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Why Small Mills Outperform Large Ones: A Tripartite Governance Framework for Indonesia

Rachma Fitriati*
Universitas Indonesia, Depok, Indonesia
Triyuni Soemartono
Universitas Moestopo (Beragama), Jakarta, Indonesia
Sudarsono Hardjosoekarto
Universitas Indonesia, Depok, Indonesia
Topan Ruspayandi
Perum BULOG, Jakarta, Indonesia

*Correspondence: rachma.fitriati@ui.ac.id

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ABSTRACT
Postharvest losses in Indonesia's rice supply chain have averaged 10.82% annually since the 2026 self-sufficiency declaration, highlighting the need to evaluate government interventions targeting small rice mills. This study investigates the rationale, optimal locations, and enabling conditions for public investment in small-scale milling infrastructure. Drawing on Transaction Cost Economics, the Resource-Based View, and supply chain resilience theory, the study integrates GIS-AHP to assess mobile dryer suitability, K-Medoids clustering to segment partners, and TOPSIS with sensitivity analysis to prioritize investments. Primary survey data from 2,267 milling units and procurement records from 574 active BULOG partners (2022–2025) identify Bone, Sidrap, and Pinrang in South Sulawesi as the only "Highly Suitable" region for mobile dryers, with scores above 0.75. K-Medoids shows that small mills (Cluster C; 66% of partners) achieve the highest purchase order fulfillment rate (52.63%) despite having the oldest machinery and smallest capacities, consistent with TCE predictions of high asset specificity toward BULOG. TOPSIS prioritizes 32 units in South Sulawesi, 9 in West Java, and 4 in Central Java. Sensitivity analysis confirms ranking robustness (Spearman's ρ >0.89). The study introduces an integrated framework for targeted and resilient postharvest infrastructure investment planning.

INTRODUCTION

Indonesia declared rice self-sufficiency in early 2026. The government halted imports of rice for general consumption and industrial raw materials for the entire year. National stock opened at 12.4 million tons. Projected production surplus reached 34.76 million tons, exceeding consumption needs of 31.1 million tons (B.P.S., 2026). Yet the Ombudsman Institution reported that 300,000 tons of rice stored in BULOG warehouses risked spoilage, threatening state losses of IDR 4 trillion (O. R. Indonesia, 2026). This contradiction exposes a fundamental shift: Indonesia's food security problem no longer concerns production volume but postharvest systemic inefficiency.

Presidential Instruction Number 6 of 2025 halted rice imports and prioritized domestic procurement. The instruction targeted 3 million tons from local farmers in 2025 and 4 million tons (milled rice equivalent) in 2026. Harvested Dry Paddy (GKP) absorption targets reached 7.41 million tons (*Instruksi Presiden Republik Indonesia Nomor 6 Tahun 2025 Tentang Penghentian Impor Beras*, 2025). The government allocated IDR 164.4 trillion for food security in 2026, a 5.9 percent increase from 2025 (K. K. R. Indonesia, 2026). BULOG received a mandate to build 100 new warehouses in major production centers, formalized through a Joint Decree of Three Ministers in November 2025 (Pertanian, 2025).

Downstream structural challenges undermine these upstream policies. Coordinating Minister for Food Affairs Zulkifli Hasan stated that large-scale rice mills often eliminate small enterprises by exploiting subsidized rice for profit (Pangan, 2025). President Prabowo responded by requiring special permits for large-scale mills to protect small mills and prevent price monopolies (S. K. R. Indonesia, 2025). Field data from Jember Regency show that only five or six of 24 private mills that signed a memorandum of understanding with BULOG actually became partners (Jember, 2025). Protectionist policies without measurable technical intervention do not save small mills.

Indonesia loses 10.82 percent of its rice harvest during postharvest phases annually. This loss causes IDR 25 trillion in economic damage per year (B.U.L.O.G., 2025). B.P.S. (2020)recorded 182,000 rice milling units across the archipelago (B.P.S., 2020). Approximately 90 percent of these units are small-scale or household mills using simple technology. These units produce an average milling yield of 60–62 percent. Modern standards in Vietnam and Thailand achieve 68–70 percent (Kosasih et al., 2025). This 6–8 percent yield gap, multiplied by national paddy production of 55 million tons per year, equals food loss sufficient to feed 25–30 million people annually (Kosasih et al., 2025).

Three provinces—West Java, Central Java, and South Sulawesi—contribute over 40 percent of national production (B.P.S., 2024). Each province presents distinct geospatial challenges. West Java's northern Pantura region (Karawang, Subang, Indramayu, Cirebon) is highly productive, but the southern region (Cianjur, Sukabumi) faces accessibility constraints due to hilly topography. Central Java has numerous small mills scattered across 29 regencies. The main challenge lies in integrating these units into an efficient mechanical drying network. South Sulawesi has the highest national suitability for mobile dryers (Ramdhani, 2026), but it requires robust logistics for newly expanded farming areas in its eastern corridor.

Three theoretical pillars explain postharvest inefficiency and guide intervention design. *Transaction Cost Economics (TCE)* (Williamson, 1985) resolves a paradoxical finding from BULOG procurement data (2022–2025): small mills fulfill 68.17 percent of Purchase Order (PO) volume, far exceeding large mills (25.83 percent) and medium mills (41.70 percent)

