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Integration of Smart Farming Technology and Agroforestry as a Climate Change Adaptation Strategy to Strengthen Food Security of Coffee Farmer Households in Indonesia

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ABSTRACT (10 PT)

Climate change threatens the sustainability of coffee production in Indonesia, which is predominantly cultivated by smallholder farmers in rural areas. Agroforestry systems have proven effective as an adaptation strategy, while smart farming technologies offer potential for increased productivity and efficiency. This article examines the existing conditions of agroforestry implementation, smart farming technology adoption, food security levels of coffee farmer households, and the impacts of climate change on coffee farming productivity and income in Indonesia. Based on a systematic literature review, this study also identifies the potential and challenges of integrating smart farming into coffee agroforestry systems as a climate change adaptation strategy. The findings indicate that coffee agroforestry has been widely implemented with various patterns; however, smart farming technology adoption remains low due to infrastructure limitations, capital constraints, and limited farmer capacity. Food security among coffee farmer households varies across regions, with some farmers still facing food insecurity. Climate change has had tangible impacts on productivity and farmer income through changes in rainfall patterns and temperature increases. The integration of smart farming into agroforestry offers substantial opportunities through resource optimization and data-driven decision-making, yet faces significant challenges related to technology access, system complexity, and supportive policies. This study recommends the development of contextual integration models and comprehensive agricultural innovation support systems to accelerate technology adoption and strengthen coffee farmers' food security.

INTRODUCTION

Indonesia is one of the world's largest coffee producers, contributing approximately 5% to global coffee production, making it the fifth-largest coffee-producing country globally after Brazil, Vietnam, Colombia, and Ethiopia (Rahmah et al., 2025). This strategic position is inseparable from the diverse agroecological conditions across the Indonesian archipelago, ranging from the Gayo highlands in Aceh to the slopes of Mount Ijen in East Java, which provide ideal growing environments for various coffee varieties, particularly Arabica and Robusta. This comparative advantage has established coffee as one of Indonesia's main agricultural commodities, contributing significantly to the national economy and employment in rural sectors (Rahmah et al., 2025).

The majority of coffee plantations in Indonesia are managed by smallholders distributed across major islands, including Sumatra, Java, Sulawesi, Bali, and Flores, with an average landholding of less than two hectares per household (Schroth et al., 2014). This characteristic of small-scale land ownership reflects the socio-economic reality of rural Indonesia, where coffee farming serves as a safety net for millions of farming families. These smallholders generally manage their plantations with limited capital and minimal access to technology, making them highly vulnerable to external shocks such as global price fluctuations and the impacts of climate change (Pratiwi et al., 2021). This condition necessitates policy interventions that favor capacity building and resilience enhancement for smallholder farmers.

Coffee is not only an important export commodity with a total export value reaching USD 1.15 billion in 2022, but also a primary livelihood source for millions of farming households in rural areas (Rahmah et al., 2025). Indonesian coffee exports are primarily destined for major markets such as the United States, Europe, Japan, and Middle Eastern countries, with export volumes showing positive trends in line with increasing global demand for specialty coffee. However, approximately 80% of Indonesia's total coffee production remains in the form of unprocessed green beans, resulting in relatively low value addition for farmers compared to domestic processing (Rahmah et al., 2025). This indicates that Indonesia's coffee value chain still has substantial room for improvement through downstream processing and value addition.

During the 2020/2021 period, Indonesia's domestic coffee consumption reached approximately 300 million kilograms per year and continues to show significant increasing trends (Rahmah et al., 2025). This consumption increase is driven by the rapid growth of Indonesia's middle class, changing urban lifestyles, and the proliferation of coffee shops in various cities, making coffee no longer merely a traditional beverage but part of contemporary Indonesian culture. This phenomenon creates substantial domestic market opportunities for coffee farmers while reducing dependence on volatile export markets. Nevertheless, smallholder farmers often face difficulties in accessing this growing domestic market due to limited market information, infrastructure, and marketing capabilities, leaving them dependent on intermediary traders who sometimes suppress purchase prices.

