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The Role of Digital Technology in Optimizing the Agrocomplex Value Chain

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Abstract

Digital technology has transformative potential in optimizing agrocomplex value chains, but its implementation in developing countries such as Indonesia still faces various challenges. This study analyzes the role of digital technology in optimizing agrocomplex value chains with a focus on implementation in Indonesia. Through a comprehensive analysis of various cases of digital technology implementation in the agricultural sector, this study identifies significant benefits including increased productivity by up to 27.3%, reduced production costs by 18.7%, and efficient use of resources. The analysis also reveals a gap in technology adoption between large and small-scale farmers, as well as the importance of a supporting ecosystem that includes digital infrastructure, capacity development, and conducive policies. The inclusive partnership model and ecosystem-based approach have proven effective in increasing the adoption rate and benefits of digital technology. This study provides a comprehensive framework for implementing digital technology in agrocomplex value chains that considers technological, socio-economic, and environmental sustainability aspects. The implications of this study are relevant for developing policies and strategies for digital transformation in the agricultural sector in Indonesia and other developing countries.

Keywords: digital technology, agrocomplex value chain, digital transformation of agriculture, precision agriculture, sustainable food systems, digital divide, agricultural policy

1. Introduction

The global agricultural sector is undergoing a fundamental transformation driven by the adoption of digital technologies. The agrocomplex, which encompasses the entire value chain from pre-production to consumption of agricultural products, now faces complex challenges such as climate change, global population growth, and limited land and resources [1]. Amid these challenges, digital technologies offer great potential to optimize the efficiency, productivity, and sustainability of the entire agrocomplex value chain [2].

The integration of digital technology in agrocomplexes includes the application of the Internet of Things (IoT), artificial intelligence, big data, blockchain, and digital mapping technology that provide new solutions to classic problems in agriculture [3]. These technologies enable data-based decision making, increased operational efficiency, reduced waste, and improved quality of agricultural products [4]. However, its implementation still faces various obstacles, ranging from inadequate infrastructure, digital divides, to the lack of digital literacy among agricultural business actors [5].

Indonesia, as an agricultural country with high biodiversity, has great potential to optimize its agrocomplex value chain through the adoption of digital technology [6]. However, the implementation of digital technology in the Indonesian agricultural sector is still in its early stages and is not evenly distributed across all regions, so that the optimization of the agrocomplex value chain has not been achieved optimally [7]. Research shows that the adoption of digital technology in Indonesian agrocomplexes can increase productivity by up to 30% and reduce production costs by 20% [8].

Various studies have shown that digital transformation in the agrocomplex value chain provides significant benefits, including increasing the efficiency of agricultural input use, reducing crop losses, optimizing logistics processes, and increasing transparency for consumers [9], [10]. However, the success of implementing digital technology in agrocomplexes depends on various factors, including technology adoption capacity, supporting infrastructure, conducive regulations, and collaboration between stakeholders [11].

This article aims to comprehensively analyze the role of digital technologies in optimizing the agrocomplex value chain, with a special focus on the Indonesian context. This study evaluates various types of digital technologies relevant to each stage of the agrocomplex value chain, identifies key factors influencing technology adoption, and proposes a strategic framework for effective implementation of digital technologies in the Indonesian agrocomplex value chain. The results of this study are expected to provide valuable insights for policymakers, agricultural industry players, and academics in developing a comprehensive digital transformation strategy to optimize the agrocomplex value chain in Indonesia.

2. Analysis of Methods

The method of implementing digital technology in the agro-complex value chain has evolved significantly in recent years. The most commonly used approach is gradual integration, where digital technology is introduced progressively in each component of the value chain, starting from production to distribution [12]. A study conducted by Mariyono and Sumarno revealed that this approach allows for better adaptation for small and medium farmers, and reduces the risk of implementation failure that often occurs in large-scale digital transformations [13]. Several recent studies have shown that a collaborative approach through a multi-stakeholder partnership model between government, academics, technology companies, and agricultural business actors results in higher levels of technology adoption compared to single interventions [14]. This partnership model facilitates investment risk sharing, human resource capacity building, and the development of technological solutions that are more appropriate to the local context.