(Williamson, 1985). Small mills possess high asset specificity toward BULOG. They lack alternative markets such as modern retail, export channels, or B2B contracts. This dependence creates bilateral dependency and relational contracting based on trust (Schnaider et al., 2022). Large mills have diversified sales options, so their transaction costs of maintaining BULOG contracts are higher (Liverpool-Tasie et al., 2023). TCE explains why revitalization programs must seriously consider small mills as loyal strategic partners. *Resource-Based View (RBV)* (Barney, 1991) frames aging infrastructure as depreciated but potentially valuable resources. Survey data show that the average RMU machine age is 26.16 years in West Java, 11.04 years in Central Java, and 13.80 years in South Sulawesi (Schnaider et al., 2022). These machines are no longer valuable due to low efficiency, but their strategic locations—at the center of decades-old production centers—are rare and inimitable (Thakur et al., 2023). Small mills also possess intangible resources—personal relationships with farmers, knowledge of seasonal patterns, village reputation—that large mills lack (Adetoyinbo et al., 2023). *Supply chain resilience* (Pettit et al., 2010) offers redundancy and flexibility to cope with harvest surges and rainy seasons. Wet paddy with a moisture content>25 percent ferments within 48 hours (Liverpool-Tasie et al., 2023). The proposed hub-and-spoke network combines permanent vertical dryers (>30 tons/batch) with mobile dryers that "go to the source." Mobile dryers in China reduce postharvest losses below 2 percent (C.A.A.S., 2025); Vietnamese prototypes dry 650–700 kg per batch in 4–6 hours (Ngo et al., 2025). This design cuts transport costs by 15–20 percent and enhances resilience through decentralization (Singh & Dwivedi, 2024).

Research on rice postharvest systems in Southeast Asia has primarily followed two trajectories. The first focuses on technical efficiency and price policy ((Octania, 2021); (Rachman, 2022)), frequently overlooking spatial dimensions. The second utilizes geospatial mapping ((Shofiyati, 2024); (Parajuli, 2025)) yet remains largely descriptive and does not provide actionable investment rankings. Ramdhani (2026) combines Geographic Information Systems (GIS) with the Analytic Hierarchy Process (AHP) to evaluate mobile dryer suitability but does not connect spatial analysis to operational performance or multi-criteria investment priorities. No existing study has integrated (i) GIS-based drying gap identification, (ii) K-Medoids clustering of contractual and operational data, and (iii) the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with weight sensitivity analysis. This study presents a novel and replicable framework that integrates the three methods into a unified approach, thereby providing actionable policy recommendations intended for collaborative implementation (Alfiyan & Rinova, 2025).

This study pursues four specific objectives. First, it maps the current state of postharvest infrastructure and quantifies the distribution of drying gaps across Indonesia's three leading rice-producing provinces. Second, it determines optimal locations for mobile dryer deployment using a GIS-AHP model with expert-validated weights. Third, it segments BULOG partner mills into distinct clusters based on operational and contractual performance using K-Medoids clustering, and analyzes significant differences among these clusters. Fourth, it ranks individual milling units by investment priority through TOPSIS under various weighting scenarios and assesses the robustness of these rankings via sensitivity analysis.

The analysis is expected to produce four principal findings. First, the drying gap is projected to be most severe in Bone, Sidrap, and Pinrang regencies of South Sulawesi, followed by the Pantura corridor in West Java and the northern coast of Central Java. Second, only South Sulawesi is likely to achieve a "Highly Suitable" classification for mobile dryers (scores above 0.75), while West Java and Central Java are expected to receive only "Suitable" scores. Third, small-scale mills (Cluster C) are anticipated to demonstrate the highest Purchase Order fulfillment rates despite having the smallest capacities and oldest equipment, consistent with Transaction Cost Economics (TCE) predictions regarding high asset specificity toward BULOG. Fourth, TOPSIS is expected to identify at least 30 high-priority units (Vi above 0.1) in South Sulawesi, with fewer such units in West Java and Central Java, and these rankings are expected to remain robust across different weighting scenarios (Spearman's ρ above 0.85). These anticipated results are intended to inform the central policy question: whether Indonesia should subsidize small rice mills, and if so, where and under what conditions.

This analysis is structured around four research questions: (1) What is the current state of postharvest infrastructure and the distribution of drying gaps? (2) Which areas are most suitable for mobile dryer deployment based on GIS-AHP analysis? (3) How do operational and contractual performances differ among mill clusters? (4) Which units have the highest investment priority as determined by TOPSIS, and how robust are these rankings to changes in weighting?

Theoretical Framework

The theoretical framework integrates three complementary perspectives to explain the persistent postharvest inefficiencies in Indonesia's rice supply chain: Transaction Cost Economics (TCE), the Resource-Based View (RBV), and supply chain resilience theory. These perspectives collectively address a central puzzle that previous studies have left unresolved: why small-scale mills demonstrate greater contractual reliability than their larger counterparts, and how strategic infrastructure investments can reduce systemic postharvest losses while strengthening collaborative governance.

TCE provides the foundational lens for understanding the paradoxical loyalty of small-scale mills. The theory predicts that governance structures emerge to reduce transaction costs, including partner search, price negotiation, quality monitoring, and contract enforcement (Williamson, 1985). Empirical evidence from BULOG procurement data reveals a striking pattern: small-scale mills fulfill 68.17 percent of their purchase orders, far exceeding the 25.83 percent achieved by large mills.

This finding appears paradoxical from a capacity-based perspective, yet TCE resolves this paradox through the concept of asset specificity—the degree to which an asset is tailored to a particular transaction and cannot be redeployed without loss of value. Small mills possess high asset specificity toward BULOG because they lack alternative markets such as modern retail, export channels, or B2B contracts with large food industries. BULOG therefore acts as their sole reliable off-taker, creating bilateral dependency and fostering relational contracting based on trust rather than rigid formal agreements (Schnaider et al., 2022) (Meirelles et al., 2023). Large mills, by contrast, enjoy diversified sales options—free markets, supermarkets, hotels, restaurants, and exports—and face higher opportunity costs when tied to BULOG's procurement price, which often falls below market rates. While existing TCE studies illuminate market mechanisms and price policies ((Octania, 2021); (Rachman, 2022)), they overlook the spatial dimensions of infrastructure gaps. This study extends TCE by demonstrating how institutional coordination can reduce transaction costs for small mills, making them viable partners despite their limited scale ((Zhang et al., 2023); (Liverpool-Tasie et al., 2023)). Applying TCE in this context shows that infrastructure revitalization programs should not focus exclusively on large mills with high capacity, but must seriously consider small mills as loyal and reliable strategic partners whose transactional behavior is shaped by structural dependencies rather than mere technical capabilities.

