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SPATIAL ANALYSIS OF DIGITAL TRANSFORMATION ON FOOD SECURITY IN SUMATRA: AMIDST CLIMATE CHANGE

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ABSTRACT

This study aims to analyze the impact of digital transformation on food security in Sumatra. The research utilizes panel data from 154 districts and cities covering the period from 2019 to 2022. Food security levels are measured using the entropy method, while the effects of digital transformation are assessed through spatial panel regression to capture both spatial and temporal variations.The results indicate that digitalization has a significant positive effect on food security in the long run. This suggests that advancements in digital technology contribute to improving food systems, enhancing distribution efficiency, and increasing access to food resources. On the other hand, fiscal decentralization policies are found to have a significant negative effect on food security, implying that disparities in regional governance capabilities may hinder efforts to improve food security across different areas. In addition to digitalization, other factors such as electrification, industrialization, and population growth show significant positive effects on food security. Electrification facilitates better access to energy, which supports agricultural infrastructure and food storage. Industrialization boosts productivity and the development of food supply chains, while population growth, despite increasing food demand, can drive agricultural expansion and improvements in food distribution when managed effectively.Overall, this study highlights the crucial role of digital transformation in enhancing food security, while also emphasizing the need for equitable fiscal policies to reduce regional disparities in food access and availability.

Keywords: *Digital Transformation, Food Security, Spatial*

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis peran transformasi digital terhadap ketahanan pangan di Sumatera. Data yang digunakan merupakan panel 154 kabupaten/kota selama 2019-2022. Teknik analisis yang dipergunakan adalah entropy untuk menghitung ketahanan pangan dan regresi panel spasial untuk menentukan dampak transformasi digital terhadap ketahanan pangan. Hasilnya bahwa digitalisasi berpengaruh positif signifikan dalam jangka panjang, kebijakan desentralisasi fiskal dinilai berpengaruh negatif signifikan terhadap ketahanan pangan. Sementara itu, elektrifikasi, industrialisasi, dan pertambahan populasi berpengaruh positif signifikan terhadap ketahanan pangan.

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Kata Kunci: *Transformasi Digital, Ketahanan Pangan, Spasial*
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Introduction

Food security is an important component for a country in achieving sustainable development. Food security is one of the efforts of a region to provide adequate access to food and its derivatives for all people. Food security support is very dominant for the economy, especially as the foundation of food security (Candelise et al., 2021), economic growth, increased productivity, and natural sustainability. In more detail, food security involves efforts to avoid hunger and malnutrition crises that can threaten social and political stability (Prosekov & Ivanova, 2018). This indicates that food security is a prerequisite for achieving stability and peace in a region. Not only that, but access to nutritious and varied food can contribute to good public health. In this case, children are well-nourished and therefore have the opportunity to grow and develop better (Kamel, 2021). Improved food security will encourage farmers to feel more secure in investing time and energy in increasing agricultural production. This condition will also encourage farmers' welfare to improve. On the other hand, this increase in productivity will support inclusive economic growth and job creation. Food security is also a form of achieving natural sustainability through the sustainable use of natural resources. For this reason, food security has become an important agenda in the Sustainable Development Goals, considering its systemic impact on social, economic, and environmental development in various regions (Bremner, 2012).

The continuity of the idea of global food security is currently faced with a situation of climate change that can threaten the existence of world food production and distribution. Climate change causes a paradigm shift in the decline of crop production and agricultural products (O'Hara & Toussaint, 2021). Extreme temperature rises can disrupt the plant development process. On the other hand, recurrent droughts and floods can damage crops and have implications for production sustainability. Climate change is also driving down water availability in many areas, reducing irrigation capacity and causing droughts. There are not many aspects that benefit from climate change; on the contrary, it complicates conditions, leading to an increase in the number of pests and diseases that harm crop yields. Changes in sea temperature and current patterns due to climate change also affect ad migration patterns, leading to a decrease in food sources of protein (Prosekov & Ivanova, 2018). Not only that, excessive heat due to climate change causes stress in animals, which can lead to reduced milk, meat and egg production. Lastly, people who depend on the agriculture and fisheries sectors for their livelihoods will be disrupted as access becomes less and less amidst disrupted resources. For this reason, the impact of climate change is very dominant on food security given its direct transmission to the economic sector and the fulfillment of people's livelihoods. In 2021, the food security paradigm began to be influenced by aspects of geopolitical risk. The impact is massive enough that several countries have experienced raw material and food shortages. The escalation of the war between Russia and Ukraine disrupted food production and distribution, supporting infrastructure was damaged, and access to land, water, and fertilizer resources was hampered.

Moreover, Ukraine is a food commodity producing country, so the implications are widespread and have a systemic impact. Not only that, tensions and trade wars between countries also disrupted the flow of international food trade. Certain countries impose tariffs and trade barriers, which have implications for reducing access for countries that depend on imported agricultural products. The post-COVID-19 pandemic situation, which still needs recovery, has left some countries unable to meet food needs and the survival of the livelihoods of many people (Surampalli et al., 2020). For this reason, several multilateral international collaborations have become one of the alternatives for the continuity of food distribution to maintain food security. Digital transformation is one of the alternatives and plays a role in tracking and developing food security programs in various regions (Amirova et al., 2022). Digital transformation plays a role in bringing technological innovations and solutions that can bring efficiency, transparency, and sustainability to the food system (Dayıoğlu & Turker, 2021). Through this digital transformation, it will provide information through the process of collecting agricultural data in real time through geographic information systems and other hardware (Pereira et al., 2022). This data can be used to supervise and monitor agricultural conditions in an area.

Not only that, but digital transformation allows the use of advanced technologies such as the Internet of Things (Gitz et al., 2016), big data, and artificial intelligence to monitor specific crop conditions and needs. In addition, the use of platforms and e-commerce makes it easier for farmers and producers to sell their agricultural products directly to consumers, thereby simplifying the food supply chain. Digital transformation also plays a role in improving food security in urban areas, for example, through the use of urban farming, verticulture, and hydroponics. These conditions allow subsistence food production to improve and can help with short-term shortages. Finally, digital transformation plays a role in the establishment of networks and information exchange between actors in the agricultural sector. Through digital transformation, collaboration systems and food market development will improve and realize sustainable food security (Baldos & Hertel, 2014). Indonesia, as an agriculture-oriented country is inseparable from potential food security uncertainties. Historically, the accumulated rice shortage in Indonesia for 20 years has reached 34 million tons with the fourth top position. This indicates that the amount of rice production is still a challenge for the food security program. Meanwhile, the other most dominant factors are the availability of agricultural land and the changing labor structure. Amidst the decline in domestic rice production, the food security index has started to increase. This is supported by equitable distribution due to better accessibility and connectivity between regions. For this reason, this phenomenon needs to be developed continuously, considering that the impact of food supply availability can support sustainable food security in Indonesia.