The methods for measuring the impact of digital technologies on agro-complex value chains have also undergone significant methodological developments. Wolfert et al. developed a comprehensive analytical framework that integrates quantitative measures (productivity, cost efficiency, post-harvest loss reduction) with qualitative parameters (user satisfaction, ease of adoption, environmental sustainability) [15]. This combined approach provides a more holistic understanding of the value generated by the implementation of digital technologies in the agricultural context. Meanwhile, Eastwood et al. proposed a multi-level evaluation methodology that considers the impact of digital technologies at the micro (individual farmer), meso (value chain), and macro (national agricultural ecosystem) levels [16]. This methodology offers a multi-dimensional perspective that is important for understanding the complexity of the impact of digital transformation in agro-complexes.

In terms of technical approaches, the implementation of digital technologies in the agro-complex value chain can be categorized into three main methods. First, a platform-based approach that integrates various technology applications in one integrated digital ecosystem, such as that developed by Trendov et al. [17]. Second, a specific solution-based approach that focuses on optimizing certain components in the value chain, such as a precision agriculture management system or blockchain applications for product traceability [18]. Third, a hybrid approach that combines the implementation of an integrated platform with specific solutions according to the needs of each stage of the value chain [19]. A comparative analysis conducted by Klerkx et al. showed that the hybrid approach provides the highest flexibility and effectiveness, especially in the context of developing countries with varying levels of digital readiness across regions [20].

Capacity building methods to support digital technology adoption in agrocomplexes have also evolved rapidly. Conventional training models with a top-down approach have proven to be less effective than participatory methods that involve technology users from the design stage to implementation [21]. Nuringsih and Puspitaningrum identified that ongoing mentoring programs with a combination of face-to-face training and online support provided the best results in increasing the level of digital technology adoption among smallholder farmers [22]. This approach is supported by the development of training materials tailored to the digital literacy level and local context of farmers, and accompanied by ongoing access to post-training technical assistance.

Regarding implementation methodology, the ecosystem-based approach increasingly dominates the discourse on digital transformation in the agro-complex value chain. This approach emphasizes the development of all components of the digital ecosystem simultaneously, including technological infrastructure, regulatory framework, capacity development, and supporting business models [23]. A comparative study by Zhang et al. in several Asian countries showed that the ecosystem approach resulted in a higher level of implementation sustainability compared to approaches that focused only on the technological aspect [24]. In Indonesia, a pilot project with an ecosystem approach implemented in several agricultural production centers showed an increase in technology adoption of up to 45% higher compared to conventional technology projects [25].

3. Results

The implementation of digital technologies in agro-complex value chains has shown diverse and multi-dimensional results. A comprehensive analysis of various implementation cases in Indonesia and other developing countries reveals several important findings. The results of a survey of 1,250 farmers in five major food-producing provinces in Indonesia showed that the adoption of digital technologies has increased productivity by an average of 27.3 % and reduced production costs by 18.7% [26]. A longitudinal study conducted over three years (2020-2023) on rice, corn, and soybean commodities showed a significant increase in the efficiency of agricultural input use, with a reduction in fertilizer use of 22.5% and pesticide use of 19.8%, without reducing yields [27]. These data confirm the great potential of digital technologies in increasing productivity while promoting sustainable agricultural practices.

Analysis of the implementation of a precision agriculture management system in the horticultural production center of West Java shows impressive results. The use of IoT sensors to monitor soil moisture and microclimate conditions has reduced water use by 35.4% and increased the quality of the harvest that meets export standards from 65% to 88.2% [28]. The implementation of a data-based smart irrigation system on 75 hectares of agricultural land in East Java Province resulted in water savings of up to 42% compared to conventional irrigation methods, while increasing land productivity by 29.3% [29]. These results illustrate the effectiveness of digital technology in optimizing the use of limited resources such as water, which is becoming increasingly crucial amid the threat of climate change.

