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Climate change impacts and adaptation strategies in coconut plantations: integrating remote sensing and real-time monitoring

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Climate change poses serious challenges to coconut plantations worldwide, affecting physiological processes, reproductive success, and overall productivity. Rising temperatures, changes in precipitation patterns, increased pest and disease incidence, and coastal degradation are threatening the sustainability of coconut production, which supports the livelihoods of millions of farmers in tropical regions. The review is a synthesis of existing information on the effects of climate change on coconut plantations and an analysis of adaptation measures incorporating advanced remote sensing and real-time monitoring systems. Satellite platforms, unmanned aerial vehicles (UAVs), and Internet of Things (IoT) sensor networks enable early and precise detection of water stress, nutrient deficiency, and disease outbreaks before the manifestation of symptoms. These technologies enable climate impact assessment, early warning, yield forecasting, and precise resource management at the palm level. To adapt successfully, it is necessary to integrate technological innovations with agronomic strategies such as the optimization of irrigation, the development of cultivar that is resistant to climatic change, and climate-wise agroforestry systems that would be more productive and create resilience. The supportive policy frameworks, institutional capacity building, affordable technology to growers and participatory research methods are the keys to the successful scaling of these solutions. Future directions involve the new biotechnologies, integration of artificial intelligence, and collaboration processes between science and practice that can offer a holistic approach to managing climate-smart coconut plantations in the face of increased environmental change.

KEYWORDS
climate change, climate-smart agroforestry, coconut, precision agriculture, remote sensing

1 Introduction

1.1 Background and global importance of coconut

Coconut (*Cocos nucifera* L.) is a perennial palm believed to have originated in the Indo-Pacific region, where it has been cultivated for thousands of years (Adkins et al., 2024). The ability to thrive in a variety of tropical habitats such as sandy coastal soils as well as inland agroecosystems has helped it to attain a wide natural distribution and worldwide adoption. The crop is a dominant plantation crop in the tropics since it is a crop that thrives in warm and humid climates with plenty of sunlight. Coconut is planted on an area of more than 12 million hectares in over 90 countries worldwide (Alouw et al., 2025). Asia Pacific region contributes about 85 percent of the total production, with the major producers of the product being Indonesia, Philippines, India, and Sri Lanka. Coconut farming is the main source of livelihood to millions of smallholder farmers, who tend to have mixed farming systems of coconuts with fruits, spices, or livestock (Dissanayaka et al., 2023; Nuwarapaksha et al., 2023). This increases farm resilience, income stability and biodiversity conservation. The coconut tree is unique in being appreciated as multipurpose, with economic or household uses in almost all its parts. Nuts that are mature are refined into copra, coconut milk, coconut oil and desiccated coconut to serve the global food industries. Tender nuts are also a source of healthy coconut water, which is a rapidly expanding export product. The husk is source of coir fibre to be used in geotextiles, ropes, erosion control materials, and horticultural substrates and the shell is utilized in charcoal, handicrafts and activated carbon industries (Atapattu et al., 2024a,b; Reddy, 2019). Construction materials, fuelwood and traditional crafts are made out of the trunk and the leaves. It is widespread root system holds the coastal soils and reduces wind erosion and forms an inherent barrier to sea spray and storms. In the majority of traditions, coconut is linked to rituals, traditional medicine, and food and symbolizes prosperity, purity, and sustenance. Besides being economically important, coconut is also an important ecological factor (Alouw et al., 2025). Consequently, coconut is an important crop in the world that sustains livelihoods, ecosystems, industries and cultural heritage in tropical areas (Nair, 2021).

1.2 Background of climate change impacts to coconut

Climate change is disrupting conditions and posing a serious threat to coconut farming (Naresh Kumar and Aggarwal, 2013). This Figure 1 shows the interrelated cycle of climate change effects on the coconut production process and how the effects such as change in precipitation, extreme weather conditions, soil erosion, and susceptibility of farming systems contribute to the decrease in crop production, soil erosion, and pests and diseases. Among them one of the most significant problems is the increase of temperatures. The increase in day and night temperatures enhances the rate of evapotranspiration, water stress, and lowers nut set and kernel development. Long heat exposure also influences the pollen viability resulting in poor fruit development (Hebbar et al., 2020). Vulnerability is also increased by changes in rainfall patterns. Unpredictable rainfall, prolonged dry periods and frequent droughts lead to a decrease in the availability of soil moisture resulting in less production of leaves, drop of flowers and low yields. On the other hand, severe rainfall occasions pose threats of water logging, root rot, soil and erosion (Bhat et al., 2024). The rise in the sea level and the erosion of the coastline endanger the large portions of coconut-bearing belts by making the soil and groundwater salty. Salt stress causes major growth retardation, diminishes nutrient uptake, and undermines palms. Moreover, climate change is changing the occurrence of pests and diseases (De Silva et al., 2025). Increased temperatures and humidity may be conducive to the outbreak of pests like the coconut mite and rhinoceros beetle, as well as, increase pressure of diseases. Higher rates of cyclones and powerful winds result in the direct physical harm of palms, which cause a reduction in yields in the long term. All in all, climate change has multifaceted and interrelated threats to the coconut productivity, sustainability and livelihoods of the farmers.

1.3 Background of remote sensing and real-time monitoring for coconut

Remote sensing has become an effective technology of surveillance of coconut plantations, as it offers quick, precise and repeatable measurements of extensive regions (Zheng et al., 2023). Remote sensing and real-time monitoring technologies have evolved to be fundamental in assisting in climate resilient coconut management by facilitating early identification, quick evaluation, and proactive decision-making (Selvam and Al-Humairi, 2025). Figure 2 shows the different altitudes and platforms of remote sensing, beginning with the ground-based UAV drones at 0.1 km up to space satellites at 700–900 km and how different technologies including aerial