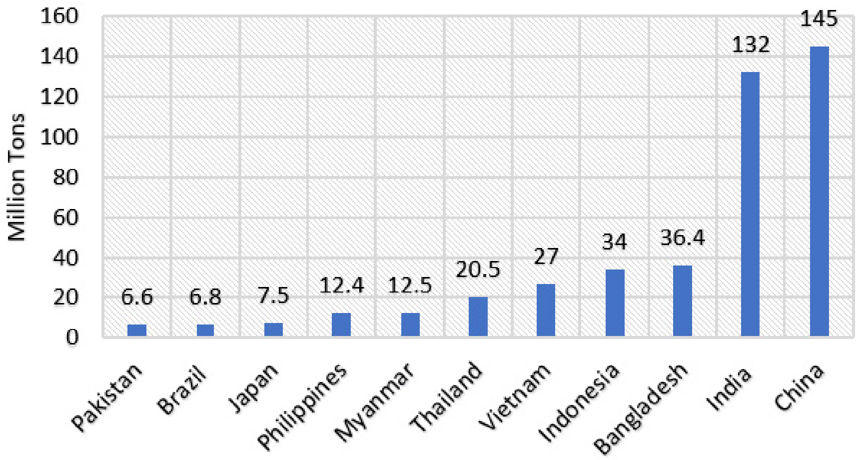

Figure 1: Accumulation of Rice Scarcity for 20 Years

Source: FITCH (2022), processed

Specifically, Sumatra and the islands are one of the important regions that can also support food security. Based on data BPS (2022), On average, food production is still concentrated in a few areas and tends to be unevenly distributed. The distribution of staple food production is still centralized in areas with good transportation access. This is confirmed by Figure 2, which is the average distribution of staple foods over the last 4 years, showing that rice is unevenly distributed in South Sumatra, Lampung, West Sumatra, and North Sumatra. Meanwhile, eggs are unevenly distributed in South Sumatra, Lampung, and North Sumatra. Chicken has a slightly similar distribution to eggs, but has been evenly distributed in the Riau and Jambi regions. On the other hand, cattle and milk production are relatively unevenly distributed, potentially leading to scarcity and lower protein consumption. Finally, the average fish production is still focused in North Sumatra, making it the main base for fish distribution throughout Sumatra. This condition makes one of the motivations for research that food security in Sumatra, especially staple foods, is still unevenly distributed. There are several regions that have absolute advantages so that their role as commercial leverage is still minimal.

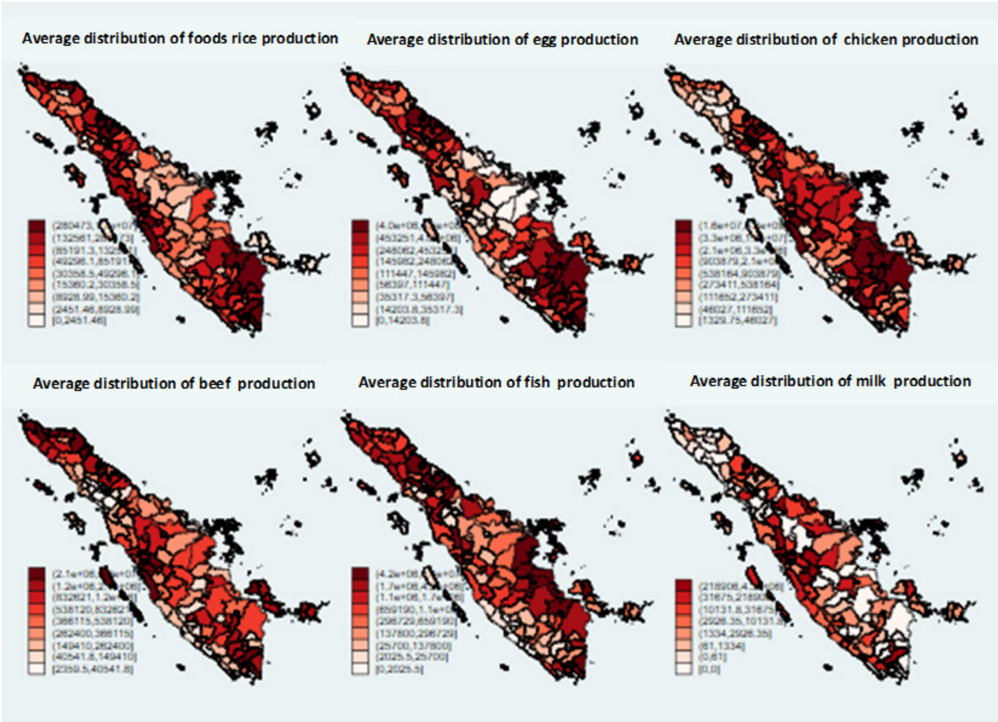

Figure 2: Average Production of Staple Foods: Rice, Eggs, Chicken, Beef, Fish, and Milk

Source : BPS (2022), processed

Several previous studies have focused on food security programs and their efforts to support inclusive economic development (Cariappa et al., 2021). Moreover, several other studies have also tried to link food security with climate change and digitalization, but they are relatively limited to reviewing geopolitical risks (Wang et al., 2021). Meanwhile, digital transformation turns out to be very important given its role in enhancing sustainable development goals. Based on this phenomenon, it is necessary to actualize the interconnection between digital transformation to accelerate the food security program in a sustainable manner. On the other hand, food security disruptions are moderated by, for example, climate change and regional political tensions. For this reason, this research tries to specifically review the efforts to develop digital transformation towards Indonesia's potential food security that is independent from the provision of food supply while supporting sustainable development connectivity. Therefore, this study aims to analyze the effect of digital transformation on Sumatra's food security amid climate change issues and geopolitical risks. As well as adapting the role of fiscal and monetary policy collaboration synergy in supporting food security. This research is expected to provide navigation for regulators to play an active role in stabilizing food security so that regions are able to create food surpluses and encourage community welfare.