In the post-harvest and logistics stage, the implementation of an integrated digital platform that connects farmers directly to the market has resulted in an average increase in farmer income of 23.5 % through a reduction in the marketing chain [30]. A case study of six farmer groups in South Sulawesi showed that the adoption of an agricultural-specific e-marketplace application increased the selling price of products by 15-27% compared to conventional marketing methods [31]. This digital platform also reduced post-harvest losses by 34.2 % through better coordination of harvest times and direct access to buyers. On the consumer side, the implementation of a blockchain-based traceability system for specialty coffee commodities in Aceh and Bali resulted in an increase in consumer trust as measured by the willingness to pay a premium of 18.7% for products with transparent origin information [32].

From a socio-economic perspective, the analysis results show that the adoption of digital technologies in agro-complex value chains has varying impacts based on the scale of the business. Medium and large-scale farmers showed higher levels of adoption and economic benefits, with an increase in net income of up to 32.5 % , while small and subsistence farmers experienced a more moderate increase of 12.7% [33]. This gap is largely due to barriers to access to technology, low digital literacy, and limited capital for initial investment. However, an inclusive partnership model involving the aggregation of small farmers in a shared digital platform showed promising results, with an increase in collective income of 28.3 % and improved bargaining position in the value chain [34].

Analysis of factors influencing successful implementation of digital technologies reveals the crucial role of the supporting ecosystem. Areas with good digital infrastructure (internet penetration > 65%) and comprehensive mentoring programs show a technology adoption rate 3.7 times higher than areas with limited infrastructure [35]. Supportive government policies, such as subsidies for digital equipment and training, have been shown to increase technology adoption rates among smallholder farmers by 48.2 % [36]. Socio-cultural factors, such as trust in new technologies and perceived benefits, also have a significant impact on implementation success, with communities with positive perceptions showing a 2.5 times higher adoption rate than communities with negative perceptions [37].

The results of the analysis also revealed the significant influence of digital technology implementation on environmental aspects in the agrocomplex value chain. The application of precision agriculture in Central Java irrigated land reduced greenhouse gas emissions by 28.7 % through optimization of fertilizer and fuel use for mechanization [38]. A digital monitoring system for oil palm plantations in Kalimantan resulted in improved forest and peatland conservation practices, with a 43.5% reduction in deforestation over a three-year period [39]. Digital technology also contributed to increasing agricultural biodiversity, with digital mapping systems and big data analysis supporting efforts to conserve local varieties and develop more sustainable agroecological practices [40].

From a policy perspective, the analysis identified four key components influencing the success of digital transformation in the agrocomplex value chain: (1) a regulatory framework that supports innovation while protecting user data, (2) an inclusive and sustainable capacity building program, (3) targeted financial incentives, and (4) adequate digital infrastructure down to the village level [41]. A comparative study of four provinces in Indonesia showed that regions with comprehensive policies covering all four components experienced a 5.2 - fold increase in technology adoption and 37.8% higher agrocomplex added value compared to regions with partial policies [42]. These findings underscore the importance of a holistic approach in developing a digital ecosystem for optimizing the agrocomplex value chain.

4. Discussion

The results of the study indicate that the implementation of digital technologies in agro-complex value chains offers significant transformative potential. However, in-depth analysis reveals complexities and challenges that need to be addressed to optimize benefits. The finding that digital technologies can increase productivity by up to 27.3 % and reduce production costs by 18.7% [26] illustrates substantial economic impacts. These results are in line with research by Schroeder et al. who found efficiency improvements of 15-30% in digital farming systems in various developing countries [43]. However, it should be noted that these benefits are not evenly distributed across the spectrum of agricultural actors, with small-scale farmers tending to receive more limited benefits compared to medium and large-scale farmers [33]. This gap creates the risk of digital inequality that can exacerbate existing socio-economic disparities in the agricultural sector.

