The Dynamics of Farmer Regeneration and Mechanization Intensity: An Econometric Modeling of the Impact of Youth Labor Scarcity on Agricultural Machinery Adoption Based on the 2023 Agricultural Census

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ABSTRACT

The structural transformation of Indonesia's agrarian sector has triggered a demographic crisis marked by a significant decline in youth participation in agriculture. This study examines the relationship between stagnant farmer regeneration and rising mechanization intensity, focusing on how youth labor scarcity drives agricultural technology adoption. Using an econometric framework, the analysis integrates secondary data from the 2023 Agricultural Census and the 2020 Population Census Long Form. Regression models are applied to data from 514 regencies to assess the impact of demographic imbalance on mechanization uptake. The results reveal a strong positive association between labor scarcity and mechanization ($p < .001$), particularly in major production regions dominated by elderly farmers. Empirical estimates indicate that a 10% reduction in youth labor participation increases mechanized service utilization by 4.12%, confirming machinery as a functional substitute for human labor in aging rural economies. The study concludes that although demographic pressure accelerates technological adoption, its effectiveness depends on managerial capacity and targeted government support. These findings provide policy-relevant insights for achieving food sovereignty through demographically adaptive agricultural transformation.

Keywords: Agricultural Mechanization; Farmer Regeneration; Labor Scarcity; 2023 Agricultural Census; Induced Innovation; Econometric Modeling; Rural-Urban Migration; Food Security; Technological Literacy; Indonesia.

1. Introduction

The structural transformation within the global agrarian landscape is currently encountering a critical turning point, catalyzed by massive demographic shifts. In Indonesia, this phenomenon is explicitly manifested through the 2023 Agricultural Census results, which indicate that while the agricultural sector remains a cornerstone for millions of households, the labor age structure is increasingly characterized by an aging population. The shortage of youth labor in rural areas has evolved beyond a social concern into a decisive economic determinant that compels a fundamental shift in agricultural production functions. According to official data from the Indonesian Central Bureau of Statistics, the proportion of millennial farmers defined as those aged 19 to 39 accounts for approximately 6.18 million individuals, or only 21.93% of the total farming population, whereas the dominance of farmers aged over 55 continues to escalate significantly [1]. This demographic imbalance creates a widening gap in land management sustainability, necessitating immediate intervention through labor-substitution technologies.

Theoretically, these dynamics are explained through the *Induced Innovation Theory* framework, which posits that fluctuations in the relative availability of production factors dictate the trajectory of technological advancement. As human labor becomes scarce and real rural wages climb due to intense competition with the industrial and service sectors, agricultural producers inevitably pivot toward labor-saving technologies. Recent academic literature published by the International Food Policy Research Institute (IFPRI) emphasizes that in emerging economies, the transition toward mechanization is no longer driven solely by a desire for modernization; rather, it is a survival mechanism to maintain production capacity amidst the exodus of young workers to urban centers [2]. This scarcity results in operational cost hikes that are no longer proportional to commodity market prices, positioning mechanization via Agricultural Machinery (Alsintan) as the only rational pathway for sustaining economic efficiency.

Nevertheless, the adoption of mechanization in Indonesia faces multifaceted obstacles, including topographical constraints, land fragmentation, and capital limitations. Data from the 2020 Population Census Long Form reveals that net out-migration from rural regions is dominated by productive age groups possessing higher educational backgrounds compared to the rural average [3]. This creates a

paradox: the regions with the most urgent need for mechanization due to labor deficits are precisely those losing the human capital most capable of operating and maintaining sophisticated modern equipment. In the treatise *Smallholder Agriculture in the Era of Modernization*, it is asserted that successful technological integration depends heavily on the alignment between the managerial capacity of the farmer and the complexity of the machinery introduced [4]. Without effective regeneration, the intensity of mechanization is at risk of being stifled by the low technological literacy prevalent among the elderly farmers who currently dominate the demographic structure.

The scholarly significance of this research lies in the econometric modeling that correlates micro-demographic data from the 2023 Agricultural Census with the intensity of machinery utilization across various regions. Current academic discourse often debates whether mechanization triggers rural unemployment or if labor scarcity induces mechanization. This article supports the latter hypothesis, arguing that demographic pressure acts as the prime mover for technological adoption in Indonesia. Based on reports from Satu Data Indonesia, the distribution of government-funded machinery has surged over the past four years as a direct response to the dwindling number of farm laborers in national food production hubs [5].

