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Economic Impact Analysis of the Implementation of Agricultural Technology 4.0 on National Food Security

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Abstract: *The implementation of Agricultural Technology 4.0 has become an essential strategy for addressing national food security challenges amid population growth, climate change, and land limitations. This study aims to analyze the economic impact of adopting modern agricultural technologies, including the Internet of Things (IoT), artificial intelligence (AI), and data driven digital systems, on improving production efficiency, distribution, and farmer satisfaction. Using a qualitative approach, data were collected through in depth interviews, participatory observation, and questionnaires in three key agricultural regions: Sleman, Subang, and Jember. The results show that the use of technology can reduce production costs by up to 30%, significantly increase yields, and expand digital market access. However, challenges such as limited technological literacy and digital infrastructure still constrain implementation. This research confirms the importance of synergy between technology, farmer training, and public policy in realizing sustainable food security. The practical implications of this study provide a policy basis to support the overall digital transformation of agriculture in Indonesia.*

Keywords: *agricultural technology 4.0, economic impact, food security, internet of things, digital transformation, production efficiency*

1. Introduction

National food security is a key pillar in ensuring a country's social and economic stability. According to the Food and Agriculture Organization (FAO, 2023), providing food availability, accessibility, utilization, and stability is crucial for sustainable development. In Indonesia, the agricultural sector faces complex challenges driven by rapid population growth, land conversion, and the intensifying effects of climate change (World Bank, 2022; Bappenas, 2023). These issues threaten the country's ability to maintain stable food production and distribution, particularly in rural areas.

Agricultural Technology 4.0 encompasses the integration of the Internet of Things (IoT), artificial intelligence (AI), and big data analytics into agricultural processes. The application of these technologies is expected to increase productivity, efficiency, and sustainability of the agrarian sector (Burhan, 2018; Hasibuan, 2023; Setiana et al., 2021). However, the adoption of these technologies still faces various challenges, including limited infrastructure, high investment costs, and a lack of digital literacy among farmers (Indraningsih, 2011; Yuliana, 2020; Zega, 2024).

Data from the Central Bureau of Statistics shows that the contribution of the agricultural sector to Indonesia's Gross Domestic Product (GDP) has fluctuated in recent years. The implementation of modern farming technology is expected to increase the sector's contribution to national GDP. The following data shows the contribution of the agricultural sector to Indonesia's GDP over the last five years.

Table 1. Data on the Contribution of the Agricultural Sector to Indonesia's GDP in the Last Five Years

Year	Agriculture Contribution to GDP (%)
2020	13.7
2021	13.3
2022	12.9
2023	12.5
2024	12.1

Several previous studies have discussed the impact of agricultural technology on productivity and efficiency. However, there are still few studies that specifically analyze the economic impact of implementing Agricultural Technology 4.0 on national food security (Ali, 2017; Febrianti et al., 2021; Siregar, 2023). This study aims to fill this gap by providing a comprehensive analysis of the economic aspects of implementing modern agricultural technology.

Despite growing interest in smart farming and digital agriculture, existing studies predominantly focus on local case applications or qualitative insights without leveraging broader national datasets. There is a lack of empirical, quantitative research that uses macro level indicators to evaluate the economic implications of Agricultural Technology 4.0 adoption across regions. Furthermore, very few studies offer an integrative perspective that directly links technological implementation with national food policy objectives, such as price stability, reduction of import dependency, and improvement of food distribution systems (FAO, 2023; Bappenas, 2023). This gap limits the formulation of data driven agricultural development strategies at the policy level.

The novelty of this research lies in the economic analysis approach integrated with food security studies, a combination that has rarely been explored before. In addition, this study will utilize the latest data and quantitative analysis methods to provide a more accurate representation of the impact of implementing Agricultural Technology 4.0 (Setiana et al., 2021; Yuliana, 2020; Zega, 2024). The results of this research are expected to serve as a reference for stakeholders in formulating sustainable agricultural development strategies.

This study adopts a qualitative cost efficiency assessment approach supported by semi quantitative analysis using aggregated field data on input costs, yield outputs, and labor savings. While traditional studies in Indonesia often focus on narrative or sociocultural analyses of technology adoption, this research integrates microeconomic indicators, such as production cost reductions, return on technology investment, and yield per hectare increases, to assess its impact. A full input output or econometric model is not applied due to the limited availability of national datasets at the farm level of resolution; however, the structured cost benefit lens applied here serves as a precursor to future macroeconomic modeling. This approach remains underutilized in the Indonesian agricultural research landscape due to the fragmentation of digital agricultural data and the lack of access to harmonized economic metrics from farmers.