However, Indonesia's coffee sector faces serious threats from climate change that jeopardize long-term production sustainability. Modeling research by Schroth et al. (2014) demonstrates that temperature increases are likely to combine with decreased rainfall in some islands and increased rainfall in others, drastically reducing the total area of climatically suitable coffee land in Indonesia by 2050. These impacts are not uniform across regions; some areas such as Bengkulu are projected to remain suitable or even become more suitable for coffee cultivation, while major production centers such as Aceh, North Sumatra, and Lampung will experience significant decreases in suitability (Schroth et al., 2014). This geographical shift in climate suitability has implications for potential plantation relocation, which if not properly managed, could drive deforestation in new areas.

In Gayo Highlands, Aceh, which constitutes Indonesia's premium Arabica coffee production center, climate change is predicted to significantly reduce the availability and suitability of land for Arabica coffee production in the coming decades (Wijaya et al., 2025). Farmers in Gayo Highlands have begun to experience climate change impacts through unpredictable rainfall patterns, increasing daily temperatures, and shifting growing seasons that disrupt flowering and fruit maturation cycles (Wijaya et al., 2025). Farmer perceptions of climate change remain moderate, although threats to the coffee industry are substantial, necessitating more intensive awareness-raising and adaptive capacity building efforts (Wijaya et al., 2025). Delays in responding to climate change could result in the loss of Indonesia's competitive advantage in the global coffee market, which increasingly demands quality and sustainability.

The impacts of climate change are exacerbated by increasing attacks from the coffee berry borer (*Hypothenemus hampei*), whose population increases with rising temperatures and changing rainfall patterns (Ritonga & Kwon, 2024). This pest is among the most destructive to coffee plants as it bores into coffee cherries and damages the beans inside, significantly reducing both quality and quantity of harvests. Research indicates that a 2°C temperature increase can shorten the pest's life cycle and accelerate population growth, leading to more frequent attacks and more severe damage (Ritonga & Kwon, 2024). Farmers often lack the knowledge and resources to control this pest effectively, especially since intensive chemical pesticide use is not always effective and can damage the environment.

Regional reviews in Southeast Asia confirm that climate change intensifies risks for coffee farmers, causing reduced yields and coffee bean quality that threaten the livelihoods of millions of families (Fuerzas & Delina, 2025). These challenges are compounded by structural vulnerabilities such as limited fertile land availability, declining soil fertility, limited financial resources, and dependence on outdated agricultural technologies that still dominate cultivation practices in most regions (Fuerzas & Delina, 2025). Coffee-producing countries in Southeast Asia, including Indonesia, Vietnam, and Thailand, face similar challenges and need to share experiences and best practices in adapting coffee production systems to climate change. Regional collaboration becomes increasingly important as climate change respects no national borders and requires coordinated collective responses.

In facing these challenges, comprehensive and integrated adaptation strategies encompassing technical, socio-economic, and policy aspects are required. Two main approaches that have received widespread attention are agroforestry and smart farming technologies, each offering specific advantages but also limitations when applied separately. Agroforestry, as a cultivation system integrating coffee trees with other plants on the same land, has proven to provide ecological and economic benefits while enhancing resilience to climate change (Rahmah et al., 2025; Sari et al., 2023). Tree diversity in agroforestry systems contributes to social-ecological resilience by providing various product options and income sources for farmers, dampening income fluctuations, and accelerating system recovery following disturbances (Sari et al., 2023). Meanwhile, smart farming offers opportunities to optimize production through technologies such as sensors, the Internet of Things (IoT), data analytics, and artificial intelligence that can help farmers make more precise and efficient decisions.