Literature Review

Digital transformation plays a crucial role in enhancing food security by promoting technological innovation, agricultural management, and marketization levels (Yao & Fu, 2023). The use of digital technologies in agriculture contributes to efficient resource management, making the sector more accurate and productive (Fesun & Qineti, 2024). Furthermore, the application of digital solutions, such as precision agriculture technologies and innovative automated methods, can help reduce food waste, increase overall efficiency, and support sustainable practices in the agrarian sector (Wu & Wen, 2023). Studies show that internet use decreases food insecurity in agricultural households in Indonesia (Ardianti & Hartono, 2022), while also improving the competitiveness of agri-food exports globally through enhanced infrastructure and security (Suroso et al., 2023). Furthermore, the internet facilitates the joint adoption of sustainable agricultural practices by farmers, leading to improved food security and agricultural development, especially in developing countries (Zhong et al., 2023). Agricultural expenditure had negative effects on food availability and utilization, emphasizing the need for a shift towards increasing private agricultural investment and improving economic infrastructure to boost food security (Atabukum et al., 2020). Inflation in agricultural prices can lead to concerns about food security it can also stimulate agricultural output and income growth, ultimately enhancing food security (Izgi et al., 2023). Money supply positively affected agricultural output, suggesting that inflation could potentially boost agricultural productivity and contribute to food security (Okuduwor et al., 2023). High inter-annual rainfall variability negatively affects food security through fluctuations in food consumption and dietary diversity (Rusere et al., 2023). Low rainfall decreases food security, leading to difficulties in accessing food and lower dietary diversity. (Randell et al., 2022). Households experiencing drier than average conditions were more food insecure compared to those with normal or wetter conditions, emphasizing the importance of rainfall levels in food security outcomes (Niles & Brown, 2017).

Hotter temperatures have been linked to negative effects on food availability and utilization, emphasizing the adverse consequences of climate variability and change on food security in the region (Mumuni & Joseph Aleer, 2023). Higher mean temperatures have been found to decrease the Global Food Security Index (GFSI) by 1.70% for every 1% increase in temperature, highlighting the detrimental impact of rising temperatures on food security globally (Singh, 2018). Political risks and weak institutions worsen food security, highlighting the detrimental effects of conflicts, corruption, and instability on food availability and quality in both developed and developing countries (Abdullah et al., 2020). This disruption, coupled with market shocks and destruction of agricultural infrastructure, has exacerbated food insecurity globally, with a notable increase in food prices and a decline in grain security levels (Borodina, 2022; Xu et al., 2023). Access to electricity and clean energy for cooking positively influences food security, encouraging investments in off-grid energy systems for vulnerable households (Pondie et al., 2023). Access to electricity significantly increases household consumption per capita, indicating a positive effect on poverty reduction, which indirectly contributes to food security (Diallo & Moussa, 2020). Several studies have found negative impacts of population growth on food security (Mohammed, 2016; Oguntegbe et al., 2018), while other studies report a positive relationship (Aiyedogbon et al., 2022; Sule & Deribe, 2023). GRDP growth in the industrial sector can lead to increased employment opportunities, income generation, and foreign exchange earnings, ultimately aiding sustainable development and enhancing food security (Asiedu et al., 2018). Additionally, the development of large economic entities, including monopolies, in the food market can positively impact the provision of local food products to the population (Pavlova et al., 2021). Growth in manufacturing positively impacts the food industry (Hamouri, 2024), while investment drives agricultural production and food security (Esquivias et al., 2023). However, expanding manufacturing activities can threaten food security (Esquivias et al., 2023). The agricultural sector's share in GDP is expected to decrease as industry and services increase (Malikov et al., 2016).

Yao & Fu (2023) and Fesun & Qineti (2024) emphasize the role of digital technologies in improving agricultural management, resource efficiency, and market access, ultimately enhancing food security. Wu & Wen (2023) explore the benefits of precision agriculture and automated farming technologies, which contribute to reducing food waste and supporting sustainable agricultural practices. Ardianti & Hartono (2022) demonstrate that internet access reduces food insecurity among agricultural households in Indonesia, highlighting the importance of digital connectivity in rural areas. Zhong et al. (2023) discuss how the internet fosters the adoption of sustainable agricultural practices, especially in developing countries, contributing to improved food security outcomes. Atabukum et al. (2020) argue that public agricultural expenditure negatively affects food availability, suggesting a shift towards private investment and improved economic infrastructure to boost food security. Izgi et al. (2023) and Okuduwor et al. (2023) analyze the complex relationship between inflation, money supply, and agricultural productivity, indicating that while price inflation can raise concerns, it may also stimulate agricultural output and income growth. Rusere et al. (2023), Randell et al. (2022), and Niles & Brown (2017) examine how rainfall variability and drought conditions negatively affect food security, reducing food consumption and dietary diversity. Mumuni & Joseph Aleer (2023) and Singh (2018) highlight the detrimental effects of rising temperatures on food availability and utilization, with global studies showing a decrease in the Global Food Security Index (GFSI) due to temperature increases.

Abdullah et al. (2020) discuss how political instability, corruption, and weak institutions exacerbate food insecurity by disrupting agricultural systems and markets. Borodina (2022) and Xu et al. (2023) explore the impact of conflicts and market shocks on food prices and grain security, underscoring the broader geopolitical factors influencing food security. Pondie et al. (2023) and Diallo & Moussa (2020) investigate the role of electrification in improving agricultural productivity and household consumption, indirectly contributing to poverty reduction and food security. Asiedu et al. (2018) and Hamouri (2024) highlight how industrial growth, particularly in manufacturing, generates employment and income, aiding food security, though Esquivias et al. (2023) caution that unchecked industrial expansion could threaten food systems. Pavlova et al. (2021) discuss how the development of large economic entities and monopolies in the food sector can enhance local food provision, contributing to food security. The impact of population growth on food security remains debated. Mohammed (2016) and Oguntegbe et al. (2018) report negative impacts, citing increased pressure on food systems, while Aiyedogbon et al. (2022) and Sule & Deribe (2023) argue that population growth can drive agricultural expansion and market demand, leading to positive outcomes. Malikov et al. (2016) note the expected decline in agriculture's share of GDP as industry and services grow, suggesting potential shifts in food security dynamics as economies develop.