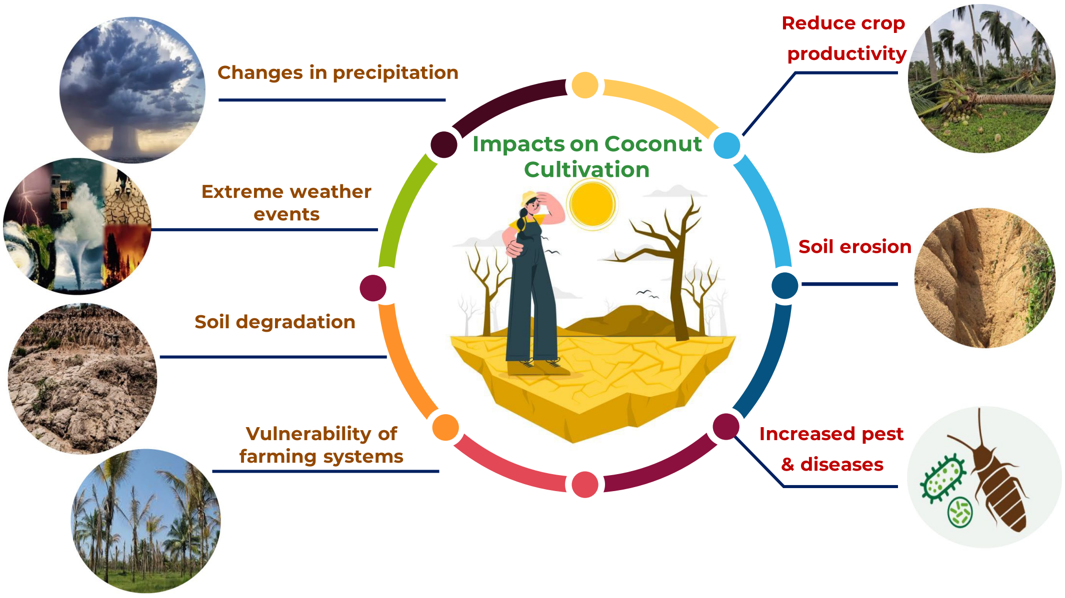

FIGURE 1
Climate change impacts on coconut cultivation (Source: figure by authors).

photography, Synthetic Aperture Radar (SAR), and optical sensors are applied at different altitudes to collect data on earth observation. Multi-temporal, continuous observations of coconut plantations by satellite-based remote sensing platforms, including Sentinel-2, Landsat-8, and MODIS can be used to detect long-term climate driven changes in plantations (Li et al., 2025). Multispectral indices (e.g., Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge (NDRE), and Normalized Difference Water Index (NDWI)) can be used to observe the health of the canopy, moisture stress, and the effects of drought (Hais et al., 2019). Radar sensors have especially been effective in the cloudy coastal areas where structural changes and storm damage can be detected even during monsoon seasons. Such data are important to map the vulnerable areas, evaluate the intensity of climate stress and prepare the adaptive management strategies. Remote sensing by drones has greater spatial resolution on climate adaptation to plantations (Guimarães et al., 2020). Multispectral, thermal, or RGB sensors on Unmanned Aerial Vehicles (UAVs) are capable of detecting early signs of water stress, heat stress, nutrient disorders, and climate-driven pest infestation (Dainelli et al., 2021). This helps in accuracy interventions like optimized irrigation, localized fertilization and early pest control. In addition to these tools, the real-time monitoring systems of Internet of Things (IoT) (soil moisture sensors, weather stations, salinity sensors) will provide field-scale data on the microclimatic conditions in real-time (Salem et al., 2024). Combined with cloud analytics systems, such as Google Earth Engine or decision-support dashboards, these systems produce alerts, predict stress events, and facilitate climate-smart management planning.

1.4 Scope and objectives of the review

Certain reviews have delved into certain aspects of the impact of climate change on coconut cultivation, including the physiological processes, agronomic adaptation strategies, or application of a specific digital method, including remote sensing (Vala et al., 2024). These studies are however largely disconnected in that they have addressed climate stressors, technological interventions and policy dimensions individually. To date, very few reviews have been produced which would integrate a mixture of climate effects, accuracy monitoring technologies, agronomic adaptation, and institutional-policy processes into a single, coherent framework, tailored to coconut-based systems. The main contribution of this review is the development of an integrated climate technology management policy framework tailored specifically for coconut systems (Lata and Osborne-Naikatini, 2025). This review integrates the knowledge on physiological responses, climate-smart agronomy, remote sensing and real-time monitoring, artificial intelligence and enabling policy environments to provide a systems-level view that goes beyond descriptive assessments (Yu et al., 2025). Through this it will bridge the divide between science and technological development and practice to the smallholder-dominated tropical coconut systems.

Although prior reviews have focused on sub-elements of this subject separately such as climate change vulnerability of tropical crops, remote sensing in plantation agriculture, and precision agriculture technologies among smallholders none has used a unified analytical framework to integrate all three critical dimensions together. The existing literature on coconuts has also focused more on single stressors like drought, heat or salinity individually, without considering the interaction effects of these stressors or the role of the emerging digital technologies in identifying and controlling them concurrently (Dos Santos et al., 2022). The missing part of this review is addressed by presenting the first climate-technology-policy framework which was specifically designed to apply to coconut systems. The framework offers a systemic association between the physiological and productivity effects of climate change on coconut and the working ability of

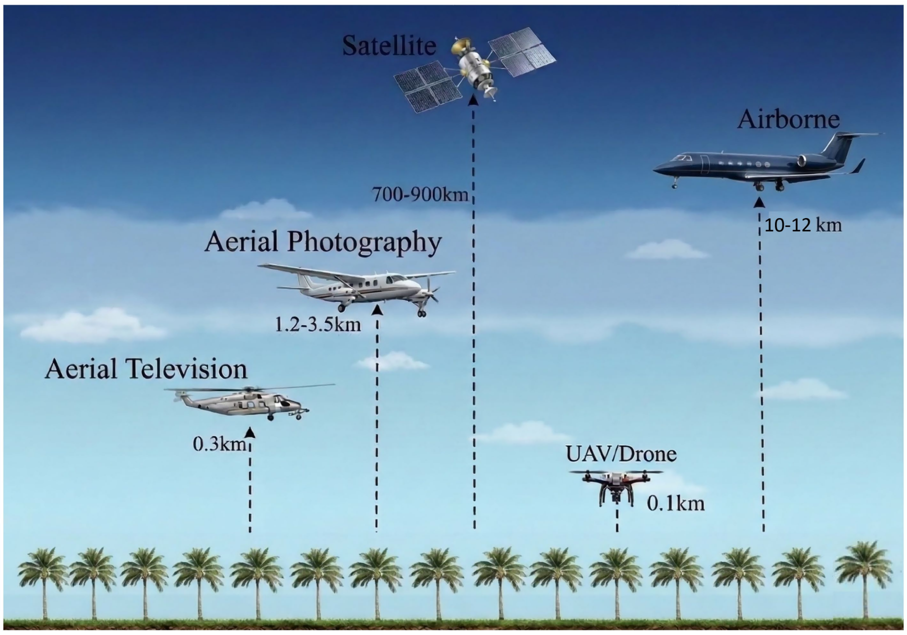

FIGURE 2
Different remote sensing platforms and altitudes (source: figure by authors).

satellite, UAV, and IoT surveillance frameworks and connects them to agronomic, genetic and policy adaptation interventions that are feasible in the environment of smallholder-based tropical agriculture (Alkhawaji et al., 2024). With the ability to generalize these dimensions into a single evidence base, this review provides researchers, extension workers, and policymakers with the analytical basis that they require to develop holistic, technology-based climate adaptation plans in coconut production systems. This review is to identify and summaries existing information on the impacts of climate change on coconut plantations and to identify the efficiency of the adaptation strategies involving the use of remote sensing and real-time monitoring technologies. The main aims are to explore the physiological, ecological, and productivity-related effects of the most important climatic stressors on the coconut plantations, evaluate the emergent agronomic, genetic, and technological solutions that can improve the climate resilience, and indicate the role of satellite, UAVs, IoT, and AI-based platforms in the early detection, resource optimization, and decision-support in the coconut farming. The review area includes the world tropical coconut areas, and it focuses on the smallholder-dominated tropical areas and covers climatic, agronomic, technological and policy aspects.