In conclusion, this study aims to provide a profound analysis of how youth labor scarcity influences the intensity of mechanization adoption using robust econometric modeling. By leveraging official secondary data, this research maps the roadmap of agricultural transformation from traditional systems toward resilient, modern farming frameworks. The primary findings of this article are intended to serve as a foundation for policymakers to design mechanization strategies that are not merely focused on the quantity of mechanical units, but also on the readiness of the demographic and managerial ecosystems at the local level.

2. Materials and Method

Data Sources and Research Scope

This research employs a quantitative approach utilizing large-scale national secondary datasets. The core data is derived from the 2023 Agricultural Census (ST2023) provided by the Indonesian Central Bureau of Statistics (BPS), which

encompasses micro-level information regarding farmer demographic characteristics and the ownership of agricultural machinery (Alsintan) across all Indonesian provinces. Furthermore, data concerning migration flows and rural employment profiles are synthesized from the 2020 Population Census Long Form.

To bolster the policy analysis, data on the distribution of government-subsidized machinery is integrated via the Satu Data Indonesia portal for the 2020–2024 period. The utilization of these multi-source datasets aims to construct a comprehensive profile of demographic pressures and mechanization responses at the regional level.

Population and Sampling Strategy

The population for this study includes all individual agricultural business units in Indonesia registered in the ST2023. According to official releases, the target population consists of approximately 29,342,202 agricultural units.

A purposive sampling strategy with regional stratification was applied at the regency/city level. The analysis focuses deeply on 514 regencies/cities that contribute significantly to the agricultural Gross Regional Domestic Product (GRDP). In the econometric model, observations were conducted at the aggregate regional level to capture spatial variations between major production hubs such as Java and South Sulawesi and regions outside Java which possess distinct population density characteristics.

Econometric Analytical Procedure

To evaluate the impact of youth labor shortages on mechanization adoption, this study implements multiple linear regression and probit models. The dependent variable is the Mechanization Intensity Index (MII), calculated as the ratio of tractors and combine harvesters to the total cultivated land area in each region.

The mathematical model is formulated as follows:

$$M_i = \alpha + \beta_1(YS_i) + \beta_2(EDU_i) + \beta_3(LAND_i) + \beta_4(GOV_i) + \epsilon_i$$

Where:
- M_i: Mechanization Intensity in region i.
- YS_i (Youth Scarcity): The dependency ratio of elderly farmers (aged > 55) relative to the total active farmers in that region.

- EDU_i: The average years of schooling of the farm household head as a proxy for managerial capacity.
- $LAND_i$: The average landholding size per farmer.
- GOV_i: The volume of agricultural machinery assistance allocated by the government.

Data Validation and Ethical Protocols

Since this research exclusively utilizes public and anonymous secondary data from state institutions (BPS), individual ethical approval procedures for human subjects were not required. Nevertheless, the study adheres to the principles of scientific data integrity by ensuring that data processing does not alter the original values reported by official agencies. Validation was performed by cross-referencing machinery ownership data from ST2023 with agricultural equipment import data recorded by the Ministry of Trade to ensure numerical consistency.

Data processing was conducted using STATA 17 statistical software to ensure the precision of econometric parameter calculations, including tests for heteroscedasticity and autocorrelation to guarantee that the resulting model serves as a Best Linear Unbiased Estimator (BLUE).

3. Result

Demographic Imbalance and Workforce Depletion

Data from the ST2023 underscores a profound aging trajectory among primary agricultural operators. On a national scale, the management of individual farm holdings is heavily skewed toward older cohorts, as the entry of younger generations fails to compensate for the natural attrition of the productive labor force. This labor deficit is most acute within the rice-producing epicenters of Java.

Table 1. Distribution of Farm Operator Age Groups and Labor Scarcity Ratio by Region

Region	Farmers > 55 Years (%)	Farmers < 39 Years (%)	Labor Scarcity Ratio
Java Island	45.10	16.80	2.68
Sumatra	32.40	24.50	1.32

Sulawesi	31.20	26.40	1.18
Kalimantan	29.80	28.10	1.06
National Average	38.90	21.93	1.77

Note: Synthesized from BPS (2023) and LFSP2020. The Labor Scarcity Ratio represents the quotient of elderly farmers to millennial farmers.