Fesun & Qineti (2024), Mumuni & Joseph Aleer (2023), Wu & Wen (2023), and Yao & Fu (2023)—These studies highlight the transformative role of digital technologies in agriculture, demonstrating how precision farming, digital platforms, and data-driven agricultural practices improve productivity, reduce losses, and enhance food security across different regions. Their methodologies typically incorporate spatial econometric models and entropy-based measures to evaluate food security, which aligns with the techniques employed in this research. Smyth et al. (2021)—This study discusses the broader impacts of digital finance, mobile banking, and digital platforms on rural agricultural communities. It provides evidence that access to digital financial services supports small-scale farmers by improving access to credit and investment opportunities, ultimately contributing to food security. Abdullah et al. (2020)—This research focuses on the role of electrification in improving agricultural productivity and post-harvest management. The findings reinforce how access to electricity for irrigation, machinery, and storage facilities contributes to higher crop yields and reduced food waste.

Asiedu et al. (2018)—This study explores the relationship between industrialization and food security, noting that technological advancements in the agricultural sector and improved food processing capabilities are key drivers of increased food availability and accessibility. Aiyedogbon et al. (2022) and Sule & Deribe (2023)—These works investigate the role of population dynamics in food security, emphasizing how population growth can lead to increased agricultural labor and market demand, stimulating food production and distribution systems. Rindayati et al. (2007) and Vasconcellos & Moura (2018)—These sources discuss the adverse effects of fiscal decentralization on food security, particularly in the context of regional disparities and governance inefficiencies. They argue that decentralized fiscal policies can lead to uneven resource allocation, negatively impacting agricultural development and food systems in marginalized areas. By synthesizing insights from these studies, this research offers a comprehensive view of the factors influencing food security in Sumatra, using robust spatial panel regression models and entropy-based metrics to ensure methodological consistency with established literature.

Data and Research Methods

This study uses secondary panel data of 154 districts/cities in Sumatra during 2015-2022. This data is taken from various data streams such as SUSENAS BPS, BPS Publications, PLN, Ministry of Agriculture, Ministry of Environment and Forestry, and World Uncertainty Index. This data starts in 2019, because it refers to the implementation of Government Regulation (PP) Number 17 of 2015 concerning the fulfillment of food and nutrition needs of the community. Meanwhile, this data ends in 2022 given the availability of the latest data. Therefore, the data used in this study is highly authentic, particularly in reflecting the adaptation of government regulation implementation. Some of these data include rice production, layer production, beef production, chicken production, milk production, fish production, gross fixed capital formation, agricultural land area, provincial land area, electricity consumption, subsidized fertilizer distribution, plastic waste, digital competitiveness index, internet users, mobile phone users, rainfall, air temperature, government expenditure, staple food price level, population, foreign investment, industrial gross domestic product, agricultural gross domestic product, and electricity consumption.

Food Security Measurement

Based on several previous studies, food security can be calculated by categorizing its indicators, including food supply security, food access security, food production stability, and food production sustainablity. From these indicators, several supporting items are grouped and measured using the entropy method, which can be expressed on Table 1. Furthermore, the various food indicators are calculated by weighting calibration so as to obtain the value of food security. In general, the value reflects that the higher the result, the better the food security and vice versa. The formula for determining the value of food security can be stated as follows:

$$FS = \begin{pmatrix} \sum_{i=1}^{n} a_{i1} \\ \sum_{i=1}^{n} a_{i2} \\ \sum_{i=1}^{n} a_{i3} \\ \sum_{i=1}^{n} a_{i4} \end{pmatrix} \times \left(\sum_{k=1}^{m} FSU_k \quad \sum_{k=1}^{m} FAS_k \quad \sum_{k=1}^{m} FPS_k \quad \sum_{k=1}^{m} FPSU_k \right) \tag{1}$$

Where FS is food security, $\sum_{i=1}^{n} a_{ij}$ is the entropy weighting coefficient of the i row and j column indicators, $\sum_{k=1}^{m} FSU_K$ is a component of food supply security, $\sum_{k=1}^{m} FAS_K$ is a component of food access security, $\sum_{k=1}^{m} FPS_K$ is a component of food production stability, and $\sum_{k=1}^{m} FPSU_K$ is a component of food production sustainability.

Digital Transformation Measurement

Based on research (Aliyeva et al., 2019), digital transformation is adapted and measured using principle component analysis where the forming factors include competitiveness and percentage of users. The measurement can be expressed as follows:

$$\begin{aligned} TD(ds, \mathrm{intern}, mob, \lambda) = \sigma_{ds}^2 + \sigma_{\mathrm{intern}}^2 + \sigma_{mobile}^2 - \lambda\,(ds^T ds + \mathrm{intern}^T \mathrm{intern} \\ + mob^T mob - 1) \end{aligned} \tag{2}$$

Where TD is a digital transformation, ds is digital competitiveness index (%), $intern$ is percentage of internet users (%), mob is the percentage of cell phone users (%), σ^2 is sigma squared of the variance of each constituent indicator and λ is lambda multiplier. The component is then adapted so that it can produce a value if it is greater, indicating a digital transformation and vice versa.

Impact of Digital Transformation on Food Security

Based on previous research, the effect of digital transformation on food security can be formulated using the durbin spatial panel regression model as follows:

$$\begin{aligned} FS_{it} = {} & \alpha_0 + \rho_1 W \times FS_{it-1} + \theta_{1k} W \times TD + \theta_{2k} W \times \inf lasi_{it} + \theta_{3k} W \times \ln FDR_{it} \\ & \alpha_2 \ln RF_{it} + \alpha_3 Temp_{it} + \alpha_4 \ln GPR_{it} + \alpha_5 \ln WUI_{it} + \alpha_6 \ln EC_{it} + \\ & \alpha_7 \ln PTBMA_{it} + \alpha_8 \ln pop_{it} + \alpha_9 indus_{it} + u_{it} \end{aligned} \quad (3)$$

Where FS is food security, TD is digital transformation, RF is average annual rainfall, $Temp$ is average annual air temperature, GPR is global geopolitical risk, WUI is global uncertainty index, $lnFDR$ is natural logarithm of government expenditure, $lnEC$ is electricity consumption, $lnPTBMA$ is natural logarithm of capital investment, $ln\ pop$ is natural logarithm of population, $indus$ is ratio of Industrial Sector GRDP to GRDP, i dan t, are province and year, respectively u is another factor.