Research on IoT implementation in Robusta coffee nurseries demonstrates that IoT-based systems can significantly improve environmental stability and seedling growth, with IoT-treated plants achieving better growth compared to conventional systems (Rosdiana et al., 2024). Automated sorting systems based on smart cameras and AI have also been developed to improve the efficiency and accuracy of coffee bean sorting, directly impacting product quality improvement and market value (Fauzi et al., 2025). Although both approaches have substantial potential, their integration in the context of Indonesian coffee farming remains underexplored and faces various challenges including technology access, agroforestry system complexity, infrastructure limitations, and farmer capacity. The synergy between agroforestry and precision technology offers substantial potential for simultaneously enhancing climate resilience and productivity, yet requires deep understanding of specific conditions across various coffee production centers. This article aims to fill this knowledge gap by examining the existing conditions of agroforestry implementation in Indonesian coffee cultivation, analyzing the level of smart farming technology adoption among coffee farmers, evaluating the food security levels of coffee farmer households, identifying the perceived climate change impacts on farmers, and analyzing the potential and challenges of integrating smart farming into coffee agroforestry systems as a climate change adaptation strategy

RESEARCH METHODS

This study employs a systematic literature review approach with a qualitative-descriptive research design. This method was chosen to provide a comprehensive overview of the existing conditions and potential for integrating smart farming with coffee agroforestry in Indonesia, based on empirical evidence from various existing studies.

Data Sources and Search Strategy

Data were obtained from secondary sources including scientific journal articles, conference proceedings, research reports, and official publications relevant to the research topic. Literature searches were conducted on indexed academic databases such as Scopus, Web of Science, SpringerLink, ScienceDirect, and DOAJ using keywords: ("agroforestry" OR "agroforestri") AND ("coffee" OR "kopi") AND ("smart farming" OR "precision agriculture" OR "IoT") AND ("climate change" OR "perubahan iklim") AND ("food security" OR "ketahanan pangan") AND "Indonesia".

Inclusion and Exclusion Criteria

The inclusion criteria for this study were: (1) publications within the last 10 years (2015-2025); (2) in Indonesian or English language; (3) discussing coffee agroforestry, smart farming, climate change, or food security in Indonesia; (4) journal articles, proceedings, or research reports that have undergone peer-review processes. Exclusion criteria included: (1) publications without full text availability; (2) opinion or editorial articles without empirical data; (3) studies not specifically addressing coffee or the Indonesian context.

Data Analysis

Data analysis was conducted using thematic and narrative synthesis approaches. Information from various literature sources was grouped according to themes corresponding to the research problem statements. Findings from various studies were compared, synthesized, and interpreted to generate comprehensive conclusions. Data validation was performed through source triangulation by comparing findings from different studies.

RESULTS AND DISCUSSION

1. Existing Conditions of Agroforestry Implementation in Coffee Cultivation in Indonesia

Agroforestry is a cultivation system widely implemented in Indonesian coffee plantations, reflecting local wisdom that has evolved over generations in sustainably managing natural resources. This system integrates coffee trees with various other plant types, both perennial species (such as fruits, timber, and other estate crops) and annual crops, within a unified land area managed in an integrated manner. Agroforestry practices have been adopted in various coffee production centers across Indonesia, including West Java, Bandung, Sumatra, Sulawesi, and other regions, with varying levels of complexity depending on local agroecological conditions and farmer preferences (Rahmah et al., 2025; Hill et al., 2025). Agroforestry systems have been proven to increase overall land productivity, reduce production costs through more efficient resource utilization, and strengthen the social and ecological resilience of farming communities through income diversification and biodiversity enhancement (Rahmah et al., 2025). These system advantages make it a highly relevant cultivation model for facing increasing climate change challenges and global economic uncertainty.