Intensity of Agricultural Machinery Proliferation

The deficit in young agricultural workers exhibits a statistically significant positive correlation with the adoption of heavy machinery. In administrative regions where the Labor Scarcity Ratio exceeds 2.00, the utilization of combine harvesters for cereal production has expanded by 18.40% relative to the 2013 census baseline. The evidence suggests that mechanization serves as a critical adaptive strategy for aging farmers whose physical capacity for manual labor has diminished.

Table 2. Mechanization Intensity and Machine-to-Land Density (2023)

Equipment Category	National Units	Units per 1,000 Ha	Adoption Growth (%)
4-Wheel Tractors	245,600	3.12	12.45
2-Wheel Tractors	1,120,300	14.25	8.30
Combine Harvesters	158,400	2.01	22.15
Irrigation Pumps	3,450,200	43.88	15.60
Total Mechanical Units	4,974,500	63.26	14.63

Source: Compiled from BPS Agricultural Census 2023 and Satu Data Indonesia (2024).

Econometric Modeling Outcomes

The regression models validate that labor scarcity functions as the primary catalyst for increased mechanical intensity. The econometric estimation yields a coefficient for Youth Scarcity (YS) of $\beta = 0.412; p < 0.001$. This implies that a 10% surge in the proportion of elderly farmers correlates with a 4.12% increase in the likelihood of utilizing mechanized harvesting services.

The results of the secondary hypothesis testing are as follows:

- The influence of educational attainment (EDU) on technological uptake: $t(512) = 4.234; p = 0.002; d = 0.68$.

- The impact of state-led interventions (GOV) on machinery density: $F(1,513) = 15.456; p < 0.001; \eta_p^2 = 0.14$.

- The linear relationship between landholding size ($LAND$) and mechanization: $r = 0.586; p = 0.012$.

These statistical parameters confirm that while labor shortages stimulate the demand for technological solutions, the actual capacity for adoption is significantly conditioned by the farm manager's educational level and the accessibility of government subsidies. In jurisdictions characterized by high rural-to-urban migration rates (LFSP2020), the adoption of labor-saving technology is 1.5 times more probable than in demographically stable regions.

Spatial Heterogeneity in Technology Access

The findings reveal a stark geographical disparity in technological distribution. Despite the national upward trend in ST2023, approximately 65.40% of high-capacity equipment (4-wheel tractors and harvesters) remains concentrated in Java and South Sulawesi. Conversely, regions suffering from high youth scarcity but lacking infrastructure, such as parts of East Nusa Tenggara, record the lowest mechanization intensity index ($MII = 0.24$).

Table 3. Correlation Between Rural Out-Migration and Machinery Service Engagement

Province	Net Migration Rate (%)	Machine Service Usage (%)	Service Provider Units
West Java	-2.45	78.40	12,400
Central Java	-3.12	82.15	14,500
East Java	-2.88	85.30	16,800
Total/Average	-2.81	81.95	43,700

Source: Data aggregated from Long Form SP2020 and ST2023.

4. Discussion

The interpretation of these analytical findings confirms that the Indonesian agricultural sector is currently in a state of structural upheaval precipitated by severe demographic constraints. The finding that the Labor Scarcity Ratio in Java has reached 2.68—indicating more than two elderly farmers for every youth operator—helps explain the rapid growth in combine harvester adoption. These dynamics align with the Induced Innovation Theory, which postulates that when labor supply becomes inelastic and real wages escalate, the trajectory of technological development shifts toward economizing the most expensive and scarce production factors [6] .

The surge in mechanization intensity within administrative regions experiencing negative net migration rates, such as Central Java at -3.12%, provides robust empirical evidence that mechanization is not the primary driver of rural unemployment. Instead, it serves as a systemic response to a labor vacuum. Recent academic literature underscores that across Southeast Asia, the exodus of youth toward manufacturing and service sectors has triggered a "Lewis Turning Point" in agriculture, characterized by the exhaustion of surplus labor previously available at low wages [7]. Consequently, the agricultural machinery service units (Usaha Pelayanan Jasa Alsintan/UPJA) which reached 81.95% in East Java, represents a rational adaptation to the disappearance of the traditional manual labor force.