1.5 Review methodology

The narrative review is a synthesis of the peer-reviewed articles that investigate the effects of climate change on coconut production and the existing adaptation options, especially remote sensing and real-time monitoring technologies. Web of science, Scopus, and Google Scholar was used to conduct the literature search between September to December 2025. The search terms were combinations of the words: coconut and climate change and remote sensing or UAV or IoT or precision agriculture or satellite monitoring. The other keywords included drought stress, heat stress, coastal erosion, and climate-smart agriculture in coconut systems. The review mainly targeted the studies that had been published in the last 30 years in order to capture the recent technological advancements. Nevertheless, previous background research was also incorporated in which they supplied valuable historical or conceptual background. The selection of articles was based on the following criteria: (I) the relevance to the impacts of climate changes on the system of coconut production; (II) the use of remote sensing, IoT, or any other real-time monitoring techniques; (III) the discussion of the agronomic/genetic/policy-based adaptation strategies; and (IV) the representation of the major coconut-producing areas to facilitate geographic diversity. Since it is a narrative review, an integrative and not a completely systematic screening method was used.

2 Climate change impacts on coconut plantations

2.1 Physiological and reproductive impacts

The impact of changes in climate in terms of temperature and precipitation on the physiological activities of coconut palms has identifiable effects on flowering intensity, ineffective nut setting, and impaired fruit development (Hebbar et al., 2020). Carbon dioxide (CO_2) levels may enhance the biomass yield of coconuts, but this advantage is usually counterbalanced by a decrease in the net photosynthesis rates at high air temperatures, which affect the total productivity. This loss of photosynthetic efficiency, together with a higher respiration rate during heat stress, causes a net decline in assimilate partitioning to reproductive organs and growing nuts, which causes smaller, low-quality coconuts and high levels of yield loss (Naresh Kumar et al., 2018). The exact effect of temperature on pollen viability and subsequent fruit set is of paramount importance because high temperatures may affect the pollen germination and pollen tube development, thereby directly affecting fruit reproduction and ultimate yield (Kumarathunge et al., 2024). The screening of seven coconut cultivar has shown that there is a variation in temperature tolerance of pollen germination, with the cardinal temperatures (T_{min}, T_{opt}, and T_{max}) varying widely across varieties. Optimal temperature of germination of pollen in cultivars was 28.3 °C with a useful temperature range of about 16.7 °C to 39.2 °C. It is interesting to note that the cultivars had varying breadths of thermal tolerance and Dwarf Green x Tall (DGT) had the largest range (T_{max}–T_{min} = 24.5 °C) and Dwarf Brown x Tall (DBT) had the smallest range (T_{max}–T_{min} = 21 °C), although DBT had the highest optimal temperature (30.2 °C) (Table 1). The results indicate the significance of cultivar selection in breeding programs to develop heat-tolerant coconut varieties because the fluctuation in pollen thermal tolerance is directly related to reproductive success in warming climates (Ranasinghe, 2013). In addition to direct physiological impacts, water shortage, which is commonly a result of the changed precipitation patterns, is a significant deterrent to the overall health of the palm, another contributor to these reproductive problems (Hebbar et al., 2013).

2.2 Effects on nut yield, pests, and diseases

The shrinking coconut productivity and quality are further worsened by the fact that changing climatic conditions lead to soil infertility and the rise in pest and disease prevalence (Aratchige et al., 2025). These decreases are associated with soil organic carbon depletion and nutrient deficiencies, which are prevalent in most areas where coconuts are cultivated, and are aggravated by continuous harvesting and

TABLE 1 Cardinal temperatures for pollen germination of different coconut cultivars.

Cultivar	Cardinal temperatures (°C)		
	T_{min} (°C)	T_{opt} (°C)	T_{max} (°C)
Tall x Tall (TT)	17	28.9	40
Tall x San Ramon (TSR)	15	28.2	39
Tall x Dwarf Brown (TDB)	17.1	27.5	38.4
Dwarf Brown x Tall (DBT)	16.5	30.2	37.5
Dwarf Brown x San Ramon (DBSR)	17.3	28.3	38.5
Dwarf Green x San Ramon (DGSR)	17.5	28	39.8
Dwarf Green x Tall (DGT)	16.5	27.5	41
Mean	16.7	28.3	39.2

Source: Authors' compilation based on data from Ranasinghe (2013).

extended droughts (Atapattu and Udumann, 2024). Hot weather may also cause fruits to mature too soon and flower to abort, which adversely affects the number and quality of coconut harvests. The effects of pre-anthesis temperature stress, such as the one on the productivity of fruits, can be severe, with pollen formation and ovule viability being affected, which have a direct impact on fruit set and development (Mehmood et al., 2025). Higher temperatures may lead to a reduction in the synthesis of defensive chemicals in coconut palms, exposing them to pathogens and insect pests. Moreover, the interruption of life cycles of the pollinators, including different insect species, may adversely influence the reproductive performance of coconut palms, which results in decreased fruit set and yield in general (Hebbar et al., 2020).

2.3 Impacts of land suitability changes

Climate change is fundamentally transforming the geographic allocation of favorable lands to grow coconuts in a number of interlinked environmental functions. Increasing temperatures above the optimum of 27–32 °C have a direct negative effect on photosynthetic performance and reproduction, making once productive areas less productive and potentially accessible cooler areas more productive (Hebbar et al., 2022). Changing precipitation patterns result in areas of higher aridness in already existing growing areas and higher moisture availability in other areas, requiring a thorough review of the cultivation potential, according to the future water balance conditions (Kang et al., 2009). With nearly 90 percent of the world coconuts plantations located on coastal areas, they are compounded with the rise of the sea level and saltwater intrusion, which gradually rise to levels that the coconuts palms cannot withstand (Palanivel and Shah, 2021). The erosion of the coastline and increased storm surges also decrease the amount of land available to cultivate, especially low-elevation deltaic and island settings. Climatic alterations in temperature and moisture regimes also influence the properties of soils by increasing the rate of decomposition of organic matter, enhance soil erosion and nutrient leaching, which compound suitability losses that were caused by climate (Rhodes, 2014).