Model Selection Rationale:

This study employs the Spatial Durbin Panel Model (SDPM) to analyze the impact of digital transformation on food security across Sumatra. The SDPM is preferred over other spatial econometric models, such as the Spatial Lag Model (SLM) or the Spatial Error Model (SEM), due to its ability to capture both direct and indirect (spillover) effects of independent variables on food security.

Incorporation of Spatial Spillover Effects:

Unlike the SLM, which only accounts for spatial dependence in the dependent variable, or the SEM, which focuses on spatial autocorrelation in the error terms, the SDPM allows for the inclusion of spatial lags in both dependent and independent variables. This is crucial in understanding how digital transformation in one district or city not only impacts local food security but also influences neighbouring regions. For example, technological advancements in one area may lead to improved food distribution networks that benefit adjacent districts.

Flexibility in Capturing Complex Spatial Interactions:

The SDPM provides greater flexibility in modelling complex spatial interactions by allowing for the differentiation between local effects (within a district) and global effects (across districts). This is particularly important in Sumatra, where regional disparities and interconnectedness can significantly influence food security dynamics.

Improved Model Specification and Robustness:

By including both spatially lagged dependent and independent variables, the SDPM reduces the risk of omitted variable bias that can arise from ignoring spatial dependencies. This leads to more robust and reliable estimates, especially when analyzing regional policies like fiscal decentralization, which may have varying impacts across different jurisdictions.

Policy-Relevant Insights:

The model's ability to distinguish between direct and indirect effects provides valuable insights for policymakers. Understanding how digital transformation in one region can affect neighbouring areas helps design more effective regional policies that promote equitable food security improvements across Sumatra.

Integrating this rationale will strengthen the methodological justification of your study, making it clear why the SDPM is the most appropriate choice for analyzing the spatial dynamics of food security in relation to digital transformation.

Table 1: **Components that make up Food Security**

No	Indicator	Component	Entropy Weighting	Obs	Mean	Source
1	Food Supply (FSU)	Rice production per unit (tons)	0.044	614	274918.7	BPS
		Egg production of laying and free-range chickens (kg)	0.052	616	1.01	BPS
		Beef production (kg)	0.037	616	1578051	BPS
		Chicken meat production (kg)	0.049	616	4.07	BPS
		Milk production (kg)	0.049	616	61452.81	BPS
		Fish production (kg)	0.041	616	2.31	
		Gross fixed capital formation in agriculture (billion)	0.047	616	128585.8	BPS
		Electricity consumption for agricultural purposes (Rp)	0.053	616	51907.82	BPS
2	Food Access Security (FAS)	Rice consumption (kkal)	0.058	616	17935.12	BPS
		Tubers Consumption (kkal)	0.058	616	1436.149	BPS
		vegetable consumption (kkal)	0.058	616	12664.09	BPS
		Meat consumption (kkal)	0.058	615	7606.031	BPS
		Consume eggs and milk (kkal)	0.058	616	7539.25	BPS
		Nut consumption (kkal)	0.058	616	2110.872	BPS
		Fish consumption (kkal)	0.058	616	14683.75	BPS
		Fruit consumption (kkal)	0.052	616	6208.873	BPS
3	Food Production Stability (FSP)	Agricultural land area (ha)	0.051	616	19935.9	BPS
		Critical land area (ha)	0.050	616	174.83	BPS
4	Food Production Sustainability (FPSU)	Distribution of subsidized fertilizer (kg)	0.058	616	333089.1	Ministry of Agriculture
		Waste plastic (%)	0.058	616	17.741	Ministry of Environment and Forestry

Based on previous research, government expenditure encourages increased food security. This indicates that the government's support through fertilizer subsidies and direct farmer assistance creates an increase in productivity, thus encouraging the achievement of good food. Meanwhile, electricity consumption has the potential to encourage an increase in food security. This indicates that electricity can be a support, especially for farmers' innovation in creating more agricultural products. On the other hand, foreign direct investment is suspected to be one of the carrying capacities of capital to create a leap in the agricultural sector consequently. This will lead to an increase in food availability through abundant production. Finally, the increase in population will allegedly have a negative impact on food security given that the increasing demand is not matched by the availability of land

Spatial weight matrix is an important player in providing information on spatial correlation between one region and another, the weight matrix contains the spatial coefficient of distance. (d) which can be expressed as follows:

$$W_{ij} = \begin{cases} \dfrac{1}{d_{ij}} ; i \neq j \\ 0 \end{cases} \tag{4}$$

Based on the weighting matrix of equation [5], the measurement process requires guidance in the form of estimating the spatial correlation between digitization and food security.

Spatial regression measurement does not stop there, the last stage is carried out to obtain direct and indirect relationships. The direct and indirect measurements of food security are as follows:

$$\left[\frac{\partial y}{\partial x_{1k}}, \frac{\partial y}{\partial x_{2k}}, \ldots, \frac{\partial y}{\partial x_{nk}}\right] = \begin{bmatrix} \frac{\partial y_1}{\partial x_{1k}} & \cdots & \frac{\partial y_1}{\partial x_{nk}} \\ \vdots & \vdots & \vdots \\ \frac{\partial y_n}{\partial x_{1k}} & \cdots & \frac{\partial y_n}{\partial x_{nk}} \end{bmatrix} = (I_n - \rho W)^{-1} \begin{bmatrix} \beta_k & w_{12}\theta_k & \cdots & w_{1n}\theta_k \\ w_{21}\theta_k & \beta_k & \cdots & w_{2n}\theta_k \\ \vdots & \cdots & \cdots & \vdots \\ w_{n1}\theta_k & w_{n2}\theta_k & \cdots & \beta_k \end{bmatrix} \tag{5}$$

Where β_K is the direct impact of technological innovation while $w_{ni}\theta_k$ is the indirect impact.