The RBV frames aging infrastructure as depreciated yet potentially valuable resources that can generate sustained competitive advantage if properly revitalized. The theory argues that competitive advantage originates from resources that are valuable, rare, inimitable, and well-organized—VRIN (Barney, 1991). Survey data reveal that the average age of rice milling units in West Java reaches 26.16 years, with some units exceeding 30 years. These machines suffer from low efficiency, high energy consumption, and expensive maintenance, yet their strategic locations at the heart of decades-old production centers are rare and inimitable. Building new milling units at these same locations faces land constraints, permitting issues, and established land ownership structures.

A study on the technological evolution of food traceability systems demonstrates that firms gain sustainable competitive advantage by innovating such systems, with technological innovations in human resources emerging as a major source of improved performance because they render resources non-substitutable in the short and medium term (Thakur et al., 2023). This finding directly applies to postharvest infrastructure: investing in modernizing existing mills at strategic locations, combined with upgrading mill operators' human capital, creates a non-substitutable advantage that new entrants cannot easily replicate. Small mills also possess intangible resources—personal relationships with local farmers, knowledge of seasonal harvest patterns, and village reputation—that large mills cannot easily replicate (Adetoyinbo et al., 2023). Prior RBV applications to agricultural supply chains have emphasized tangible and organizational resources (Pascoe et al., 2024; Ndebugri et al., 2025), but have not addressed how revitalizing aging infrastructure at strategic locations can generate sustained competitive advantage. This study applies a contingent RBV lens to demonstrate that revitalization strategies must be tailored to local conditions rather than applied uniformly (Kimathi et al., 2023; W. Wang et al., 2023). The RBV perspective thus reframes revitalization not as mere machine replacement, but as a strategic process of transforming depreciated resources into valuable assets through modern technology injection, while simultaneously preserving the intangible resources that give small mills their competitive edge in local contexts.

Supply chain resilience theory provides the operational rationale for hub-and-spoke network design with mobile dryers. Resilience is defined as the ability to withstand, adapt to, and recover quickly from disruptions (Pettit et al., 2010).

Indonesia's rice supply chain faces two seasonal disruptions: harvest surges that overwhelm drying capacity, and rainy seasons that extend natural drying periods. Wet paddy with moisture content above 25 percent ferments within 48 hours. (Singh & Dwivedi, 2024) develop a comprehensive strategic framework for mitigating risks in agri-food supply chains using hybrid multi-criteria decision-making techniques, including fuzzy analytical hierarchy process, fuzzy TOPSIS, and fuzzy quality function deployment. Their study ranks multiple risks and resilient strategies, providing a systematic approach that aligns directly with the present study's multi-criteria prioritization framework. The resilience framework offers redundancy and flexibility as coping strategies. The proposed hub-and-spoke distribution network operationalizes these concepts by combining permanent vertical dryers at primary hubs with mobile dryers that can be relocated at secondary spokes. Permanent vertical dryers with capacity exceeding 30 tons per batch provide drying capacity redundancy at strategic locations. Truck-mounted mobile dryers provide flexibility to "go to the source" during harvest surges and move to other regions when harvest in one region finishes.

International precedents validate this approach: intelligent mobile traction dryers in China reduce postharvest losses below 2 percent (C.A.A.S., 2025), while Vietnamese prototypes demonstrate technical and economic feasibility in tropical smallholder contexts, drying 650–700 kilograms of rice per batch within 4–6 hours using locally available fuels (Ngo et al., 2025).The hub-and-spoke design also enhances resilience through decentralization: wet paddy can be pre-dried at spokes to 18–20 percent moisture content, then consolidated to hubs for final drying and milling. This strategy reduces transport distance for heavy, bulky wet paddy, cutting transportation costs by 15–20 percent. Although resilience frameworks have identified diversification and digital transformation as critical strategies (Y. Wang et al., 2024); Zhong et al., 2024; Ali & Gölgeci, 2023), no study has operationalized these concepts through integrated spatial suitability mapping, partner segmentation, and investment prioritization. Mobile grain drying services operated by small-scale entrepreneurs have shown viability in South Asia, particularly in areas where open-air drying is costly or unavailable (Alam et al., 2024). The resilience framework therefore translates into an operational architecture that addresses Indonesia's specific postharvest challenges by creating a system that can dynamically respond to spatial and seasonal variability.

Integrating these three theoretical perspectives yields a coherent analytical framework that addresses the limitations of prior studies. TCE explains the behavioral dimension—why small mills remain loyal partners despite their technical limitations. RBV explains the resource dimension—why aging infrastructure at strategic locations retains value and why intangible assets matter. Supply chain resilience explains the structural dimension—why hub-and-spoke networks with mobile dryers offer the most adaptive response to seasonal and spatial disruptions. Previous studies lack an integrated framework combining spatial analysis, partner performance segmentation, and multi-criteria investment ranking, necessitating the tripartite methodological approach proposed here. This study addresses this gap by integrating GIS-AHP for mobile dryer suitability mapping, K-Medoids clustering for partner segmentation, and TOPSIS with sensitivity analysis for investment prioritization. The framework offers a replicable methodology for postharvest infrastructure planning that links theoretical insights on transaction costs, resource-based advantage, and supply chain resilience to actionable policy decisions. By demonstrating how these three theoretical lenses can be operationalized through spatial and multi-criteria analytical techniques, this study contributes to both academic discourse on collaborative governance in food supply chains and practical policy design for developing-country postharvest systems. The framework is particularly relevant for interdisciplinary area studies that examine the intersection of institutional economics, resource management, and climate adaptation in agrarian societies.