3 Adaptation strategies for climate change impacts

3.1 Agronomic and water-management practices

The agronomic adaptations include diverse practices to increase resilience, including the use of soil moisture conservation methods, including biochar application, mulching and cover cropping, which help keep the soil moisture when it is drying (Dissanayaka et al., 2022; Dissanayake et al., 2023). Such practices play a vital role in maintaining productivity considering the fact that there is a decline in flowering intensity and low nut set due to climate variability. The judicious use of the summer or drip irrigation systems also alleviates water stress and ensures the constant water supply at the periods of significant growth (Atapattu et al., 2024b). Moreover, the accurate control of fertilisers, depending on the specifics of the soil and the needs of the crops, is necessary to maximize the absorption of nutrients and increase the overall resistance of coconut palms to environmental factors (Atapattu et al., 2025a,b,c,d). Furthermore, the use of better cultivation methods, including the correct use of spacing and density control, can lead to a better use of the resources, as well as reduce the competition between the palms, thus making them more resistant to climatic shocks (Mrudula et al., 2025). These and frequent observation of the health indicators of plants are essential to ensure timely observation of the symptoms of stress and provide prompt interventions to reduce yield losses.

3.2 Genetic improvement and climate-resilient cultivars

The most important future resilience is the creation and adoption of better cultivars and hybrids, those that have been proven to be more resistant to drought, heat, and salinity (Yang et al., 2018). Such varieties that are frequently produced by either traditional breeding or molecular breeding can greatly reduce losses in yield to unfavorable climatic conditions and sustain productivity. Biotechnological innovations, including *in vitro* propagation, further enhance the multiplication of high-quality, climate-resistant coconut cultivars, which will guarantee the greater and more rapid distribution of high-quality planting material (Henrietta, 2025). This involves the study of stomatal responses to the vapor pressure deficit in order to understand the relations of plants to water under stress and the identification of temperature limits to good nut setting that are essential in predicting yield stability and reproductive success. Moreover, the use of genetically modified varieties that are more resistant to certain pests and diseases will allow reducing the loss of crops and minimizing the use of chemical interventions, which will contribute to a more sustainable agricultural ecosystem (Arumugam and Hatta, 2022).

3.3 Climate-smart agriculture and agroforestry systems

Climate-smart agriculture is a new method of dealing with the effects of climate change on coconuts production, where adaptation, mitigation and sustainable productivity improvement are incorporated in one framework (Atapattu and Udumann, 2024; Udumann et al., 2025b). This strategy focuses on practices that enhance the ability to withstand climate variability and minimize the environmental impact and enhance the livelihoods of the farmers. The strategic implementation of the integrated pest management in the climate-smart agricultural systems diminishes the use of synthetic pesticides, which improves the environmental sustainability and fosters biodiversity. One of the pillars of climate-smart agriculture in the production of coconuts is the adoption of agroforestry systems which incorporate coconut palms with other complementary crops and trees (Aguilar et al., 2023). Such diversified systems do not only enhance the resilience of the climate shocks by enhancing the health of the soil and the water retention level and the control of the microclimate, but also provide a range of income sources that protect the farmers against any losses in production caused by the alterations in the climate (Nuwarapaksha et al., 2025a; Nuwarapaksha et al., 2024a,b,c). The study carried out in Siri Kandura Estate, Dodanduwa, Sri Lanka, proves that significant productivity is attainable by using climate-smart mixed cropping systems (Table 2). Coconut intercropping with coffee produced 8,216 nuts/ha/year, which was 34% more than monoculture (6,123 nuts/ha/year). The coconut-cinnamon systems produced 7,623 nuts/ha/year (26 percent increment), coconut-cocoa systems produced 7,504 nuts/ha/year (22 percent increment), and coconut-clove intercropping produced 7,191 nuts/ha/year (17 percent increment). These results indicate that climate-smart agroforestry practices can be effective in enhancing productivity, diversify farm revenue, and enhance climate variability resilience simultaneously (Nuwarapaksha et al., 2022). To scale climate-smart farming activities, policy interventions and active participation of communities are required to help farmers have access to the required knowledge, resources, and financial incentives to implement such sustainable adaptation solutions (Udumann et al., 2025a).

TABLE 2 Effect of mixed cropping systems on coconut yield at Siri Kandura Estate, Dodanduwa, Sri Lanka.

Cropping system	Mean nut yield/ ha/ year	Increment percentage
Coconut only	6,123	–
Coconut + Cocoa	7,504	22
Coconut+ Coffee	8,216	34
Coconut + Pepper	6,424	5
Coconut + Clove	7,191	17
Coconut + Cinnamon	7,623	26

Source: Authors' compilation based on data from Gunasena (1995).

4 Remote sensing and real-time monitoring-based systems for climate change impact adaptation

4.1 Satellite, UAV, and aerial systems

Modern remote sensing technologies provide multi-scale monitoring capabilities for managing coconut plantations under climate change. However, no single platform is universally suitable, as each involves trade-offs between spatial resolution, temporal frequency, cost, and practical accessibility (Zhang and Zhu, 2023). Sentinel-2 and Landsat-8 moderate-resolution satellite systems offer revisit times of 5–10 days and spatial resolutions of 10–30 m (Maciel et al., 2020). The main benefits of them are that they are cost-effective, have a wide geographical scope, and the data is free or low-cost. Which makes them the most scalable when it comes to regional drought assessment, canopy stress mapping, and planning at the policy level. Nonetheless, a 10–30 m pixel is the sum of the spectral response of several palms, soil patches and understory vegetation, making the detection of individual palm-level stress, localized nutrient deficiencies or young pest outbreaks virtually undetectable at this resolution (Srestasathiern and Rakwatin, 2014). This is not a technical shortcoming but a basic limitation to the agronomic usefulness of satellite data to make decisions on a farm level. This restriction of optical sensors is exacerbated by cloud cover, but SAR data may partially overcome this by offering all-weather observational capability. However, SAR interpretation involves specialized skills that are not common at the farm or extension level, and therefore its application in practice is limited even in areas where the data exists (Dingle Robertson et al., 2020).