Research on tree diversity and social-ecological resilience of agroforestry following volcanic ash deposition in Indonesia provides strong empirical evidence of the role of tree diversity in coffee-based agroforestry systems for system resilience (Sari et al., 2023). Following the eruption of Mount Kelud, which blanketed agricultural land with 15 cm of volcanic ash, farmers managing coffee-based agroforestry with high tree diversity demonstrated faster recovery capabilities compared to farmers with monoculture or simple agroforestry systems (Sari et al., 2023). Farmers reported that diversity and flexibility in coffee-based agroforestry supported faster system recovery compared to annual crops, as deep tree root systems helped maintain soil structure and nutrient cycles despite surface disturbances (Sari et al., 2023). Furthermore, this system also played a role in dampening income fluctuations because when one crop type failed due to specific disturbances, other crop types could still provide alternative income sources (Sari et al., 2023). Adaptive farmer responses to increase species diversity following disturbance events contributed to agricultural resilience by maintaining the basic structure and functions of agroforestry, while increasing the diversity of products generated and income obtained in the long term (Sari et al., 2023).

The coffee value chain in Indonesia reveals interesting dynamics in how farmers integrate coffee with other commercial crops in their cultivation systems. Research on inclusive business models in the West Java coffee value chain reveals that the value chain structure involves various actors ranging from smallholder farmers, collector traders, processing factories, coffee shops with roasting facilities, to farmer cooperatives (Mulyati et al., 2024). Farmers tend to begin with cropping patterns dominated by annual crops to meet consumption needs and short-term income, but over time, they gradually shift composition toward greater dominance of perennial crops such as coffee, fruits, and timber that provide more stable long-term income. Business model analysis indicates that collector models in Pangalengan and Lembang prioritize efficiency and market access but may overlook specific farmer needs, while coffee shop and roastery models in Bogor foster direct relationships with farmers to improve quality and collaborative decision-making, and cooperatives in Garut emphasize collective action and farmer empowerment despite facing governance and market access challenges (Mulyati et al., 2024). These findings indicate that farmers have adequate market knowledge but still face barriers to direct market access due to limited capital, infrastructure, and marketing networks.

Findings on the Indonesian coffee value chain also highlight that coffee traders of various scales dominate farm-level sales, while only a few farmers sell directly to cooperatives or village-owned enterprises. Research in Bolaang Mongondow Timur Regency shows that the Robusta coffee supply chain involves farmers, collector traders, processing factories, retail industries, and coffee roasters, with farmers obtaining varying profit margins depending on the type of product sold—ranging from 42-43% for wet coffee beans to 63-71% for mixed dried coffee beans (Kumajas et al., 2024). This dominance of intermediary traders creates a lengthy value chain where value addition that should be enjoyed by farmers accumulates at the trader level, resulting in relatively small profit margins for farmers compared to the final consumer price. Rahmah et al. (2025) confirms the existence of a significant economic gap between farmers and coffee processors with a profit ratio of 1:2.71, indicating that coffee processors obtain almost three times the profit compared to farmers. This imbalanced value chain structure constitutes one factor hindering the improvement of coffee farmer welfare, despite their increasing productivity and production quality.

From the climate change mitigation perspective, coffee agroforestry provides significant positive contributions through carbon sequestration and biodiversity conservation. Research on the multifunctionality of coffee agroforestry demonstrates that complex agroforestry systems have higher Shannon-Wiener diversity indices (0.57-2.05) and can mimic the diversity levels of disturbed forests, while total carbon stocks show positive relationships with diversity indices across all vegetation growth stages (R^2=0.13-0.57) (Sari et al., 2025). These findings emphasize the importance of maintaining total carbon stocks through diverse vegetation in agroforestry systems to support climate change mitigation and biodiversity conservation (Sari et al., 2025). Rahmah et al. (2025), in their research on circular economy in sustainable coffee agroforestry in Indonesia, demonstrate that converting coffee waste, which has often been discarded and become an environmental pollutant, into organic fertilizer and animal feed has substantial potential to reduce greenhouse gas emissions, improve resource efficiency, and enhance overall economic value. The system dynamics model developed shows that both circular economy scenarios (waste conversion to organic fertilizer and waste utilization as animal feed) can significantly increase farmer incomes and promote fairer profit distribution in the coffee value chain (Rahmah et al., 2025).