Findings related to increased resource efficiency, such as a reduction in water use of up to 35.4 % through the implementation of IoT sensors [28], provide an important perspective on the contribution of digital technologies to environmental sustainability. In the context of climate change and increasingly intense resource scarcity, such efficiencies are crucial. The results of this study are consistent with the study by Walter et al. who reported water savings of 30-40% in a precision farming system in a dry region [44]. However, discussions about the environmental aspects of digital technologies should not stop at resource efficiency. The carbon footprint of the digital infrastructure itself, including the energy required for data centers, networks, and electronic devices, should also be considered. Several studies have shown that the net environmental benefits of digital farming systems are still positive, but a full life cycle approach is needed for sustainability analysis [45].

The role of the supporting ecosystem as a crucial factor in the successful implementation of digital technology [35] underlines the importance of a systems approach in the digital transformation of agrocomplexes. These results confirm that technology is not just a technical solution, but rather part of a complex socio-technical system. The finding that areas with good digital infrastructure and comprehensive mentoring programs have a 3.7 times higher technology adoption rate is in line with the argument of Klerkx et al. regarding the importance of innovation networks in the digital transition of agriculture [46]. In Indonesia, infrastructure challenges are more complex due to the geographical conditions of the archipelago, so a regional differentiation approach is needed in developing a digital ecosystem for agrocomplexes. Implementation strategies that take local characteristics into account, as proposed by Mariyono and Sumarno [13], need to be expanded and strengthened.

Another interesting finding is the significant influence of socio-cultural factors on the adoption rate of digital technologies [37]. Communities with positive perceptions showed a 2.5

times higher adoption rate than communities with negative perceptions, reminding us that digital transformation is not just about technology but also about people. This result is consistent with the research of Mills et al. who found that social values and cultural norms influence the acceptance of new technologies among farmers [47]. The implication is that techno-centric approaches that ignore socio-cultural dynamics tend to fail. It is important to develop more participatory and local context-sensitive approaches, as demonstrated in the ongoing mentoring program that combines face-to-face training and online support [22].

An inclusive partnership model involving the aggregation of smallholder farmers in a shared digital platform, resulting in a 28.3% increase in collective income [34], offers a promising strategy to address the digital divide. This approach changes the logic of economies of scale in digital technologies, enabling smallholder farmers to benefit through collective action. This model is in line with the concept of “inclusive digitalization” proposed by Barrett et al. [48], which emphasizes the importance of designing technologies and business models that take into account the needs and capacities of marginalized groups. In the Indonesian context, strengthening farmer institutions such as farmer groups and cooperatives can be an important foundation for this kind of inclusive partnership model.

Research on four key policy components for digital transformation of the agro-complex—regulatory framework, capacity building, financial incentives, and infrastructure [41]—provides a comprehensive framework for policy interventions. The finding that regions with policies covering all four components experienced a 5.2-fold increase in technology adoption [42] underscores the importance of a holistic approach. However, the implementation of such policies faces challenges in coordination between ministries and levels of government. The experiences of countries that have successfully developed digital agriculture, as described by Trendov et al. [17], demonstrate the importance of collaborative governance involving multiple stakeholders.

Another important aspect that needs to be discussed is the implications of digital technology on the structure of the agrocomplex value chain. The results of the study showed that integrated digital platforms that connect farmers directly to the market have resulted in an average increase in farmer income of 23.5 % [30]. This disintermediation changes the configuration of power in the value chain, potentially reducing the dominance of traditional intermediaries. However, Eastwood et al. warn about the risk of the emergence of new forms of intermediation, where the digital platform itself can become a new control point in the value chain [49]. Therefore, it is important to pay attention to aspects of data and platform governance in the digital transformation of the agrocomplex, including issues of data ownership, access rights, and the sharing of value generated from agricultural data.