In comparison, UAVs have ultra-high spatial resolution of 1–5 cm and multispectral image with centimeter-level accuracy that allow palm to palm assessment of health status, canopy structure, and early signs of stress or disease that cannot be detected by satellite platforms (Zhang and Zhu, 2023). This accuracy is of a qualitatively different type of information -actable at the level of individual plants- and thus more directly applicable in farm management decisions. Such accuracy however does not come without a structural cost that cannot be underestimated. Capital costs of between 5 and 10 million (LKR) per unit plus the need to have skilled pilots, regulatory authorization, maintenance capacity, and weather-related operational restrictions puts the cost of owning a single UAV squarely out of the reach of small-scale farmers. Most importantly, cooperative ownership and UAV-as-a-service models have been suggested as resolutions, although the literature shows little evidence of their long-term cost-efficiency and implementation at scale in tropical smallholder coconut systems (Singh and Singh, 2025). The presumption that cooperative models will address the accessibility gap is therefore to be considered a hypothesis to be proved by empirical evidence as opposed to a given solution. Table 3 summarizes spectral bands and spatial resolutions of the UAV multispectral systems and Landsat-8, which demonstrates the underlying trade-off between spatial accuracy and spectral-spatial coverage between platforms.

4.2 Ground-based sensors and IoT systems

The type of monitoring value offered by ground-based sensor networks and IoT systems is fundamentally different than the type of monitoring value offered by remote sensing platforms: it is not spatial coverage, but continuous temporal resolution at a specific point or plot, monitoring real-time change in soil moisture, temperature, salinity, nutrient availability, and microclimate conditions (Kadrolli and Kalnoor, 2024). Combined with dendrometers and spectral sensors they can measure physiological responses to stress, such as changes in stem growth rates or canopy reflectance, much faster than visual observations or periodic overpasses of remote sensing, and allow more timely and targeted interventions to be taken in irrigation scheduling, fertilizer application, and resource management. Nevertheless, an objective evaluation of the IoT systems within the smallholder setting will indicate that there is a significant discrepancy between the hypothetical potential of the systems and their feasibility of implementation than commonly recognized (Antony et al., 2020). The stable connectivity infrastructure, the uninterrupted power supply, the frequent calibration of the sensors, and the technical ability to maintain and interpret the data are the key factors to the reliable IoT performance (Moore et al., 2020). These preconditions are not always fulfilled in most tropical smallholder settings such as large areas of the coconut-producing countries in South and Southeast Asia. In rural agricultural regions, connectivity is often unreliable or even non-existent; power is sometimes intermittent; and the technical expertise needed to maintain sensors and process the data is often lacking at the farm level unless it is maintained externally (Imoize et al., 2021). This implies that the high temporal resolution benefit of the IoT systems is not absolute but dependent, and its actualization requires infrastructure

TABLE 3 The spectral bands and resolutions of multispectral drone and landsat-8 satellite.

Multispectral drone			Landsat-8 satellite			
Spectral band	Wavelength (nm)	Resolution (cm) at 100 m altitude	Spectral band	Wavelength (nm)	Band number	Resolution (m)
Blue	450 ± 16	~5	Coastal aerosol	433–453	1	30
Green	560 ± 16	~5	Blue	450–515	2	30
Red	650 ± 16	~5	Green	525–600	3	30
Red edge	730 ± 16	~5	Red	630–680	4	30
NIR	840 ± 26	~5	NIR	845–885	5	30
			SWIR1	1,560–1,660	6	30
			SWIR2	2,100–2,300	7	30
			Panchromatic	500–680	8	15
			SWIR/Cirrus	1,360–1,390	9	30

Source: Authors' compilation based on data from Javhar et al. (2019).

investment and capacity building programs that are often not a part of technology adoption discourses.

Moreover, IoT systems are also point-level or plot-level, which restricts their spatial representativeness in heterogeneous plantation settings where soil variability, microclimate variability, and unique palm variability is frequent (White et al., 2020). Increasing the size of IoT coverage to the scale of a farm or a landscape is significantly more expensive, which constitutes a scalability limitation, similar to, but not identical to, the cost barriers of UAV deployment. Initial installation costs and the maintenance cost that is required especially by the smallholder farmers who are on narrow margins is a serious economic risk especially when the payback of the investment in terms of better yield or saving of resources cannot be easily determined in advance (Hebsale Mallappa and Bansal, 2026). Nevertheless, these drawbacks do not negate the complementary functions that IoT systems provide that cannot be imitated by satellite and UAV platforms, namely, continuous and high-frequency streams of data that allow managing dynamically and responsively, instead of evaluating periodically. Their best application in the smallholder environment is thus probably to be focused and selective - prioritized on climate-smart or high-value plots, combined with extension-supported data interpretation services, and applied via common infrastructure models, as opposed to farm investment (Cohn et al., 2017). In the absence of these institutional conditions, the transformative potential of the IoT monitoring will probably be not achieved by the majority of the smallholder coconut farmers.

4.3 AI and machine learning techniques

The analytical layer, which, in theory, can transform the information produced by satellite, UAV, and IoT systems into predictive and prescriptive management advice, is artificial intelligence and machine learning - a shift in perspective towards predictive decision support, rather than the descriptive monitoring that is currently in place (Jung et al., 2021). IoT networks integrated with clouds have the potential to allow predicting stress in real-time, automated irrigation timings, and optimization of fertilization depending on soil, weather, and crop specifications. ML models that utilize multisource data streams can predict disease outbreak risk, identify anomalies that may reflect the onset of stress and generate farm-specific advisories, which otherwise would be extremely cumbersome to generate using traditional agronomic evaluation (Foluke Ekundayo, 2024). Yet, a critical assessment of AI and ML use in this field of application shows that there are a number of substantive weaknesses that are often disregarded in technology-optimistic analyses. To begin with, the quality, volume, and representativeness of training data are the key factors that define the performance of the ML models. The majority of published crop stress detection, disease classification, and yield prediction models have been designed and tested on datasets of intensively managed agricultural systems and in many cases in the temperate region with fairly homogeneous cropping conditions (Josephine and Subhashini, 2025). Implementation of these models without recalibration by region has a real risk of producing false advice that will destroy the trust that farmers have in digital advisory systems and negate more extensive adoption of technology.