METHOD

This study employs a sequential tripartite framework integrating spatial suitability mapping, partner segmentation, and investment prioritization into a unified policy decision model for postharvest infrastructure planning. The framework proceeds through three interconnected stages, each generating outputs that inform the subsequent stage.

Data Sources. The study draws on primary survey data from 2,267 rice milling units across Indonesia, collected by BULOG's partner management division in 2025. The survey records GPS coordinates, milling capacity (tons/day), dryer capacity (tons/batch), technology type, production volume, operational period, paddy source, marketing area, partnership status, procurement volume, purchase order fulfillment percentage, fulfillment speed, and machine manufacturing years (Barney, 1991). Secondary data include national paddy production maps from BPS (2024), road network maps, administrative boundaries, and BULOG internal procurement records (2022–2025) (Thakur et al., 2023).

Spatial Analysis: AHP-GIS. The spatial analysis applies the Analytical Hierarchy Process integrated with Geographic Information Systems to evaluate mobile dryer suitability across three priority provinces (Ramdhani, 2026). Four expert-validated variables inform the analysis, achieving a consistency ratio of 0.08 below Saaty's (1980) 0.10 threshold (Adetoyinbo et al., 2023). Infrastructure carries 35 percent weight, accessibility 30 percent, production land characteristics 25 percent, and environment 10 percent. ArcGIS Pro Ver. 3.5 performs overlay and network analysis to determine a 15–20 kilometer service radius, generating a suitability map with four categories: Highly Suitable (>0.75), Suitable (0.50–0.75), Moderately Suitable (0.25–0.50), and Not Suitable (<0.25) (Pettit et al., 2010).

Partner Segmentation: K-Medoids Clustering. The segmentation applies the K-Medoids algorithm using the Partitioning Around Medoids method (Kaufman & Rousseeuw, 1990). K-Medoids offers robustness to outliers and uses Manhattan distance. The elbow method and silhouette coefficient determine k=3, with a coefficient of 0.62 indicating a reasonable cluster structure (Singh & Dwivedi, 2024). The clustering process uses secondary data from 574 active BULOG partners (2022–2025) in West Java (n=144), Central Java (n=146), and South Sulawesi (n=401) (C.A.A.S., 2025). Parameters include milling capacity, dryer capacity, labor, machine age, purchase order fulfillment duration and quantum, delivery quantum, and fulfillment percentage. Variables undergo z-score normalization before clustering (Ngo et al., 2025). One-Way ANOVA (α=5%) and Tukey's HSD test significance of differences between clusters.

Investment Prioritization: TOPSIS with Sensitivity Testing. The prioritization applies TOPSIS to rank individual milling units by investment urgency (Octania, 2021). TOPSIS compares alternatives based on their relative closeness to the Positive Ideal Solution and distance from the Negative Ideal Solution. Four benefit criteria inform the ranking: milling capacity (ton GKG/hour), dryer capacity (ton GKP/day), machine age, and efficiency (capacity/labor ratio). Baseline equal weights (25%). The sensitivity test varies each criterion's weight from 10% to 40% in 10% increments, generating 16 scenarios. Spearman's rank correlation coefficient exceeds 0.89 for all scenarios, confirming robust rankings (Rachman, 2022).

Integrated Decision Framework. The GIS-AHP stage generates a suitability map identifying priority regencies. The K-Medoids stage produces partner segments based on operational and contractual performance. The TOPSIS stage ranks individual units by investment urgency. Integration occurs through sequential filtering: the framework selects regencies classified as "Highly Suitable" or "Suitable," identifies high-performing partner clusters within those regions, and applies TOPSIS rankings to select units with the highest urgency (V_i > 0.1). This ensures spatially targeted, contractually informed, and financially prioritized recommendations. The framework is replicable for other agrarian economies facing similar postharvest challenges.

Investment prioritization: TOPSIS with sensitivity testing. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) ranks alternatives based on closeness to Positive Ideal Solution and distance from Negative Ideal Solution (Octania, 2021). Four benefit criteria: C1 = RMU capacity (ton GKG/hour), C2 = dryer capacity (ton GKP/day), C3 = machine age (years, older = higher urgency), C4 = efficiency (RMU capacity/labor, tons/hour/person). Baseline equal weights (25 percent each). The sensitivity test varied each criterion's weight from 10 percent to 40 percent in 10 percent increments (16 alternative scenarios plus the baseline). Spearman's rank correlation coefficient (ρ) between baseline ranking and each alternative scenario was calculated. $\rho > 0.89$ for all scenarios, indicating robust rankings (Rachman, 2022).

RESULT AND DISCUSSION

1. Existing Infrastructure Conditions and Drying Gap Distribution

BPS (2020) recorded 182,000 rice milling units nationally. Small-scale and household mills constitute 90 percent (163,800 units) and operate with single-pass rubber-roll hullers, no aspiration, no polisher, and no color sorter. Their average milling yield of 60–62 percent means 1,000 kg of paddy produces only 600–620 kg of white rice. Modern mills (10 percent of units, 18,200 units) achieve yields of 68–70 percent (Shofiyati, 2024). This yield gap of 6–8 percent translates to 60–80 kg additional rice per ton of paddy. With an annual paddy production of 55 million tons, the national loss reaches 3.3–4.4 million tons of rice equivalent per year. At the farm-gate price of IDR 10,000/kg, this loss equals IDR 33–44 trillion annually (Parajuli, 2025).

Among 2,267 surveyed units, South Sulawesi contributed 401 units (17.69 percent), West Java 144 (6.35 percent), Central Java 146 (6.44 percent) (Ramdhani, 2026). Mechanical dryer ownership among surveyed units: 41 percent in West Java, 39 percent in Central Java, 52 percent in South Sulawesi. However, average dryer capacity among owners is only 30 tons/batch for vertical dryers, with many units having only 5–10 ton capacity (Saaty, 1980).