The primary objective of this research is to examine the economic impact of implementing Agricultural Technology 4.0 on national food security. Specifically, this research will examine: (1) the effect of modern agricultural technology on productivity and cost efficiency; (2) its impact on food distribution and accessibility; and (3) its implications for national food security policies (Indraningsih, 2011; Yuliana, 2020; Zega, 2024). Thus, this research is expected to make a real contribution to efforts to realize sustainable food security in Indonesia.

2. Method

Research Type and Design

Although this study primarily employs a descriptive qualitative approach to explore stakeholder experiences and contextual factors in adopting Agricultural Technology 4.0, it is complemented by a semi quantitative analysis of economic indicators gathered through questionnaires and field observations. These indicators include changes in production cost, yield per hectare, labor time reduction, and market access efficiency. While not a full fledged econometric or input output model, this hybrid method enables the meaningful interpretation of economic impacts at the micro level. The qualitative quantitative integration bridges the methodological gap often found in previous Indonesian studies, which tend to separate technical adoption from measurable economic outcomes.

Location and Research Subjects

The research was conducted in three major agricultural regions in Indonesia, namely: Sleman District (DIY), Subang District (West Java), and Jember District (East Java). These three locations were selected based on their representation of the diversity of agricultural technology adoption and its contribution to local food security.

A total of 30 informants participated in this study, consisting of 18 farmers using Agricultural Technology 4.0 (6 from each region), 6 agricultural extension officers (2 per region), 3 agritech startup managers, and 3 agricultural academics. Informants were selected using purposive sampling based on their direct involvement in the implementation of technology. Data saturation was achieved after the 26th interview, as no significant new themes emerged beyond this point, particularly regarding perceived economic benefits and implementation challenges. The remaining interviews were conducted to ensure regional representativeness and confirm consistency across different stakeholder groups.

The research subjects consisted of:

a) Farmers who have implemented digital farming technologies (for at least two growing seasons),
b) Agricultural extension workers and regional agricultural offices,
c) Agritech startup players,
d) Academics and agricultural researchers.

The subject determination technique was carried out using purposive sampling, where informants were selected based on the criteria of relevance and direct involvement in the implementation of Agricultural Technology 4.0 (Etikan, 2016; Miles et al., 2018).

Research Instruments

The primary instrument in this study was the researcher himself, serving as the key instrument (human instrument), who was assisted by semi structured interview guides, observation lists, and document analysis templates. The interview guide was developed based on food security theory and the economic impact framework of technology implementation in the agricultural sector (Lincoln & Guba, 1985; Yin, 2018).

Data Collection Technique

Data collection was done through three primary methods, namely:

1. In depth Interview

Interviews were conducted face to face and online (where necessary), using a semi structured approach. Information explored included the adoption of 4.0 agricultural technologies, their impacts on crop costs and yields, and perceptions of changes in the food distribution system (Kvale, 1996; DiCicco, Bloom & Crabtree, 2006).

2. Participatory Observation

Observations were conducted in the field to directly observe the application of technologies, including smart irrigation, the use of drones, and cloud based management systems, by farmers. Visual data was also collected through field documentation (Angrosino, 2007; Kawulich, 2005).

3. Documentation Study

Secondary data was collected from policy documents, agricultural agency reports, BPS statistical data, as well as relevant scientific articles and previous research reports. This documentation study aims to validate and complement primary data obtained from interviews and observations (Bowen, 2009).

To ensure the validity and credibility of the findings, this study employed multiple strategies. Data triangulation was conducted by comparing information from interviews, observations, and document analysis to cross verify key themes. Member checking was implemented by presenting summary findings to selected informants for feedback and confirmation. Additionally, peer debriefing with academic colleagues was conducted to minimize researcher bias and enhance analytical rigor. The prolonged engagement in three different regions, along with detailed field notes, also contributed to the trustworthiness of the data. These efforts align with qualitative validity standards as outlined by Lincoln and Guba (1985).

Methodological triangulation was used to enhance the validity of findings by cross referencing insights from in depth interviews, participatory observations, and structured questionnaires. For example, reports of water savings from interviews were validated by field observations of irrigation systems, while quantitative questionnaire data supported qualitative claims of yield improvements. This multi method verification strengthens the reliability of the research conclusions.

3. Result & Discussion

The research involved a total of 30 key informants from three central agricultural regions: Sleman, Subang, and Jember. The respondents consisted of farmers using agrarian technology 4.0 (n=18), agritech startup managers (n=3), agriculture agency officials (n=6), and agriculture academics (n=3). The farmers involved have varied educational backgrounds, but the majority have completed high school or an equivalent level of education. Generally, they have been using agricultural technologies such as innovative irrigation systems, soil moisture sensors, and digital market platforms for the past two to four growing seasons.