The implementation of circular economy in sustainable coffee agroforestry also contributes to the achievement of Sustainable Development Goals (SDGs), particularly Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 8 (Decent Work and Economic Growth), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action) (Rahmah et al., 2025). This circular economy approach creates a positive feedback loop where sustainable agricultural practices increase productivity and income, which in turn enables farmers to invest more in sustainable practices and environmentally friendly technologies (Rahmah et al., 2025). Furthermore, research on agroforestry implementation in West Lampung demonstrates that complex agroforestry systems (CAFS) significantly improve coffee farming performance with the highest sustainability score (60.20) compared to simple agroforestry systems (57.39) and monoculture systems (53.80), while also identifying improvement strategies encompassing land conservation enhancement, road access improvement, capital availability, and market access (Prasmatiwi et al., 2025). However, the transition toward circular economy in coffee agroforestry faces various challenges, including substantial initial investment requirements, limited technical knowledge among farmers, and immature waste processing infrastructure at the village level (Rahmah et al., 2025). Hill et al. (2025) also caution that agroforestry value chain interventions present complex trade-offs between increasing farmer incomes, increasing rural income inequality, and landscape environmental impacts. Therefore, integrated policy support is required, including providing incentives for farmers implementing circular economy practices, developing appropriate and affordable waste processing technologies, and sustainable training and mentoring programs to enhance farmer capacity in optimally managing agroforestry systems and their waste products (Rahmah et al., 2025; Prasmatiwi et al., 2025).

2. Level of Smart Farming Technology Adoption among Coffee Farmers

The adoption of smart farming technology among Indonesian coffee farmers still shows significant gaps between the importance and performance of technology in the field. Research in Central Aceh, a major coffee production center, reveals that farmers rate the importance of smart farming technology as "very high," but its performance level is only rated as "high," indicating a gap that needs to be bridged (Saiful Bahri et al., 2025). This gap is caused by low technology performance in small-scale coffee plantations and low farmer competency in utilizing available technology (Saiful Bahri et al., 2025). The research identified that smart farming is characterized by the application of modern tools and machinery as well as efficient and intensive resource utilization, yet its implementation at the farmer level still faces various structural barriers (Saiful Bahri et al., 2025).

The development and application of IoT technology for coffee plantations has shown promising results in various locations. Research on real-time monitoring and control systems for precision coffee farming developed an ESP32-based prototype with DHT22 sensors (temperature and air humidity), YL-69 (soil moisture), and BH1750 (light intensity), achieving average accuracy rates of 97.1% for temperature, 94% for air humidity, 84.5% for light intensity, and 79.2% for soil moisture (Firmansyah et al., 2025). This system is equipped with actuators such as cooling fans, spray pumps, and water pumps that are automatically activated based on determined threshold values—if air temperature exceeds 27°C, the cooling fan activates; if air humidity drops below 70%, the spray pump activates; and if soil moisture drops below 74%, the water pump activates to increase soil moisture (Firmansyah et al., 2025). The average system response time, i.e., the time required to receive data from the microcontroller and display it on the website, was recorded at 1.660 seconds, indicating efficient performance for real-time monitoring (Firmansyah et al., 2025).

Technological innovation has also been applied to post-harvest processes to improve coffee bean quality. The development of an IoT-based portable solar dryer in Harjokuncaran Village, South Malang, was designed to address coffee drying problems still conducted conventionally with durations of 7-14 days and results not always meeting SNI quality standards (Fauzi et al., 2025). This portable dryer was designed with an 80-100 kg capacity and knockdown system for easy relocation, with advantages including energy efficiency, stable temperature at 50°C, minimal contamination, and faster drying time of 3-4 days (Fauzi et al., 2025). Sucofindo laboratory testing of coffee beans dried with this tool showed results conforming to SNI standards, for both conventional drying and using the dryer (Fauzi et al., 2025). Surveys of 25 farmers showed positive responses and understanding regarding operation, maintenance, and application usage, indicating that this innovation has the potential to become a sustainable solution in improving post-harvest coffee quantity and quality (Fauzi et al., 2025).