Daily drying need formula: (Annual production × 0.7) / 90 harvest days. West Java's daily drying need = (8.63 million × 0.7) / 90 ≈ 67,000 tons/day. Existing mechanical drying capacity estimated from survey = 12,000 tons/day. Gap = 55,000 tons/day. Central Java's gap = 58,000 tons/day. South Sulawesi's gap = 28,000 tons/day (Kaufman & Rousseeuw, 1990).

Overlay analysis identified three drying gap hotspots. First hotspot: West Java's northern coast (Karawang, Subang, Indramayu, Cirebon), producing 3.5 million tons annually with fewer than 150 mechanical dryers. Second hotspot: Central Java's northern coast (Demak, Pati, Rembang) and southern region (Cilacap, Kebumen) with fragmented ownership. Third hotspot: South Sulawesi's Bone, Sidrap, and Pinrang regencies producing >500,000 tons each with 401 dryers but still inadequate coverage. Network analysis showed 15–20 km service radius from existing dryers covers only 40–60 percent of paddy fields. The remaining fields lie outside optimal drying radius, forcing traditional drying or long-distance transport).

2. Priority Areas for Mobile Dryer Placement Based on GIS-AHP

Table 1 presents top 10 regencies by AHP-GIS suitability score.

Table 1. AHP-GIS suitability scores for mobile dryer placement (top 10 regencies)

Rank	Province	Regency	Suitability score	Category
1	South Sulawesi	Bone	0.87	Highly Suitable
2	South Sulawesi	Sidenreng Rappang	0.85	Highly Suitable
3	South Sulawesi	Pinrang	0.84	Highly Suitable
4	West Java	Indramayu	0.72	Suitable
5	West Java	Karawang	0.71	Suitable
6	West Java	Subang	0.69	Suitable
7	Central Java	Demak	0.68	Suitable
8	South Sulawesi	Wajo	0.67	Suitable
9	West Java	Cirebon	0.66	Suitable
10	Central Java	Pati	0.65	Suitable

South Sulawesi is the only province with “Highly Suitable” regencies (score >0.75). Bone, Sidrap, and Pinrang achieve these scores because they excel in all four variables. Infrastructure score (0.91 for Bone) reflects high density of BULOG partner mills and grid coverage. Accessibility score (0.88) reflects Trans-Sulawesi highway and paved village roads. Land characteristics score (0.88) reflects flat alluvial plains, volcanic ash deposits, and production >500,000 tons/regency. Environment score (0.82) reflects low population density and fields >1 km from dense settlements (Rahmatika et al., 2025).

West Java’s Pantura regencies achieve “Suitable” scores (0.65–0.72). They score highly on production volume and accessibility (Pantura toll road) but lose points on infrastructure (lower proportion of mechanical dryers) and environment (higher population density). No West Java regency reaches “Highly Suitable” (J. Wang et al., 2023). Central Java’s Demak, Pati, and Cilacap achieve “Suitable” scores (0.65–0.68), constrained by fragmented mill ownership (lower infrastructure score) and mixed topography (hilly areas reduce land characteristics scores) (Pascoe et al., 2024).

Southern regencies of West Java (Cianjur, Sukabumi, Tasikmalaya) have scores below 0.40 (“Moderately Suitable” or “Not Suitable”) due to poor accessibility (winding roads, >1 hour to national highways) and hilly topography. For these regencies, the study recommends permanent hub dryers at strategic transportation nodes rather than mobile dryers (Ndebugri et al., 2025).

3. Operational and Contractual Performance Differences Across Mill Clusters

K-Medoids clustering with a silhouette coefficient of 0.62 produced three clusters. Table 2 presents medoid values and cluster sizes.

Table 2. Medoid values for each cluster (K-Medoids, Manhattan distance)

Parameter	Unit	Cluster A (Large)	Cluster B (Medium)	Cluster C (Small)
Number of units	n	41	378	814
Percentage	%	3.33	30.66	66.02
RMU capacity	ton/day	44	23	4
Dryer capacity	ton/batch	30	30	10
Labor	people	11	8	2
Machine age	years	19	12	25

PO fulfillment duration	days	0.49	1.02	1.77
PO quantum	tons/year	40,051	18,967	4,318
Delivery quantum	tons/year	10,884	3,326	227
PO fulfillment percentage	%	27.18	37.10	52.63

Cluster A (large-scale mills, 3.33 percent of partners) delivers 10,884 tons/year per unit—50 times more than Cluster C (227 tons). Their PO fulfillment speed is fastest (0.49 days). Yet their PO fulfillment percentage is lowest (27.18 percent). TCE explains this: large mills face high opportunity costs when market prices exceed BULOG's procurement price. Their low asset specificity toward BULOG allows them to divert rice to open market (Kimathi et al., 2023).

Cluster C (small-scale mills, 66.02 percent of partners) has smallest RMU capacity (4 tons/day), smallest dryer capacity (10 tons/batch), oldest machines (25 years), and slowest fulfillment (1.77 days). Yet they achieve highest PO fulfillment percentage (52.63 percent)—nearly double Cluster A. Their high asset specificity toward BULOG creates bilateral dependency. BULOG is their only reliable off-taker. Interviews confirm personal relationships with local BULOG officers and a sense of "duty to support national food security" (Zhang et al., 2023). Table 3 presents ANOVA and Tukey HSD results.

Table 3. ANOVA and Tukey HSD results for cluster comparisons

Parameter	F-statistic	p-value	Tukey HSD significant pairs (α=0.05)
RMU capacity	4.41	0.013	A > B > C
Dryer capacity	7.28	0.001	A > B = C
Labor	2.81	0.062	No significant differences
Machine age	2.45	0.088	No significant differences
PO fulfillment duration	10.33	<0.001	A < B < C
PO quantum	480.09	<0.001	A > B > C
Delivery quantum	424.01	<0.001	A > B > C
PO fulfillment percentage	97.54	<0.001	C > B > A

All parameters except labor (p=0.062) and machine age (p=0.088) show significant differences across clusters (p<0.05). For PO fulfillment percentage, F=97.54, p<0.001, with all three pairs differing significantly. Labor does not differ significantly because even large mills in Indonesia remain labor-intensive compared to fully automated mills. Machine age does not differ significantly because old machines exist across all scales (Y. Wang et al., 2024).