Training and deploying advanced ML models demand computational infrastructure, such as cloud connectivity, data storage, processing capacity, which is not always present in smallholder environments, and the cost of the infrastructure is not often included in technology adoption evaluations (Ramamoorthi, 2025). Although the AI-generated advice may be technically correct, the translation of the advice into farmer behavior change is contingent on the delivery of extension services, digital literacy, and trust in algorithmic recommendations, social and institutional factors that are fully outside the technical domain and are often underemphasized in the current literature on AI in agriculture. The financial benefit of AI-based interventions on coconut systems in particular has been ill-measured (Atapattu et al., 2024a,b). Coconut is a long-cycle perennial crop, unlike annual crops, in which the economic benefits of optimized management are accrued in only one growing season, and in which the economic benefit of precision management decisions can take years to show benefits and is hard to attribute to individual interventions (Sudha et al., 2021). This renders the cost–benefit evaluation of AI implementation especially difficult and highlights the necessity of long-term experimental data and not extrapolation of short-term or crop-specific research in other systems.

4.4 Integrated multi-scale monitoring framework

A critical analysis of the technologies considered in the previous sections shows that the argument of integration is not based merely on the additive advantages of integration of platforms, but on the need to counteract the structural constraints that each platform can bring about separately. Satellites are cheap and cover large areas but are not able to make decisions at farm level. UAVs offer the accuracy required to conduct farm-level diagnostics, but are structurally unavailable to the majority of smallholders without institutional intermediation (Satpati, 2026). IoT sensors offer the time continuity unavailable to either of the remote sensing platforms, but they rely on infrastructure that is not uniformly distributed over target areas. AI and ML have the analytical ability to derive actionable knowledge on multi-source data, yet their applicability in tropical smallholder coconut settings has not been well-validated and their practical implementation relies on under-funded extension systems (Ugwu et al., 2025). In the light of these interdependencies, it is suggested that smallholder coconut systems should be adopted in a tiered framework that directly considers practical limitations instead of assuming equal access to technology. On a regional level, the baseline monitoring layer should be represented by freely available satellite data, especially the Sentinel-2 and SAR products, which can be used to provide drought early warning and canopy stress surveillance in addition to policy planning at the landscape level (Holik et al., 2025). This level can be implemented immediately using the current data infrastructure, and it does not need an investment at the farm level. At the farm level, cooperative UAV service models, in which expenses are distributed among groups of farmers and operations are operated by trained service providers, are the most plausible route to precision diagnostics to smallholders, but only when farmer organizations or government programs can subsidize the coordination and initial capital expenses (Adel et al., 2026). This conditionality should be expressed: without this kind of institutional structures, UAV-based monitoring will not be available to the majority of the target population. On the plot scale, the targeted deployment of IoT in climate-smart or high-value locations, with the assistance of shared infrastructure and data interpretation extensions, can offer the real-time responsiveness that is unavailable to satellite monitoring or UAV monitoring.

The interface layer, which converts multi-source monitoring information into farm-specific recommendations, is represented by AI-based advisory tools, provided as easily accessible extensions, e.g., mobile applications or SMS-based systems, but their implementation has to be supported by long-term extension capacity and validation of the model by region (Soussi et al., 2024). It should be noted that this framework has a number of institutional preconditions, namely cooperative structures, government subsidy programs, extension service investment, and digital infrastructure development, which cannot be assumed to exist in all target regions and which are major uncertainties in the practical implementation of the framework. Improved climate adaptation outcomes are a condition that requires monitoring technologies but not a sufficient one (Hübner and Finkbeiner, 2025). The human and institutional structures upon which better data is communicated, interpreted and acted upon are equally important to the translation of better data into better decisions, and are as much the subject of research and policy as are the technologies themselves. Future studies must thus focus not on technical validation of monitoring platforms within coconut systems, but on empirical analysis of institutional model of technology delivery, economic analysis of cost and returns of adoption at the smallholder level, and long-term analysis of the correlation between precision monitoring and climate adaptation outcomes in tropical perennial crop systems (Omar et al., 2023).

5 Applications of climate change adaptation for coconut plantations

5.1 Climate impact and vulnerability assessment

The technologies of remote sensing and real-time monitoring are critical in determining the complex effects of climate change on coconut plantations to generate granular data to guide the specific adaptation measures. These techniques allow the accurate measurement of the environmental stress factors, including the intensity of drought heat stress, pest and diseases and their consequent impact on physiological parameters and yield dynamics of coconut crops (Ahmad et al., 2021). As indicated by the Figure 3 NDVI where the normal values are 0.6 to 0.9 of healthy coconut canopies, indicates a reducing photosynthetic activity under drought conditions, and in the stressed areas, the values are usually below 0.5 (Samarakoon et al., 2025). NDWI detects the lack of moisture in the canopy, with the value above 0.3 indicating sufficient water condition, whereas the values below 0.1 indicate the serious water stress in need of irrigation intervention (Chauhan et al., 2025). NDRE, 0.08 to 0.65 in coconut palms as displayed in map, is used to monitor healthy plants with the values of above 0.65 which implies adequate nutrients (Samarakoon et al., 2025). These indices enable early identification of physiological alterations that are signs of stress, which occur 2–4 weeks prior to the onset of visual symptoms, which allows proactive management responses (Zuckerman et al., 2024). In addition, these technologies enable constant observation of the health of the plantations, which provides a dynamic evaluation of the impact of environmental changes on growth, productivity, and overall stability of the ecosystem over a long period, including weekly monitoring and multi-year trend analysis (Fuentes et al., 2025). Such thorough analyses are needed to understand the susceptibility of the area and develop precise and evidence-based adaptation strategies in accordance with the specific climatic and ecological environment, and the spatial resolution of 5–10 cm can be employed to control the palm-level.

5.2 Early detection of stress and disease outbreaks

The spectral data is processed by remote sensing systems to detect indicators of plant stress before the symptoms are visible, which allows to prevent active irrigation and nutrient provision (Rosa et al., 2023). With the help of advanced hyperspectral and multispectral imaging, it is possible to distinguish between types of stress, detecting certain diseases or nutrient deficiencies before they cause massive damage (Terentev et al., 2022). The palm-by-palm visualization enables targeted intervention, with stress categories