Despite various technological innovations, smart farming adoption among coffee farmers still faces significant barriers, particularly related to human resource readiness. Research on digital transformation readiness in the coffee farmer supply chain in Paya Tumpi Baru Village reveals that although the government has introduced the Pasar Desa Digital (PDD) e-commerce platform, many farmers still struggle to utilize it effectively due to limited digital literacy and understanding (Hasan et al., 2025). Assessment of 182 coffee farmers showed they demonstrated readiness in aspects of personal motivation, commitment, and optimism, but still lacked in learning ability and knowledge (Hasan et al., 2025). This research identified six key factors influencing digital transformation readiness: personal motivation, learning ability, commitment, optimism, skills, and knowledge, all validated by experts with 75% agreement levels (Hasan et al., 2025). These findings indicate that digital literacy training and workshop programs are essential to bridge the gap and improve overall readiness, particularly in human resource development (Hasan et al., 2025).

Other barriers to technology adoption include limited access to production technology, dependence on weather conditions, limited market access, and capital and investment constraints (Saiful Bahri et al., 2025). Research on Arabica coffee supply chain efficiency in Bondowoso identified that weather dependence received the highest score as an internal weakness (0.39), while limited production technology also constituted a significant inhibiting factor (0.26) (Bahri et al., 2024). However, opportunities from increasing specialty coffee demand (score 0.41) and government and international program support (0.38) can be leveraged to drive technology adoption (Bahri et al., 2024). External factor evaluation also identified that global coffee price fluctuations (0.38) and climate change (0.37) constitute threats requiring adaptation strategies, including through smart farming technology implementation (Bahri et al., 2024). Thus, increasing smart farming adoption requires an integrated approach encompassing farmer capacity strengthening, technology infrastructure development, capital access, and policies supporting digital transformation in the coffee farming sector.

3. Food Security Levels of Coffee Farmer Households

Food security among coffee farmer households in Indonesia varies across regions. A study in Belatungan Village, Tabanan, Bali found that the average income of coffee farmers reached IDR 73.46 million per year or approximately IDR 6.12 million per month (Enjelia, 2025). Household welfare levels were rated as good, indicated by average rice consumption equivalent to 1,440 kg per person per year (Enjelia, 2025). A total of 83.67% of households were classified as food secure because food expenditure was less than 60% of total household expenditure, although 16.33% of households remained food insecure (Enjelia, 2025).

However, coffee farmers face various challenges such as price fluctuations, limited market access, and high production costs that impact household income and food security (Enjelia, 2025). Research on food security development strategies for coffee farming households in Kledung District, Temanggung Regency shows that development strategies based on SWOT analysis place coffee farmer household food security in Quadrant I with an aggressive (SO) approach, namely leveraging strengths and opportunities by increasing productivity through the use of latest technologies, such as faster coffee processing (Bahri et al., 2024).

Agent-based modeling of agroforestry agricultural contracts in Bandung, Indonesia shows that coffee contracts can achieve income increases for farmers and increased agroforestry land cover (Hill et al., 2025). However, transaction costs can prevent many households from accessing contract coffee markets, resulting in trade-offs between higher incomes and increased rural income inequality (Hill et al., 2025). These findings indicate that agroforestry value chain interventions present trade-offs when attempting to address complex landscape challenges, and complementary non-market interventions are required to align smallholder incentives with environmental policy objectives (Hill et al., 2025).

4. Climate Change Impacts on Coffee Farming Productivity and Income

Climate change has had tangible impacts on coffee farming productivity and income in Indonesia. Modeling studies on current and future climate suitability for Arabica coffee in Indonesia show that temperature increases are likely to combine with decreased rainfall in some islands and increased rainfall in others, drastically reducing the total area of climatically suitable coffee land in Indonesia by 2050 (Schroth et al., 2014). However, research also shows that there is still more land with suitable climate and topography for coffee cultivation outside protected areas than is currently used, although most locations differ (Schroth et al., 2014). This indicates the potential for coffee plantation area relocation as an adaptation strategy, but could become a major driver of deforestation if not properly managed (Schroth et al., 2014).