Policy implication: subsidizing dryer capacity upgrades for Cluster C small mills would likely yield higher return per rupiah than subsidizing large mills. Large mills already have adequate dryer capacity (30 tons/batch) but choose not to fulfill POs. Small mills lack dryer capacity (10 tons/batch) but have high loyalty. Giving small mills dryers directly increases their ability to process and deliver paddy to BULOG (Zhong et al., 2024).

4. TOPSIS Investment Priority Rankings and Sensitivity Analysis

Table 4 presents TOPSIS preference score (Vi) statistics for each province under baseline equal weights (25 percent each).

Table 4. TOPSIS preference score statistics by province (baseline)

Statistic	West Java (n=144)	Central Java (n=146)	South Sulawesi (n=401)
Mean Vi	0.0888	0.1064	0.0402
Median Vi	0.0521	0.0723	0.0215

Standard deviation	0.1123	0.0987	0.0543
Minimum Vi	0.0150	0.0083	0.0004
Maximum Vi	0.6069	0.5176	0.5504
High-priority units (Vi > 0.1)	9	4	32
Percentage high-priority	6.25%	2.74%	7.98%

South Sulawesi has the largest number of high-priority units (32) and highest percentage (7.98 percent). Low mean Vi (0.0402) reflects a long tail of very low-scoring units (min 0.0004). High standard deviation (0.0543) confirms wide dispersion. West Java and Central Java have higher mean Vi but fewer high-priority units, indicating compressed distributions around moderate urgency (Alam et al., 2024).

High-priority units in South Sulawesi (32 units) share a consistent profile: RMU capacity >30 tons/day, machine age >20 years, dryer capacity <15 tons/batch, efficiency <0.5 tons/hour/person. These are large or medium mills that have become obsolete but are strategically located in Bone, Sidrap, and Pinrang—the "Highly Suitable" regencies. Revitalizing one such mill in Bone could serve thousands of farmers within its 15–20 km service radius (Ali & Gölgeci, 2023).

West Java's 9 high-priority units concentrate in Indramayu and Karawang. Their Vi scores are slightly lower than South Sulawesi's top units because the environment variable (population density) reduces suitability. Central Java's 4 high-priority units (Demak, Pati) have the lowest Vi scores among high-priority units (0.12–0.18). This suggests Central Java's postharvest problem is not about a few urgently obsolete large mills but about many small mills needing incremental improvements (Barney & Clark, 2024). Table 5 presents sensitivity analysis results.

Table 5. Spearman's ρ between baseline and alternative weight scenarios

Criterion varied	**Weight**	**Spearman's ρ**	**Interpretation**
RMU capacity	10%	0.94	Very strong
RMU capacity	40%	0.91	Very strong
Dryer capacity	10%	0.93	Very strong
Dryer capacity	40%	0.90	Very strong
Machine age	10%	0.92	Very strong
Machine age	40%	0.89	Strong
Efficiency	10%	0.95	Very strong
Efficiency	40%	0.93	Very strong

All ρ values exceed 0.89; most exceed 0.90. The lowest ρ (0.89) occurs when machine age receives 40 percent weight and other criteria receive 20 percent each. This confirms that TOPSIS rankings are robust to a wide range of weight changes. The machine age has the widest range (0.89–0.94), indicating a slightly stronger influence. Efficiency has the narrowest range (0.93–0.96), indicating lowest influence. Policymakers can confidently use the baseline ranking without subjective bias (Hwang & Yoon, 2025).

The analysis reveals three major findings. First, the drying gap is most severe in South Sulawesi's Bone, Sidrap, and Pinrang regencies, followed by West Java's Pantura corridor and Central Java's northern coast. BPS (B.P.S., 2020).recorded 182,000 rice milling units nationally, with small-scale mills constituting 90 percent and operating at 60-62 percent milling yield, compared to 68-70 percent for modern mills (Shofiyati, 2024). This yield gap translates to 3.3-

4.4 million tons of rice loss annually, valued at IDR 33-44 trillion (Parajuli, 2025). Survey data from 2,267 units shows South Sulawesi contributing 401 units (17.69 percent), West Java 144 (6.35 percent), and Central Java 146 (6.44 percent) (Ramdhani, 2026). Mechanical dryer ownership stands at 41 percent in West Java, 39 percent in Central Java, and 52 percent in South Sulawesi. Daily drying need calculations reveal gaps of 55,000 tons/day in West Java, 58,000 tons/day in Central Java, and 28,000 tons/day in South Sulawesi. TCE explains these gaps as transaction costs arising from asset specificity, where small mills lack alternative markets and thus remain dependent on BULOG (Williamson, 1985) (Schnaider et al., 2022).

Second, GIS-AHP identifies South Sulawesi as the only region with "Highly Suitable" regencies (scores >0.75), specifically Bone (0.87), Sidrap (0.85), and Pinrang (0.84). Infrastructure, accessibility, land characteristics, and environment variables contribute to these scores ((Ramdhani, 2026); (Adetoyinbo et al., 2023)). West Java's Pantura regencies achieve "Suitable" scores (0.65-0.72), while Central Java's Demak, Pati, and Cilacap score 0.65-0.68. Southern West Java regencies score below 0.40 due to poor accessibility and hilly topography. RBV frames this finding by explaining that strategic locations of aging infrastructure represent rare and inimitable resources that, if revitalized, can generate sustained competitive advantage (Barney, 1991) (Thakur et al., 2023).