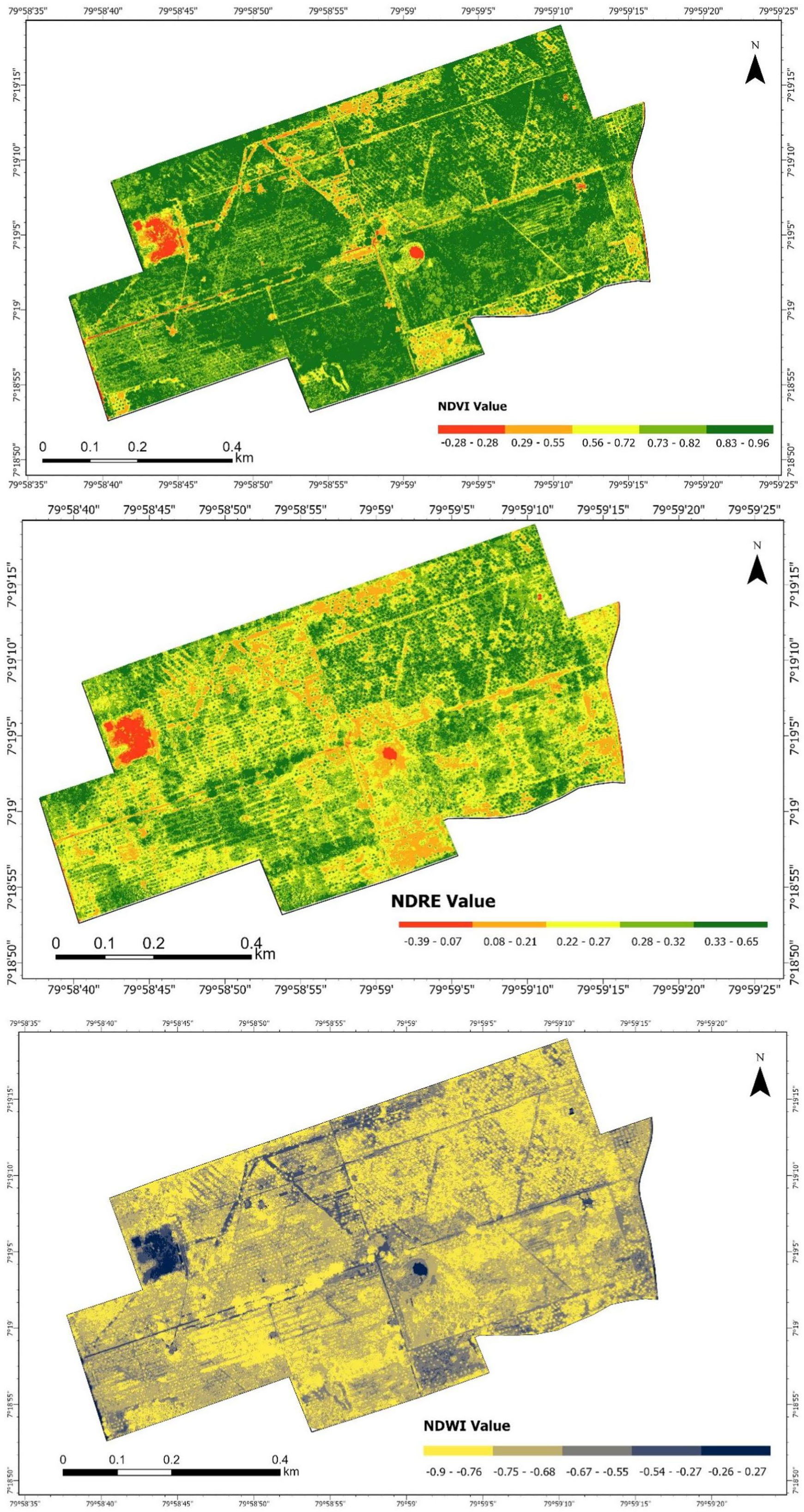

FIGURE 3
Multispectral vegetation analysis using NDVI, NDRE, and NDWI for precision agriculture monitoring (source: figure by authors).

assigned at 5–10 cm spatial resolution across the entire plantation. An example of such an ability in practice is the Coconut Palm Health Monitoring System implemented at Makandura Research Center, Sri Lanka that classifies individual palm health status in real-time with NDVI values measured using multispectral drone imaging and verified against field measurements

(Supplementary Material S1 to give detailed specifications of the system and classification statistics). These datasets can be further improved by machine learning to detect small variations in the health of vegetation, which improves the accuracy of early warning systems to detect drought, heat stress, and disease outbreaks (Burchfield et al., 2016).

5.3 Precision resource management and nutrient optimization

With the help of remote sensing and AI-based technologies, the nutrient conditions in coconut plantations can be accurately evaluated and controlled at the palm level, which will make it possible to optimally apply the fertilizer depending on the individual needs of a palm (Manoharan et al., 2024). Multi spectrum imagery spectral analysis can be used to detect spatial distributions of nutrient deficiency at a plantation scale, which can be used in variable-rate fertilization practices to maximize resource and minimize unnecessary chemical use and costs (Atapattu et al., 2025a,b,c,d). An elaborate case study on palm-level potassium mapping in Makandura Research Center is presented in Supplementary Material S2. In addition to nutrient management, remote sensing and real-time IoT systems allow controlling the irrigation and fertilization rates of plants at the same time, preventing water wastage and chemical runoff and enhancing the overall sustainability and cost-effectiveness of the plantation management (Ali et al., 2023; Nakachew et al., 2024). However, the implementation of palm-level precision nutrient management depends on the availability of high-resolution imagery, precise calibration models, and farmer interpretations and response to decision-support information. Satellite-based monitoring combined with selective field validation would be a more affordable and scalable solution to large-scale implementation.

6 Future directions and research needs for mitigating climate change impacts

6.1 Emerging biotechnologies and genome editing for climate resilience

More research is required on the use of modern biotechnologies, including genetic engineering and CRISPR-Cas9, to create climate-resistant coconut varieties that are more drought-tolerant, resistant to pests, and better yield-stable (Mmbando, 2025). Moreover, the combination of machine learning and AI with remote sensing data will potentially transform the climate impact predictive modeling and the optimal resource allocation strategy in coconut plantations. IoT devices and sensor networks can be used to monitor the health of crops and environmental stressors in real-time, which can be used to provide actionable information to precise agriculture and implement interventions to reduce risks associated with climate (Mansoor et al., 2025). Further research of the plant physiological adaptations to climate stressors, such as stomatal responses to vapor pressure deficit and thermal limitations to nut set, are necessary in developing crops with water-conserving traits and those that germinate and reproduce under erratic conditions. Moreover, real-time soil nutrient monitoring by genetically modified microbiological inoculants and nano-sensors will greatly increase the nutrient uptake and tolerance of plants to unfavorable environments (Atapattu et al., 2025a,b,c,d; Dissanayaka et al., 2025). At the same time, the creation of climate-resilient varieties, based on innovative breeding programs, combining both traditional and modern methods of genetic enhancement, is one of the priorities of the coconut industry in the future (Arumugam and Hatta, 2022).

