches by about 38%, although the magnitude of the response was influenced by the age of the plant and the internal production cycle. However, an increase in water use efficiency is not always followed by an increase in the overall ecological function. Rinandyta and June (2025) found that oil palm is able to conserve water through stomata regulation during drought and haze, but carbon sequestration remains declining. These findings show a compromise between the plant's ability to retain water and its carbon mitigation function.

In the aspect of nutrient management, the success of CSA is determined by the accuracy of the type, dose, time, method, and location of fertilizer application. This explains why fertilization does not always result in the same productivity increase at every location. Tambunan et al. (2024) showed that the effectiveness of oil palm fertilization is greatly influenced by the suitability of application time with rainfall patterns and field conditions. Meanwhile, Saputra et al. (2024) found that the use of ash and organic matter can improve the acidity and ionic status of the soil. Thus, the use of empty bunches, ash ash, compost, and other plantation biomass not only increases soil fertility, but also reduces waste and supports the implementation of a circular economy in oil palm plantations.

A total of 16 articles (41.0%) discussed precision agriculture, while 14 articles (35.9%) reported improved monitoring and prediction capabilities. The technology forms a sensing-decision-action mechanism, where data from sensors, satellite imagery, weather, and field observations are processed into information to determine irrigation, fertilization, crop control, and harvesting more precisely. Khan et al. (2022) prove that machine learning can use rainfall, root zone humidity, temperature, wind speed, and number of rainy days to predict oil palm yields. At the operational level, Rambe et al. (2022) showed that production taxation based on the observation of harvest density and janjang weight can achieve an accuracy of 95%. Thus, the contribution of technology to resilience comes not only from the addition of inputs, but also from increased decision accuracy, labor efficiency, and the ability to take adaptation actions early.

The six articles that produced conditional findings and two articles that did not show consistent changes in productivity confirmed that CSA is not a uniform technology package. Differences in soil type, plant age and genotype, initial plantation conditions, drought intensity, management quality, and delayed biological response can affect yields. Wandana et al. (2024), for example, found that temperature had no significant effect when it was still within the optimal range, while rainfall was more related to productivity. This difference does not contradict the initial proposition of the study, but it does show that the relationship between climate and yield is moderated by site and plant characteristics. Therefore, the implementation of CSA must be based on location-specific conditions, not simply adopting technology uniformly.

Obstacles to the implementation of CSA were found in 14 articles (35.9%), mainly in the form of technological and infrastructure limitations, investment costs, farmer knowledge, extension services, and institutional support. The findings broaden the understanding that plantation resilience is a socio-technical system. Technology will only deliver results if it is supported by user capabilities, economic feasibility, access to financing, data availability, and collaborative governance. For smallholders, the implementation of CSA should be phased out through soil conservation, site-specific fertilization, climate recording, simple water management, and low-cost digital technology. The support of farmer groups, companies, financial institutions, extension workers, and the government is needed so that the benefits of CSA are not only accessible to large plantations.

Theoretically, this study contributes by showing the relationship between resource efficiency, ecosystem buffer capacity, adaptability, and productivity stability within a framework of oil palm plantation resilience. However, the frequency of articles in the synthesis only shows the amount of evidence available, not the measure of effect or the certainty of cause-and-effect relationships. Indicator heterogeneity, dominance of studies from Southeast Asia, differences in study design, potential publication bias, and non-meta-analysis limited the generalization of results. Follow-up research needs to use multi-site and longitudinal experiments with standardized indicators, such as productivity of fresh fruit bunches, water and nutrient efficiency, soil carbon, emissions, adoption costs, and farmers' incomes. Research also needs to evaluate genotype–environmental interactions, the economic feasibility of CSA technology, and the effectiveness of collaboration models in accelerating adoption in smallholder plantations.

## CONCLUSIONS AND RECOMMENDATIONS

Based on a systematic review of 39 articles, Climate-Smart Agriculture (CSA) has the potential to strengthen the resilience of oil palm plantations to climate change through efficient water and nutrient management, soil quality improvement, the use of adaptive planting materials, precision agriculture, and data-based monitoring systems. The application of such practices helps to maintain productivity, increase adaptation capacity, and reduce environmental impact. However, the effectiveness of CSA is influenced by the characteristics of the location, age and genotype of the plant, soil conditions, intensity of climate risks, and the quality of plantation management.

The implementation of CSA is recommended to be site-specific and gradual by prioritizing affordable technology, efficient resource management, and sustainable climate and productivity monitoring. The government, plantation companies, research institutions, extension workers, and farmer groups need to strengthen training, financing, digital infrastructure, and collaborative governance. This support is important so that CSA can be implemented inclusively, especially by smallholders, while supporting long-term productivity and environmental sustainability.

## FURTHER STUDY

Further research needs to use multisite and longitudinal experiments to measure the influence of CSA on FFB productivity, water and nutrient efficiency, soil carbon, emissions, farmer incomes, and adoption costs. Quantitative meta-analysis as well as genotype–environmental interaction research are also required to determine the most effective combination of CSA practices in various plantation conditions.

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