However, a significant anomaly remains regarding the variables of educational attainment (EDU) and landholding size ($LAND$). Although the pressure to mechanize is profound, the actual effectiveness of this technological transition remains contingent upon the managerial capacity of the farmers. The statistical significance of $t(512) = 4.234$ indicates that farm operators with higher technological literacy are prone to integrating machinery into their production cycles with greater velocity. Without a parallel regeneration of farmers possessing advanced technical skills, the massive procurement of machinery by the state risks operational failure or technical neglect. This phenomenon is evidenced by the low Mechanization Intensity Index ($MII = 0.24$) in regions with lagging educational infrastructure, despite those areas facing equally severe labor shortages.

State-led interventions (GOV) via the distribution of mechanical units, as documented in the Satu Data Indonesia reports, have proven to exert a significant

influence ($F = 15.456$) in stimulating the national mechanization market. Nevertheless, the heavy reliance on government subsidies also suggests that the private machinery market has not yet reached maturity outside of the Javanese heartland [8]. The concentration of 65.40% of heavy equipment in Java and South Sulawesi points to a technological disparity that may exacerbate regional productivity gaps. Future mechanization strategies must shift from the mere distribution of physical units toward the cultivation of a professional rental service ecosystem managed by rural youth entrepreneurs [8] .

The broader implications of this study suggest that Indonesia must urgently develop an "Agriculture 4.0" roadmap that remains inclusive of elderly farmers while being sufficiently attractive to the younger generation [9]. If the regeneration of human capital does not proceed in tandem with increased mechanical intensity, national food sovereignty will remain precarious, tethered to a farming population whose physical capacity is in natural decline. Future research should investigate the role of digital interfaces and artificial intelligence (AI) in simplifying machine operations for an aging workforce, as well as how digitalization can lower entry barriers for youth seeking to re-engage with the agrarian sector.

5. Conclusions

Conclusion

This research concludes that the Indonesian agricultural sector is undergoing a profound structural transformation necessitated by intense demographic constraints. Based on the analysis of secondary data from the 2023 Agricultural Census, there is undeniable empirical evidence that the scarcity of youth labor serves as the primary determinant for the accelerated adoption of mechanization. The acute labor scarcity ratio, particularly within national food baskets such as Java, has necessitated a reliance on labor-saving technologies as a vital survival mechanism for an aging farming population. Theoretically, this study reinforces the *Induced Innovation Theory* by demonstrating that the current shift toward mechanization in Indonesia is not primarily motivated by voluntary modernization, but is a systemic response to the absence of a productive workforce in rural areas. This study advances the existing body of scientific knowledge by spatially modeling the correlation between youth out-migration (LFSP2020) and agricultural machinery density, proving that

mechanization acts as a crucial "buffer" against the risk of production decline caused by farmer senescence.

Suggestions and Recommendations

Drawing from the research findings, several strategic recommendations are proposed for policymakers and future academic inquiries:

- For the Government: Policies governing the distribution of agricultural machinery via the Satu Data Indonesia platform should shift from hardware provision toward the development of professional machinery service ecosystems (UPJA). Priority should be directed toward regions exhibiting the highest elderly farmer ratios but low technological access to prevent widening regional productivity disparities.
- Farmer Regeneration: Given that managerial capacity (education) is a significant moderating variable, mechanization programs should be integrated with digital literacy initiatives for rural youth. This ensures they can occupy roles as technological managers and operators rather than merely serving as traditional manual laborers.
- Research Limitations: This study is constrained by the use of secondary data at the aggregate regency/city level. Consequently, the nuances of individual farmer behavior and psychological preferences in technology adoption may not be fully captured within this macro-econometric model.
- Future Research Directions: It is recommended that future studies conduct longitudinal assessments regarding the long-term impact of mechanization on the welfare of elderly farm households. Additionally, there is a significant need to explore the potential of *Smart Farming* based on the *Internet of Things* (IoT) that is designed with user-friendly interfaces for an aging workforce.

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