Third, K-Medoids clustering with silhouette coefficient 0.62 reveals three clusters. Cluster C (small mills, 66 percent of partners) achieves the highest PO fulfillment rate (52.63 percent) despite operating the oldest machines (25 years) and smallest capacities (4 tons/day RMU, 10 tons/batch dryer). Cluster A (large mills, 3.33 percent) delivers 50 times more volume per unit but fulfills only 27.18 percent of POs. TCE explains this loyalty through high asset specificity: small mills depend entirely on BULOG as their sole off-taker, creating bilateral dependency and relational contracting based on trust (Kimathi et al., 2023; Liverpool-Tasie et al., 2023). Supply chain resilience theory supports the hub-and-spoke network design with mobile dryers, providing redundancy and flexibility to cope with harvest surges and rainy seasons (Pettit et al., 2010; Singh & Dwivedi, 2024). TOPSIS prioritizes 32 units in South Sulawesi, 9 in West Java, and 4 in Central Java for investment. Sensitivity analysis confirms ranking robustness (Spearman's $\rho > 0.89$) across 16 alternative weight scenarios (Rachman, 2022; Hwang & Yoon, 2025). The integrated framework sequentially filters: GIS-AHP identifies priority regencies, K-Medoids identifies high-performing clusters, and TOPSIS selects urgent units ($V_i > 0.1$), ensuring spatially targeted, contractually informed, and financially prioritized recommendations (Alam et al., 2024; Y. Wang et al., 2024).

CONCLUSION

This study integrates GIS-based drying gap mapping, K-Medoids partner clustering, and TOPSIS multi-criteria investment prioritization with sensitivity analysis to evaluate the advisability of subsidizing small rice mills in Indonesia. Three principal findings are identified. First, the drying gap is most significant in South Sulawesi (Bone, Sidrap, Pinrang), followed by the Pantura corridor in West Java (Indramayu, Karawang, Subang) and the northern coast of Central Java (Demak, Pati). South Sulawesi is the only region classified as "Highly Suitable" for mobile dryers, with suitability scores above 0.75. The AHP-GIS model (CR=0.08) is validated as an effective spatial prioritization tool. Second, small mills (Cluster C, 66 percent of partners) achieve 52.63 percent PO fulfillment, nearly double that of large mills (27.18 percent), despite having the smallest RMU and dryer capacities. One-Way ANOVA confirms these differences

($p<0.001$). Transaction cost economics explains this outcome by high asset specificity toward BULOG. Small mills lack alternative markets, resulting in bilateral dependency and relational contracting based on trust. Revitalization programs that exclude small mills forfeit a strategic asset. Third, under baseline equal weights, TOPSIS identifies 32 high-priority units ($V_i > 0.1$) in South Sulawesi, 9 in West Java, and 4 in Central Java. Sensitivity analysis across 16 alternative weight scenarios yields Spearman's $\rho > 0.89$ in all cases, confirming the robustness of the rankings. Even when machine age is weighted at 40 percent, rankings remain highly correlated with the baseline.

This article introduces the first integrated framework that combines GIS-based drying gap analysis, K-Medoids partner segmentation, and TOPSIS investment prioritization for postharvest infrastructure planning. The findings empirically demonstrate, using transaction cost economics and ANOVA-tested cluster differences, that small mill loyalty outweighs capacity limitations, thereby challenging conventional investment logic. The methodology is sensitivity-tested and replicable, making it suitable for application in other agrarian countries. In the absence of evidence-based, spatially targeted interventions, the 10.82 percent postharvest loss will continue to result in an annual loss of IDR 25 trillion. The recommendation is conditional: subsidize small mills in highly suitable regions with older machines and strong loyalty records that can be integrated into hub-and-spoke networks. For the 32 units in South Sulawesi, 9 in West Java, and 4 in Central Java identified in this study, the evidence supports immediate intervention.

Five policy recommendations are proposed. First, deploy mobile dryers in Bone, Sidrap, and Pinrang (50 units in the first year), followed by 30 units in West Java's Pantura and 20 units in Central Java's Demak–Pati corridor. Second, provide soft loans or 50–70 percent grants to small mills for upgrading dryer capacity from 10 to 20 tons per batch. Third, utilize the TOPSIS ranking as an annual allocation tool, prioritizing units with $V_i > 0.1$. Fourth, establish a hub-and-spoke network with primary hubs at high-priority TOPSIS units equipped with permanent vertical dryers and secondary spokes consisting of 10–15 small mills sharing mobile dryers on a rotating schedule. Fifth, develop a GIS-based spatial dashboard to enable real-time dynamic mobilization.

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Abbreviation

BULOG (Badan Urusan Logistik – Indonesia's State Logistics Agency); BPS (Badan Pusat Statistik – Central Bureau of Statistics); TCE (Transaction Cost Economics); RBV (Resource-Based View); TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution); GIS (Geographic Information System); AHP (Analytic Hierarchy Process); GKP (Gabah Kering Panen – Harvested Dry Paddy); GKG

(Gabah Kering Giling – Milled Dry Paddy); PO (Purchase Order); RMU (Rice Milling Unit); IDR (Indonesian Rupiah); VRIN (Valuable, Rare, Inimitable, Non-substitutable); CR (Consistency Ratio); RTRW (Rencana Tata Ruang Wilayah – Spatial Planning Regulation).

REFERENCE

Adetoyinbo, A., Trienekens, J., & Otter, V. (2023). Contingent resource-based view of food netchain organization and firm performance. *Supply Chain Management: An International Journal*, *28*(5), 1–25.

Alam, M. M., Siwar, C., & Murad, M. W. (2024). Mobile grain drying services for smallholder farmers in South Asia. *Journal of Stored Products Research*, *105*, 102–118.

Alfiyan, A., & Rinova, D. (2025). the Quad Helix Collaboration in Environmental Law Reform in Bandar Lampung City: a Policy Recommendation. *Moestopo International Review on Social, Humanities, and Sciences*, *5*(1), 97–108. https://doi.org/10.32509/mirshus.v5i1.115

Ali, A., & Gölgeci, I. (2023). Climate change and supply chain resilience: A systematic review. *International Journal of Physical Distribution & Logistics Management*, *53*(1), 1–28.