Finding and Discussion

Estimation Results

Based on the calculation results in Table 2, the average food security in Sumatra is relatively well distributed and close to the maximum value. Meanwhile, digital transformation still does not indicate an even distribution, this is indicated by an average of 0. Internetization also tends to be unevenly distributed, this is indicated by the maximum gap which is still high. Meanwhile, the share of local governments through fiscal decentralization tends to be close to the maximum, meaning that all of them allocate a relatively balanced portion. The relatively low price level indicates that the success of price control through TPID is quite significant. Rainfall, temperature, global uncertainty, electricity use, population, and industrialization are in moderate condition, approaching the maximum value.

Based on the estimation results of the calculation of food security entropy, that historically food barn areas such as North Sumatra, parts of West Sumatra, South Sumatra, and Lampung are still the basis for food sustainability throughout Sumatra. The high density of resilience is affixed through various lines such as the availability of adequate production, including the potential for investment sustainability in the agricultural sector. Meanwhile, the uneven distribution of food security is caused by the supply of one component that is not available in certain areas, such as beef and milk, and poor accessibility. This is still a separate concentration in supporting an even distribution pattern. Meanwhile, from the aspect of distribution, the main staples of rice and eggs are still relatively widely available throughout Sumatra.

Table 2: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
fs	616	8.699	0.808	5.466	10.523
td	616	0	1	-2.527	2.698
internet	616	122.177	101.539	4	790
lnfdr	616	19.344	5.078	6.733	28.955
inflasi	616	1.881	1.54	-.75	5.76
lnrf	616	6.612	1.346	2.833	8.061
temp	616	27.248	1.202	25	29
lngpr	616	4.591	.288	4.348	5.079
lnec	616	14.929	1.358	12.11	16.827
lnpop	616	12.371	1.038	8.028	14.73
indus	616	12.857	2.713	6.746	17.747

Based on the estimation results in Table 3, food security from outside the district/ city area has a significant positive effect. This means that there is a positive spillover effect between regions. Meanwhile, digital transformation in the short term, fiscal moderation to digital transformation, village internetization, inflation, rainfall, and geopolitical risk have no significant effect on food security. On the other hand, digital transformation in the long run, population, and electrification have significant positive effects. Finally, industrialization has two different effects, negative and significant positive. Implicitly, there are error variables originating from outside and inside the region that cannot be explained in the model. For this reason, special treatment is needed in adapting the interpretation of food security as a whole by using marginal effects.

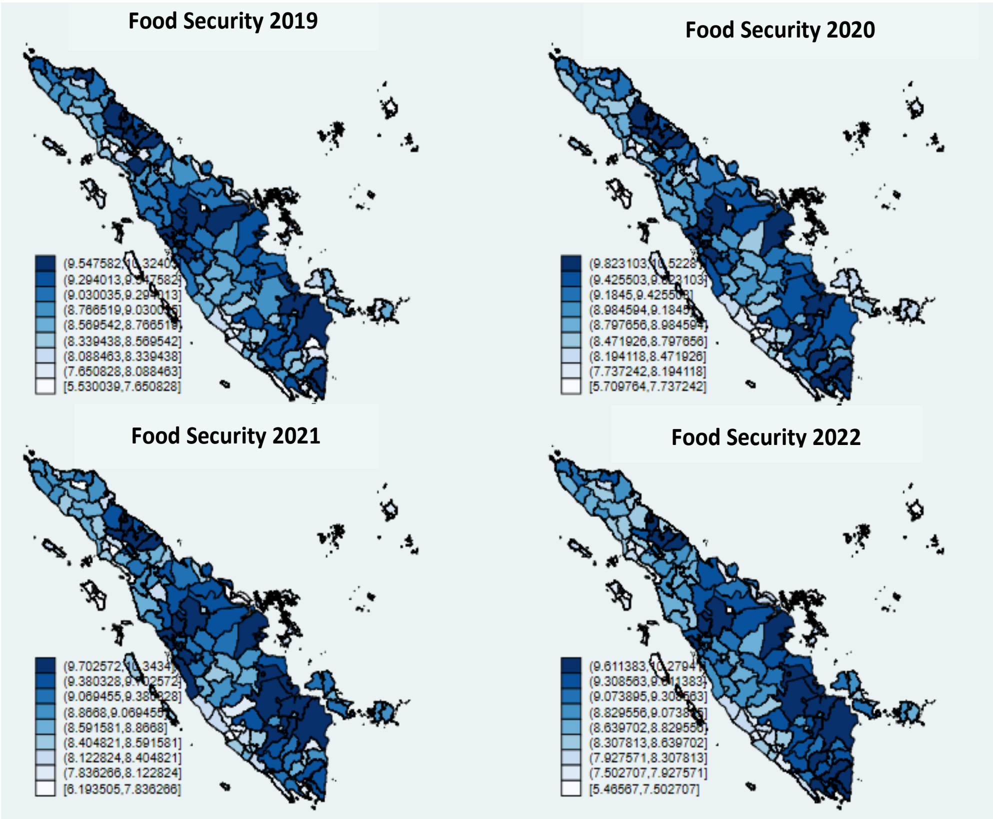

Figure 3: Food Security Distribution

Following Table 4 presents the marginal effects in the form of direct and indirect spillover effects from the spatial model. Based on the estimation results, the positive effect of digital transformation on food security is influenced by within the region and the remaining small part is influenced by surrounding regions. Meanwhile, the negative effect of air temperature on food security is influenced by other regions. On the other hand, the positive effect of electrification on food security is still largely influenced by within the region and the rest is influenced by other regions. The positive effect of population on food security is due to the increase in population within the region without any influence from outside regions. Finally, the positive effect of industrialization on food security is still supported by the region itself.

Furthermore, in order to know the spatial impact with regional boundaries, Figure 4 is presented which shows the spread effect of digitization, electrification, industrialization, and population on food security. In general, the effect of digitalization on food security is still dominant in North Sumatra, followed by West Sumatra and Riau. The effect of electrification on food security is dominated by North Sumatra and followed by Riau, South Sumatra and

Lampung. Meanwhile, the impact of industrialization on food security is dominated by Aceh, Lampung and Bangka Belitung Islands. Finally, the effect of population on food security is dominated by Lampung, North Sumatra, and a small part of Riau.