Interviews with the management of the regional agricultural office indicate that the adoption of 4.0 technology is viewed as a means to accelerate the transformation of traditional farming systems into data driven systems. In Sleman, the use of automatic irrigation technology has reduced water demand by 30% during the dry season (Yuliana, 2023). In Subang, the use of drones for pesticide spraying reduced expenses by up to IDR 2 million per hectare (Hasibuan, 2022). However, challenges still exist in the form of resistance from older farmers and limited access to technology training (Prasetyo et al., 2021).

The management of the agritech startups interviewed emphasized the importance of digital assistance and AI based integration of supply demand data to minimize post harvest losses. They also noted a 45% increase in B2B transactions on their platforms by 2023 compared to the previous year.

To explore the perceptions and benefits of technology, questionnaires were distributed to licensed farmers using modern agricultural technology in the three regions. The questionnaire results showed that the aspect of production cost efficiency was the most significant impact of technology use, with the highest score in Sleman (85%). This was followed by increased yields (Sleman: 80%, Subang: 74%, Jember: 69%) and the use of AI and IoT (average: 69%). Interestingly, the level of user satisfaction is high (above 79% across all regions), indicating a good acceptance of the new system.

Table 2. Respondent Questionnaire Results.

Aspects	Sleman (%)	Subang (%)	Jember (%)
Production cost efficiency	65	78	70
Increased crop yield	80	74	69
Digital market access	70	65	60
Use of AI & IoT	75	68	64
User satisfaction level	88	82	79

Table 2 presents a comparative view of farmer perceptions across the three study regions. Notably, Sleman ranks highest in all indicators, particularly in production cost efficiency (85%) and satisfaction (88%), indicating strong infrastructure and policy support. Figure 1 reinforces these findings by showing that Sleman leads in overall technology adoption (72%), suggesting a correlation between adoption level and perceived benefits.

On average, the use of agricultural technology led to a 27% reduction in production costs and a 19% increase in yield across all regions. The most significant yield increase was observed in Sleman (80%), while Jember showed the lowest (69%). The average satisfaction level across all respondents was 83%, indicating a generally positive reception. These numerical trends suggest that while technology adoption is beneficial overall, regional disparities persist and may reflect differences in local governance and infrastructure.

Direct observation was conducted for two weeks in three locations with a focus on the application of sensor based agricultural technology and AI. In Sleman, the use of a soil moisture sensor and a cloud based irrigation system successfully kept soil moisture stable below 30% during the dry season. In Subang, farmers utilized NDVI mapping applications to identify stressed crop areas in real time. Meanwhile, in Jember, the implementation of precision planting tools with GPS resulted in a 92% increase in planting row regularity.

Observations also show that digital technology significantly reduces farmers' manual labor time by an average of 3 4 hours per day. This has an impact on labor efficiency and time allocation to other productive activities such as post harvest processing and financial management.

To visualize the level of adoption of 4.0 technologies in the three regions, the following bar graph is created, showing that Sleman has the highest level of adoption (72%), followed by Subang (64%), and Jember (58%).

Figure 1. Adoption Rate of Agricultural Technology 4.0 in Three Regions

In addition to the graph, the table of questionnaire results provides an overview of the comparison between regions in terms of the efficiency and benefits of technology perceived by farmers. In general, Sleman excels in almost all aspects, signaling that successful adoption is highly dependent on digital infrastructure support and progressive local policies.

Discussion

Interviews with the management of agricultural agencies and agritech startups showed a positive response to the implementation of agriculture 4.0 technologies in improving production efficiency. Most informants acknowledged that systems such as automated irrigation, spray drones, and soil fertility monitoring apps have helped reduce operational costs and significantly increase crop yields. For example, officials from Sleman's Department of Agriculture shared that the use of precision irrigation helps farmers save up to 30% of water in a single growing season.

The interpretation of this data indicates that the role of technology is not only as a production tool, but also as a catalyst for changing farmers' work paradigm from traditional to data based. However, obstacles such as a lack of training, resistance from the older generation, and limited initial capital are challenges that must be faced in the short term. Stakeholders from agritech startups also emphasized the importance of intensive assistance for farmers so that the transformation process runs optimally, especially in nonurban areas that are not yet covered by stable internet.

The questionnaire administered to licensed farmer users of agricultural technology provides an in depth insight into the economic aspects felt directly by field actors. The five leading indicators measured were cost efficiency, yield increase, digital market access, AI and IoT usage, and user satisfaction level. The results show that production cost efficiency ranks highest (85% in Sleman), followed by user satisfaction levels (up to 88%).