Climate change impacts also affect the coffee berry borer (*Hypothenemus hampei*). Research on coffee production and coffee berry borer conditions in Indonesia related to climate change effects summarizes that climate change can directly affect coffee production or indirectly affect it through its effects on coffee pests (Ritonga & Kwon, 2024). In Indonesia, coffee is a critical export commodity, and climate change can have major impacts on many farmers if not properly addressed (Ritonga & Kwon, 2024).

Reviews on climate change and resilience strategies in Southeast Asian coffee communities confirm that climate change intensifies risks for coffee farmers, causing reduced yields and coffee bean quality (Fuerzas & Delina, 2025). These challenges are compounded by structural vulnerabilities such as limited fertile land, declining soil fertility, limited financial resources, and dependence on outdated agricultural technologies (Fuerzas & Delina, 2025). Despite facing severe challenges, Southeast Asian coffee communities demonstrate tangible resilience through adaptive practices such as shaded systems, intercropping, and improved farm management (Fuerzas & Delina, 2025).

Company-community partnerships have proven effective in increasing the adaptive capacity of smallholder farmers to climate change. Studies in Lampung show that such partnerships positively influence smallholder adaptive capacity through increased agricultural income and reduced income vulnerability, as well as through increased propensity to adopt resource conservation techniques and agroforestry (Pratiwi et al., 2021).

5. Potential and Challenges of Smart Farming and Agroforestry Integration

a. Integration Potential

The integration of smart farming technology into coffee agroforestry systems offers substantial potential. Complex agroforestry systems with interactions between trees, soil, and crops require sophisticated management approaches. IoT and sensor technologies can provide real-time data on critical environmental parameters such as soil moisture, temperature, and pest activity (Rosdiana et al., 2024). This data is invaluable for complex agroforestry systems as it enables farmers to respond quickly to changing environmental conditions.

The development of automated sorting systems based on smart cameras and AI demonstrates that technology integration can significantly improve coffee production efficiency and quality (Fauzi et al., 2025). This system not only reduces sorting time but also improves selection accuracy and daily productivity, ultimately increasing farmer incomes (Fauzi et al., 2025).

Smart farming integration also supports the implementation of Climate Smart Agriculture, which emphasizes simultaneous productivity enhancement, climate change adaptation, and greenhouse gas emission mitigation. System dynamics models for circular economy-based sustainable coffee agroforestry show that converting coffee waste into organic fertilizer and animal feed can significantly increase farmer incomes, reduce emissions, and promote fairer profit distribution in the coffee value chain (Rahmah et al., 2025).

b. Integration Challenges

Despite its substantial potential, integrating smart farming into coffee agroforestry faces several significant challenges.

First, technology accessibility. Smart farming adoption remains low due to infrastructure, capital, and farmer capacity limitations. Research on company-community partnerships shows that farmers with motor vehicles, larger land sizes, and active local networks are more likely to adopt technology and adaptive practices (Pratiwi et al., 2021). This indicates an access gap that needs to be addressed.

Second, agroforestry system complexity. Agroforestry involves complex interactions between various plant species, making precision technology application more complicated compared to monoculture systems (Rahmah et al., 2025). The parameters that need to be monitored and optimized in agroforestry systems are far more numerous and interrelated.

Third, policy and support limitations. Reviews on climate change in Southeast Asia identify significant gaps in integrating long-term climate adaptation strategies into national agricultural policies (Fuerzas & Delina, 2025). Existing policies often favor monoculture systems over agroforestry (Fuerzas & Delina, 2025). Strengthening policy frameworks is essential to address climate-related exposures while supporting sustainable coffee communities (Fuerzas & Delina, 2025).