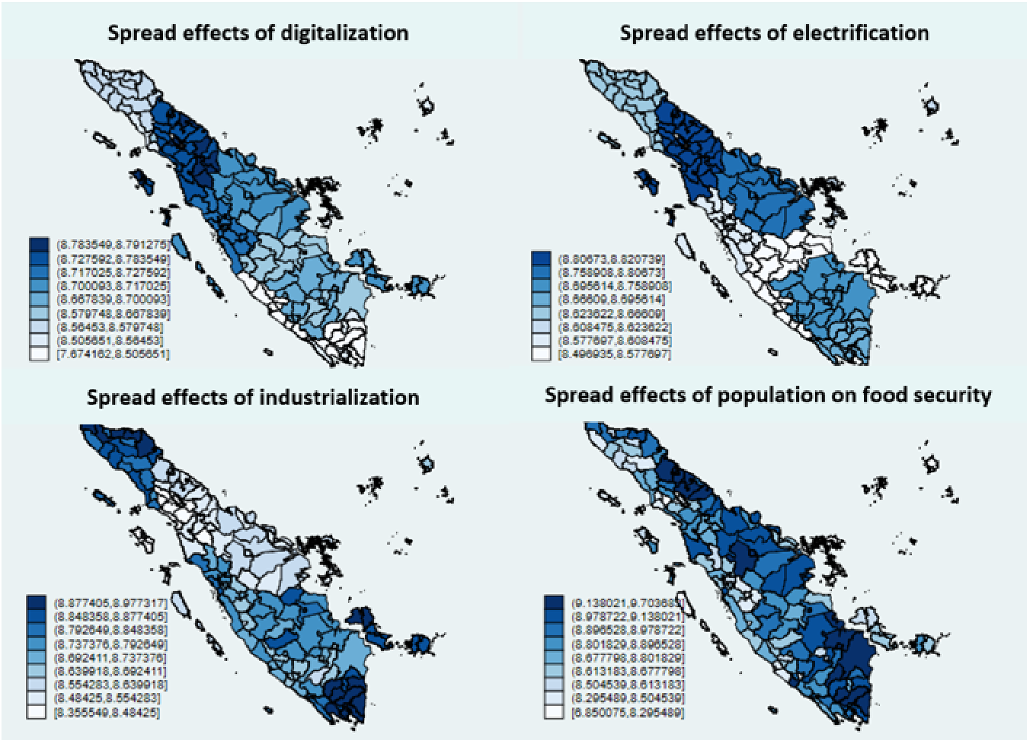

Figure 4: Spread effects of digitalization, electrification, industrialization and population on food security

Table 3: Spatial Panel Regression Estimation Results

	(1)	(2)	(3)	(4)
	fs	fs	fs	fs
td	0.065	0.053	0.046	0.033
	(.088)	(0.09)	(0.082)	(0.084)
tds	0.035***	0.034**	0.046***	0.045***
	(0.013)	(0.013)	(0.013)	(0.013)
td_fdr	-0.004	-0.002	-0.002	-0.001
	(0.004)	(0.005)	(0.004)	(0.004)
kabkotainternet	0.0002	0.0002	0.0003	0.0001
	(0.001)	(0.001)	(0.002)	(0.003)
lnfdr	-0.037**	-0.036**	-0.002	-0.002
	(0.018)	(0.018)	(0.012)	(0.012)
inflasi	0.003	0.007	-0.002	0.002
	(0.016)	(0.017)	(0.016)	(0.017)
lnrf	-0.011	-0.01	-0.023	-0.022
	(0.017)	(0.017)	(0.015)	(0.015)
temp	-0.115**	-0.119**	-0.024	-0.027
	(0.049)	(0.049)	(0.036)	(0.036)
lngpr	-0.097	-0.1	-0.097	-0.102
	(0.067)	(0.068)	(0.067)	(0.068)

	(1)	(2)	(3)	(4)
	fs	fs	fs	fs
lnec	0.179***	0.179***	0.108***	0.108***
	(0.051)	(0.051)	(0.037)	(0.037)
lnpop	0.07	0.071	0.149***	0.151***
	(0.096)	(0.096)	(0.048)	(0.048)
indus	-0.066*	-0.067*	0.039*	0.038*
	(0.04)	(0.04)	(0.023)	(0.023)
_cons			5.348***	5.429***
			(1.437)	(1.441)
Wc:lnfdr	0.029	0.025	-0.018	-0.021
	(0.023)	(0.024)	(0.016)	(0.016)
Wc:inflasi	0.018	0.011	0.008	0
	(0.022)	(0.024)	(0.023)	(0.025)
Wc:fs	0.414***	0.417***	0.151***	0.159***
	(0.072)	(0.072)	(0.037)	(0.039)
Wc:td_fdr		-0.002		-0.002
		(0.002)		(0.002)
sigma_e:_cons	0.291***	0.291***	0.308***	0.307***
	(0.01)	(0.01)	(0.01)	(0.01)
sigma_u:_cons			0.508***	0.509***
			(0.035)	(0.035)
Observations	616	616	616	616
Pseudo R^2	0.011	0.011	0.426	0.423

Notes : *significant of p<0.01; **significant of p<0.05; *significant of p<0.1

Table 4: Direct and Indirect Spillover Effects

Spatial Variable	Direct	Indirect	Total
td	0.0329	0.0041	0.0371
tds	0.0449**	0.0056**	0.0506**
td_fdr	-0.0007	-0.0014	-0.0021
kabkotainternet	0.0002	0.0000	0.0003
lnfdr	-0.0021	-0.0168	-0.0189
inflasi	0.0024	0.0005	0.0029
lnrf	-0.0223	-0.0028	-0.0251
temp	-0.0269	-0.0034**	-0.0303**
lngpr	-0.1021	-0.0128	-0.1149
lnec	0.1086**	0.0136**	0.1222**
lnpop	0.1511**	0.0190	0.1700**
indus	0.0383*	0.0048	0.0431*

Notes : *significant of p<0.01; **significant of p<0.05; *significant of p<0.1

Discussion

Estimation results are generally consistent with the research (Fesun & Qineti, 2024; Mumuni & Joseph Aleer, 2023; Wu & Wen, 2023; Yao & Fu, 2023) where it states that there is a positive influence of digital transformation on food security. The increase in digital transformation directly impacts agricultural productivity. By utilizing digital transformation and more precise information, farmers can optimize the use of agricultural inputs such as water, fertilizers, and pesticides. Additionally, digital transformation can also directly drive loss reduction. Through digital transformation, developers will be assisted in identifying technical agricultural problems, such as monitoring pest attacks and water quality. This condition will allow for early prevention, thus reducing the risk of farmer losses. On the other hand, digital transformation encourages innovation in creating new types of product varieties, beyond rice and other caloric foods.