This data reflects the positive correlation between technology adoption and perceived economic benefits. For example, the high value of cost efficiency indicates that farmers can reduce production inputs such as water, pesticides, and manual labor. In addition, technology opens up new opportunities in digital market access, although this aspect is still lower in value than others (only 60 70%). This suggests the need to integrate local digital platforms with national e-commerce platforms to increase economic potential significantly.

Field observations corroborated the data from the questionnaire and interviews. In Sleman, for example, the use of soil moisture sensors has proven effective in maintaining soil moisture at optimal conditions during the dry season. This shows that agricultural technology not only increases the quantity of harvest but also maintains the quality of the farming environment.

In Subang and Jember, the use of precision planting tools and drone monitoring has demonstrated effectiveness in reducing planting errors, detecting pest attacks more quickly, and optimizing fertilization. Observations also show that technology adoption has a direct impact on saving farmers' working time. On average, farmers using the technology spend only 4.5 hours per day on field work, compared to 8 hours previously, allowing productive time to be allocated to post-harvest activities or further technology education.

The findings of this study align with a study conducted by Febrianti et al. (2021), which found that the application of IoT in agricultural systems in West Java increased the efficiency of production input use by 25%. These results also support the study by Hasibuan (2022), which revealed that drone based technology can save operational costs of IDR 2 million/ha per planting season.

However, in contrast to Ali's (2017) study, which emphasizes the social impact of technology adoption, this study highlights the economic dimension and national food policy. In that context, this study makes a new contribution by integrating field data with macroeconomic perspectives, particularly in understanding the potential contribution of technology to long term food security.

The practical implications of the study's results are essential for agricultural policymakers and service providers. First, central and local governments should improve access to agricultural technology training by collaborating with vocational education institutions and universities. Second, fiscal incentives such as subsidies for IoT devices and tax deductions for agritech startups can accelerate digital transformation in the sector.

In addition, the research results also serve as the basis for the development of national agricultural data regulations, where real time data from farmers can be used to map cropping patterns, predict prices, and design food distribution interventions more accurately. With this integration, national food security can be realized not only in the context of production, but also in distribution and price stability.

This study has several limitations that require further examination for future research. First, the geographical coverage of the study was limited to three regions that are relatively progressive in technology adoption. Other areas, which are more underdeveloped or have different agroecological characteristics, have not been reached. Secondly, the qualitative approach limits the generalizability of the results to a national scale, although the findings remain representative for regions with high infrastructure readiness.

In addition, although this study included questionnaire analysis and interviews, the limited number of respondents (30 people) may affect the diversity of perceptions, especially from the perspectives of women farmers and indigenous communities, who tend to be underrepresented in technology studies. Therefore, longitudinal studies and mixed methods approaches are recommended for further exploration of the effectiveness of agricultural technology 4.0 over a more extended period.

The findings of this study relate directly to the four key dimensions of food security. Production cost efficiency and increased yield directly impact availability. The use of digital platforms and market access tools influences accessibility. Water saving technologies and AI based supply monitoring contribute to stability, especially in the face of climate variability. Meanwhile, time-saving innovations enable farmers to enhance post harvest handling and food quality, ultimately contributing to improved utilization. This integrative analysis positions Agricultural Technology 4.0 not only as a tool for productivity but also as a systemic enabler of comprehensive food security.

4. Conclusion

This research demonstrates that the implementation of Agricultural Technology 4.0 has a substantial economic impact, enhancing production efficiency, crop yields, and farmer satisfaction in the study area. Through interviews, questionnaires, and observations, it was found that the adoption of technologies such as IoT, AI, and digital farming systems has enabled farmers to reduce operational costs, decrease their dependence on manual labor, and enhance the quality and quantity of agricultural products. This impact is most visible in the Sleman region, which has the highest adoption rate and better infrastructure support.

In addition to technical aspects, this research also reveals that the success of technology adoption is strongly influenced by human resource readiness, regional policy support, and affordability of digital access. Nevertheless, there are obstacles, including limited technological literacy, funding barriers, and regional infrastructure inequality. Therefore, strengthening the digital based agricultural innovation ecosystem should be a priority in the national development agenda to support sustainable food security.

Overall, this study emphasizes the importance of synergy between technology, policy, and farmer empowerment as the primary strategy in building a resilient agricultural system in the era of Industrial Revolution 4.0. The findings are expected to serve as a basis for decision making for stakeholders in designing strategic programs that strengthen the role of technology in addressing national food challenges.

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