Fourth, economic-environmental trade-offs. Agent-based modeling of agroforestry agricultural contracts in Bandung shows that agroforestry value chain interventions present complex trade-offs (Hill et al., 2025). Coffee contracts can achieve income increases for farmers and increased agroforestry land cover, but transaction costs can prevent many households from accessing contract coffee markets, resulting in trade-offs between higher incomes and increased rural income inequality (Hill et al., 2025). Furthermore, coffee contracts displace low-input agroforestry where opportunity costs are low, resulting in significant decreases in biomass carbon and increased soil erosion—an outcome similar to the Jevons Paradox (Hill et al., 2025).

c. Synthesis and Policy Implications

The integration of smart farming and coffee agroforestry in Indonesia faces significant challenges but also offers substantial opportunities to strengthen coffee farmer food security amid climate change. An integrative approach requires interventions at three levels: (1) farmer level through capacity building and technology access; (2) system level through the development of contextual integration models; and (3) policy level through comprehensive agricultural innovation support systems.

Policy recommendations that can be considered include:

1) Strengthening partnerships and market access: Company-community partnerships have proven effective in increasing smallholder adaptive capacity through income enhancement and conservation technique adoption (Pratiwi et al., 2021). Policies need to encourage inclusive partnerships and reduce transaction costs for smallholder farmers.

2) Investment in digital infrastructure: Smart farming technology adoption requires investment in digital infrastructure in rural areas, including internet access and affordable IoT devices (Rosdiana et al., 2024).

3) Development of contextual integration models: Smart farming and agroforestry integration models need to be developed based on specific socio-economic and agroecological characteristics across various Indonesian coffee production centers (Hill et al., 2025).

4) Farmer capacity strengthening: Training and mentoring are needed to improve digital literacy and farmer capacity in implementing technology (Fauzi et al., 2025).

5) Integrated climate adaptation policies: Policies need to encourage coffee plantation expansion to areas that will remain suitable in the medium term, are not under legal protection, and have experienced deforestation so that coffee cultivation can contribute positively to landscape restoration (Schroth et al., 2014).

CONCLUSION

This study examines the existing conditions and potential for integrating smart farming technology with coffee agroforestry systems in Indonesia as a climate change adaptation strategy to strengthen coffee farmer household food security. Based on the literature review conducted, it can be concluded that:

1) Agroforestry implementation in Indonesian coffee cultivation has been widely conducted with various patterns, ranging from simple to complex agroforestry. This system provides ecological benefits through biodiversity enhancement, soil structure improvement, and carbon sequestration, as well as economic benefits through increased farmer incomes. Tree diversity in agroforestry systems contributes to system resilience against external shocks (Rahmah et al., 2025; Sari et al., 2023).

2) Smart farming technology adoption among coffee farmers remains low. Although technologies such as IoT and AI have shown promising results in improving efficiency and productivity, their implementation remains limited due to infrastructure, capital, and farmer capacity constraints (Rosdiana et al., 2024; Fauzi et al., 2025).

3) Food security of coffee farmer households varies across regions. Most farmers in some areas are classified as food secure, but a significant proportion still face food insecurity due to price fluctuations, limited market access, and high production costs (Enjelia, 2025).

4) Climate change impacts on coffee farming productivity and income have been tangible, particularly through changing rainfall patterns and temperature increases that reduce suitable land area for coffee cultivation and increase coffee berry borer pest populations (Schroth et al., 2014; Ritonga & Kwon, 2024).

5) Smart farming and agroforestry integration offers substantial potential through resource optimization, data-driven decision-making, and production efficiency improvement. However, this integration faces significant challenges related to technology access, agroforestry system complexity, policy limitations, and complex economic-environmental trade-offs (Hill et al., 2025; Fuerzas & Delina, 2025).

Future research is recommended to develop contextual smart farming and agroforestry integration models based on specific socio-economic and agroecological characteristics across various Indonesian coffee production centers, as well as to examine the effectiveness of agricultural innovation support systems in accelerating technology adoption and strengthening coffee farmer food security.

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