In general, digital transformation can take the form of digital platforms and e-commerce, allowing farmers to access a wider market for their products. This can lead to increased farmer income and greater food availability for consumers. Mobile apps and online marketplaces connect farmers directly with consumers, cutting out middlemen and reducing food prices. Digital payment systems and mobile banking enable financial inclusion for small-scale farmers and rural communities. Access to credit, insurance and savings facilities can help farmers invest in better farming practices that are resilient to shocks, thereby improving food security(Smyth et al., 2021). Digital technologies such as GPS-guided tractors and drones enable precision farming, optimizing resource use. Farmers can use precise amounts of water, fertilizers, and pesticides on specific areas of their fields, reducing waste and environmental impact while increasing crop yields. Digitalization also accelerates research and development in agriculture. Artificial intelligence and big data analytics can help scientists develop new crop varieties that are more resistant to pests, diseases, and changing climate conditions.

Meanwhile, fiscal policy decentralization hinders food security. This corresponds with research from (Rindayati et al., 2007; Vasconcellos & Moura, 2018). This can be affixed with some information, e.g. fiscal decentralization can exacerbate regional disparities. If resource allocation is not done fairly or if some local governments do not have the capacity to manage their finances effectively, then this can lead to disparities in access to resources for agricultural development, infrastructure, and social services related to food security. This can put marginalized regions at a disadvantage. Fiscal decentralization may increase competition among local governments for limited resources. In such cases, local governments may prioritize other sectors over agriculture and food security, especially if they see greater political or economic benefits in doing so (Vale, 2016). This may result in reduced investment in agriculture and related programs. Decentralization can lead to the fragmentation of policies and regulations related to agriculture and food security. Different programs and institutional statuses may adopt different approaches, standards, and regulations, which can create confusion and inefficiencies in the food supply chain and may compromise food safety and quality. Centralized programs and initiatives often benefit from economies of scale, allowing for cost-effective implementation. When responsibilities are devolved to smaller local governments, they may struggle to achieve the same level of efficiency and effectiveness in delivering food security programs and services

On the other hand, electrification has a significant positive effect on food security. In line with research conducted by (Abdullah et al., 2020) That the role of electrification could have come from various transmissions, for example, enabling the use of electric pumps for irrigation, reducing farmers' dependence on rainfall and increasing crop yields. Access to electricity can power machinery, such as tractors and threshers, making the farming process more efficient and less labor-intensive. Electricity is essential for post-harvest activities such as milling, grinding, and drying mills. Access to electric mills and grain processing equipment allows farmers to add value to their crops and reduce post-harvest losses. Refrigeration and cold storage facilities powered by electricity help preserve perishable foods, such as fruits, vegetables, and dairy products. This prevents spoilage and extends the shelf life of products, reducing food waste. In addition, electrification also supports food processing industries, including canning, bottling, and packaging. These industries can increase the value of agricultural products, create jobs, and contribute to food security by reducing seasonal fluctuations in the availability of processed food.

Meanwhile, industrialization has a significant positive effect on food security, which is in line with several previous research studies (Asiedu et al., 2018) Industrialization often results in higher agricultural productivity through the use of sophisticated machinery, technology, and inputs. This can increase food production and availability. Productivity processes in industry allow for the development of food processing industries that can efficiently convert raw agricultural products into processed and packaged foods. This can help reduce post-harvest losses and extend the shelf life of food products. Industrialization can lead to the development of efficient food distribution and logistics systems. This can increase access to food in both urban and rural areas, reduce food deserts, and improve food security. Industrialization often contributes to economic growth and job creation, which can reduce poverty and improve household food security by increasing income levels.

Finally, population has a positive effect on food security. This is consistent with research conducted by (Aiyedogbon et al., 2022; Sule & Deribe, 2023), where the transmission comes from any increase in population can drive a more significant labor force for agriculture, which can increase food production. More people potentially means more labor to work in agriculture and contribute to food supply (Wang et al., 2021). The larger population can create a larger domestic market for food products, which can incentivize farmers and agribusinesses to produce more food to meet growing demand. This can increase food availability and potentially lower prices for consumers. Population growth can encourage investment in agricultural innovation and technology, such as improved crop varieties, irrigation systems, and mechanization, which can increase agricultural productivity.

Conclusion

This study concludes that digitalization has a significant positive effect in the long run, while fiscal decentralization policy is considered to have a significant negative effect on food security. Meanwhile, electrification, industrialization, and population growth positively influence food security. Spatially, the influence on food security also stems from out-of-region resilience. This indicates that the potential for inter-regional trade highly depends on accessibility and network availability. On the other hand, electrification, industrialization, and population support the agricultural sector to advance and encourage sustainable economic growth. The implications of this research include the relatively uneven distribution of food security in Sumatra, indicating that staple food production remains relatively low. Additionally, connectivity between regions is hampered by topographical barriers such as mountains and accessibility issues. For this reason, digital transformation is crucial in supporting and actualizing food security sustainably through various means such as market access and farmland navigation. As integrated support, this research actualizes the roles of electrification, industrialization, and population in promoting equitable food security. This study recommends that digitalization be optimized in conjunction with the availability of adequate internet and mobile accessibility. By supporting the digitalization program, the potential to establish food security will improve. Furthermore, electrification and industrialization are key factors in achieving food security. The government should strive to enhance fiscal capacity to support equitable agricultural industrialization in selected regions, thereby expediting distribution channels and preventing impulsive price increases.

Declaration

Authors' Contributions

MNF was responsible for the overall conceptualization of the study, and contributed to the writing of the introduction, literature review, methodology, results, discussion, conclusion, and manuscript revision. FAW contributed to the literature review and data collapsing process. BPP handled the translation and lay outing of the manuscript. All authors have read and approved the final version of the manuscript.

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Availability of Data and Materials

No new data were created or analyzed in this study

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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