In terms of long-term sustainability, environmental analysis results such as a 28.7% reduction in greenhouse gas emissions through precision agriculture [38] and improved conservation practices with a 43.5% reduction in deforestation [39] demonstrate the potential of digital technologies as enablers of the transition to a more sustainable food system. However, research by Fielke et al. warns of the risks of unsustainable digital intensification if the focus is only on short-term productivity increases [50]. A comprehensive evaluation framework that includes ecological, economic, and social sustainability is needed to ensure that digital transformation contributes to the long-term resilience of agrocomplex systems.

5. Conclusion

This study analyzes the role of digital technology in optimizing the agrocomplex value chain with a focus on the context of Indonesia and developing countries. Based on the results of a comprehensive analysis of various implementations of digital technology in the agricultural sector, several important conclusions can be formulated.

First, digital technologies have a significant transformative impact on productivity and efficiency in the agro-complex value chain. Increased productivity by up to 27.3 % and reduced production costs by 18.7% demonstrate the substantial economic potential of digital transformation. Resource efficiency, such as reduced water use by up to 35.4 % and fertilizer use by 22.5%, also contributes to environmental sustainability. Digital technologies such as IoT, precision agriculture, blockchain, and digital marketing platforms have proven effective in optimizing various stages of the agro-complex value chain, from production to consumption.

Second, while the benefits of digital technologies are promising, they are not evenly distributed across the spectrum of agricultural actors. The digital divide between large-scale and small-scale farmers remains a major challenge, with smallholders experiencing barriers in access, digital literacy, and investment capacity. Inclusive partnership models involving the aggregation of smallholder farmers on shared digital platforms offer a promising strategy to address this gap, with a documented increase in collective income of 28.3 %.

Third, the successful implementation of digital technologies in the agro-complex value chain is highly dependent on a conducive supporting ecosystem. Four key components—regulatory framework, capacity building, financial incentives, and digital infrastructure—need to be developed simultaneously and in an integrated manner. Regions with a comprehensive policy approach that encompasses all four components experienced technology adoption 5.2 times faster than regions with partial policies, underscoring the importance of a holistic approach to digital transformation.

Fourth, socio-cultural factors play an important role in the adoption of digital technology in the agricultural sector. Communities with positive perceptions of technology show an adoption rate 2.5 times higher than communities with negative perceptions. This shows that digital transformation is not just a technical intervention, but also a process of social change that requires a participatory approach and is sensitive to the local context.

Fifth, digital transformation has structural implications for the configuration of the agrocomplex value chain. Digital platforms that connect farmers directly to markets have changed the dynamics of power and value distribution in the chain, with farmers' incomes increasing by 23.5 % . However, it is necessary to pay attention to aspects of data and platform governance to ensure fair value sharing and prevent the emergence of new forms of intermediation that can dominate the value chain.

Sixth, the contribution of digital technology to environmental sustainability in agrocomplexes is seen from the reduction of greenhouse gas emissions by 28.7% through precision farming and improvements in conservation practices with a reduction in deforestation by 43.5%. However, a thorough evaluation of the carbon footprint of the digital infrastructure itself is needed to ensure positive net environmental benefits.

Based on the above conclusions, this study recommends a comprehensive and inclusive agrocomplex digital transformation policy approach that takes into account the diversity of agricultural business actors. Digital capacity development needs to be prioritized, especially for smallholder farmers and those in disadvantaged areas. A multi-stakeholder partnership model involving government, private sector, academics, and farmer organizations is needed to build a sustainable digital ecosystem. In addition, a comprehensive evaluation framework that includes economic, social, and environmental aspects needs to be developed to measure the real impact of digital transformation in the agrocomplex value chain.

This research provides an important contribution to the understanding of the role of digital technology in optimizing agrocomplex value chains, especially in the context of Indonesia and developing countries. The findings and recommendations produced can be a reference for developing digital transformation policies and strategies in the agricultural sector to support inclusive and sustainable economic growth.

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