6.2 Integrating AI and remote sensing to climate models

Precision agriculture methods in coconut plantations through the integration of remote sensing data and machine learning algorithms can support spatial models, which helps to provide precision agriculture methods to increase the efficiency of resource utilization and improve climate adaptation strategies. The technologies may be applied to assist in the more accurate prediction of diseases, more efficient irrigation, and providing an early warning of pest outbreaks, which will reduce losses of crops and maintain the sustainability of production during the climate variability. This high level of analysis also goes further to determine the best planting time and cultivars to use in particular microclimates, which has greatly enhanced productivity and resilience to climate (Rivero et al., 2022). Climate models developed by AI forecast the future climate conditions and determine potential effects on the feasibility of crops, soil quality, water availability, and agricultural productivity, which can be used as key aspects of strong adaptation and mitigation strategies (Kumari et al., 2025). These predictive models have the ability to combine a wide range of data, such as the past weather patterns, soil properties, and crop yield data, to produce spatially explicit guidance regarding the best agricultural practices and cultivar choice (Hernández Hernández et al., 2025).

6.3 Institutional and policy support for technology transfer mechanisms

Policies should be effective to encourage the implementation of climate-intelligent farming methods and allow the required technological transfer of smallholder farmers (Nagar and Machavaram, 2025). These frameworks must encompass monetary mechanisms, e.g., subsidies on climate-resilient infrastructure and crop insurance plans, in order to reduce the economic risks of climate change to agricultural populations (Mishra et al., 2025). Moreover, institutional facilitation in the form of strong extension services and trainings to farmers is essential to strengthen local capacity in the adoption of precision agriculture methods and interpretation of complex data on remote sensing and real-time monitoring systems (Thangamani et al., 2025). These policies must also encourage new climate-resistant coconut varieties and sustainable food production and production, which would provide food security and economic stability in the long term in coconut-reliant areas. Moreover, the governments are to focus on investments in green technologies and control the use of pesticides to decrease the emission of CO_2 and make the agricultural sphere environmentally friendly (Yasmeen et al., 2022). International cooperation and relationships also play an important role in the international exchange of best practices and technologies in the context of crossing the borders and developing a global attitude to climate change adaptation in coconuts production.

6.4 Strategies for scaling adoption among smallholder farmers

Some of the barriers that need to be overcome to achieve effective upscaling include limited access to finance by farmers, lack of technical knowledge, and the digital divide, which requires specific interventions and inclusive policies (Mollel et al., 2025). This involves the development of strong digital infrastructure, offering access to digital tools at affordable rates, and the development of extensive training programs to make farming communities more digitally literate. Moreover, it should encourage the private sector to create and spread climate-resilient technologies that can fit smallholder farmers, and create a market-based solution to adaptation. Furthermore, the digital financial inclusion and climate-smart agricultural technology can be successfully integrated to boost the uptake of resilient agricultural practices by smallholder farmers (Asante et al., 2025). The strategy entails connecting microfinance facilities and ecosystem service payment schemes with the implementation of new agricultural practices, whereby economic gains are consistent with the sustainable agricultural transformation. These solutions should be flexible to support different agricultural systems, geographical areas, and types of farms and acknowledge the different socio-economic backgrounds of the coconut growers. However, there are significant obstacles to the mass adoption of these digital agricultural solutions, including high initial cost, complex adoption, privacy, and the environmental impact of technology per se, in addition to the digital divide (Wang et al., 2025). To solve these issues, a multi-faceted strategy, including government and non-governmental investment in infrastructure, specific programs of digital literacy, and regulatory measures that focus on the privacy of data and fair access to technology is necessary (Uzoamaka et al., 2024).

6.5 Priority research needs and participatory approaches

The research should be directed in the future by developing less expensive and easy-to-use digital solutions that are specifically tailored to the needs and constraints of the smallholder coconut farmers who reside in different ecological environments (Lamsal et al., 2023). Additional research is also necessary to consider the possibility of applying blockchain technology to improve the transparency of the supply chain and the monitoring of carbon sequestration in coconut production, as well as the use of nanotechnology to achieve better nutrient delivery and soil health management (Atapattu et al., 2025a,b,c,d; Nuwarapaksha et al., 2025b; Nuwarapaksha et al., 2024a,b,c). The genetic mapping of coconut root systems should also be a priority in the research to gain a better understanding of the nutrient uptake mechanisms to implement more accurate fertilization strategies. Also, the studies of genetically modified microbiological inoculants that increase nutrient uptake and tolerance of plants to abiotic stresses may transform the fertilization practice so that it becomes more efficient and sustainable to the environment (Sudheer et al., 2020). Additionally, the research on the production of new organic fertilizer formulas that can respond to changing weather conditions is essential to guarantee effectiveness and mitigate the environmental impact (Verma et al., 2020). Lastly, participatory research models with local farmers are also necessary to formulate context-specific agroforestry models and climate-resilient practices that are appropriate and easily implemented.

7 Conclusion

Climate change is a multidimensional and interacting threat to the world coconut plantations, which impacts physiological processes, reproductive success, land suitability, pest and disease interactions, and ultimately, livelihoods of millions of smallholder farmers in tropical areas. These challenges have been discussed in this review in terms of an integrated climate-technology policy framework the first of its kind to coconut systems - that explicitly relates the impacts of climate change, remote sensing and IoT-based monitoring, and agronomic, genetic, and policy adaptation strategies to a single analytical framework. In contrast to the earlier reviews that studied these dimensions individually, this framework shows the potential of dealing with compounding stresses like concurrent drought, heat, and salinity that can be observed in multispectral indices, like NDVI, NDRE, and NDWI, in weeks before the manifestation of symptoms, to be dealt with by integrated evidence-based interventions at the individual palm level. Remote sensing and real-time monitoring technologies have been shown to have a transformative potential, allowing early detection of stress, yield forecasting, accurate resource management, and climate-aware decision support on a scale never seen before. These tools, when combined with climate-resilient cultivar development, efficient water and nutrient management, and climate-smart agroforestry systems, offer a promising pathway for sustaining coconut production under growing environmental uncertainty. Notably, coconut-coffee intercropping systems reviewed here demonstrated yield increases of up to 34%. But to actualize this potential, collective effort is required at a number of levels. Good policy regimes should encourage the adoption of technology; institutional provision of extension services and training should be used to develop local capacity; low-cost access to technology should be made available to resource-bound smallholders; and participatory research should be used to ensure that solutions are both context-specific and farmer-focused. Future research priorities are cost-effective sensor development, AI-based predictive modeling, biotechnological solutions to stress tolerance such as CRISPR-based genome editing, and other effective technology transfer mechanisms. Finally, the sustainability of the coconut industry in the long-term is pegged on the convergence of scientific knowledge, technological advancement, and the historical wisdom of the farming communities in the tropical world to find inclusive solutions that would ensure productivity without compromising environmental sustainability.

Author contributions

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