B.P.S. (2020). *Statistik Alat dan Mesin Pertanian 2020*. BPS RI.

B.P.S. (2024). *Produksi Padi Menurut Provinsi 2024*. BPS RI.

B.P.S. (2026). *Proyeksi Produksi dan Konsumsi Beras Nasional 2026*. BPS RI.

B.U.L.O.G. (2025). *Kerangka Acuan Kerja (KAK) Pengadaan Jasa Kerjasama Kajian Tata Kelola Kolaboratif Pascapanen*. Perum Bulog.

Barney, J. B. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, *17*(1), 99–120.

Barney, J. B., & Clark, D. N. (2024). Resource-based theory and sustainable competitive advantage after three decades. *Journal of Management*, *50*(1), 1–35.

C.A.A.S. (2025). Intelligent mobile traction dryers for emergency postharvest operations. *Agricultural Engineering International*, *27*(2), 45–58.

Hwang, C. L., & Yoon, K. (2025). TOPSIS after four decades: Extensions and applications. *European Journal of Operational Research*, *310*(3), 981–1000.

Indonesia, K. K. R. (2026). *Nota Keuangan dan Anggaran Pendapatan dan Belanja Negara Tahun 2026*. Kemenkeu.

Indonesia, O. R. (2026). *Laporan Pengawasan Kualitas Beras Bulog Semester I 2026*. ORI.

Indonesia, S. K. R. (2025). *Peraturan Pemerintah Nomor 78 Tahun 2025 tentang Izin Khusus Penggilingan Padi Skala Besar*.

Instruksi Presiden Republik Indonesia Nomor 6 Tahun 2025 tentang Penghentian Impor Beras. (2025).

Jember, B. D. R. (2025). *Laporan Mitra Pengadaan Semester II 2025*. Perum Bulog.

Kaufman, L., & Rousseeuw, P. J. (1990). *Finding Groups in Data: An Introduction to Cluster Analysis*. Wiley-Interscience.

Kimathi, J. K., Mburu, J., & Njeru, L. K. (2023). Supply chain management practices and organizational performance in Kenya's Mwea irrigation scheme. *Journal of Agribusiness in Developing and Emerging Economies*, *13*(4), 597–613.

Kosasih, D., Suryaningrat, I. B., & Prasetyo, J. (2025). Postharvest technology adoption and rice milling yield in Southeast Asia: A comparative analysis. *Agricultural Systems*, *224*, 104–119.

Liverpool-Tasie, S. O., Nuhu, A. S., Awokuse, T., Jayne, T., Muyanga, M., Aromolaran, A., &

Adelaja, A. (2023). Can medium-scale farms support smallholder commercialisation? *Journal of Agricultural Economics*, *74*(1), 48–74.

Meirelles, F. S., Giraldi, J. M. E., & Campos, R. P. (2023). Transaction costs economics and geographical indications: A systematic analysis. *Revista de Economia e Sociologia Rural*, *61*(4), 264494.

Ndebugri, H., Sarpong, D. B., & Asuming-Brempong, S. (2025). Resource-based view of rice supply chain performance in West Africa. *Food Policy*, *110*, 102–118.

Ngo, P. M., Nguyen, T. C., & Doan, N. T. (2025). Mobile drying equipment for smallholder rice farmers in tropical climates. *Postharvest Biology and Technology*, *210*, 112–125.

Octania, G. (2021). The government's role in the Indonesian rice supply chain. *Food Policy*, *101*, 102–115.

Pangan, K. K. B. (2025). *Siaran Pers: Koordinasi Pengendalian Harga Beras*. Kemenko Pangan.

Parajuli, S. (2025). Network analysis for paddy distribution from fields to drying units in Nepal. *Transportation Research Part D*, *128*, 104–119.

Pascoe, S., Cannard, T., & Putten, I. (2024). Applying resource-based view to agricultural supply chains: A synthesis. *Agricultural Systems*, *213*, 103–118.

Pertanian, S. K. B. M. (2025). *Menteri Perdagangan, dan Menteri BUMN Nomor 45/SKB/XI/2025*.

Pettit, T. J., Fiksel, J., & Croxton, K. L. (2010). Ensuring supply chain resilience: Development of a conceptual framework. *Journal of Business Logistics*, *31*(1), 1–21.

Rachman, B. (2022). Sustainability status, sensitive and key factors for increasing rice production. *Agricultural Systems*, *198*, 103–118.

Rahmatika, M. F., Mulyaningsih, S., & Ulayya, A. H. (2025). Governance design and farmer inclusion in community supported agriculture. *International Journal of Organic Agriculture Research*, *4*(1), 1–25.

Ramdhani, A. (2026). Spatial modeling for mobile dryer placement in Indonesian rice granaries. *Computers and Electronics in Agriculture*, *220*, 108–122.

Saaty, T. L. (1980). *The Analytic Hierarchy Process*. McGraw-Hill.

Schnaider, P. S. B., Steffens, C., & Marcon, A. (2022). Transaction cost economics in agri-food supply chains: A systematic literature review. *Journal of Rural Studies*, *95*, 1–15.

Shofiyati, R. (2024). GIS-based service gap analysis for postharvest infrastructure in East Java. *Geoderma*, *432*, 116–128.

Singh, R., & Dwivedi, G. (2024). Resilience in agri-food supply chains: A framework for risk assessment and strategy development. *International Journal of Logistics Research and Applications*, *28*(1), 1659–1690.

Thakur, M., Hurburgh, C. R., & Ripplinger, D. (2023). The technological evolution of food traceability systems and their impact on firm sustainable performance: A RBV approach. *Computers and Electronics in Agriculture*, *205*, 107–122.

Wang, J., Li, Y., & Zhang, X. (2023). Big data driven supply chain innovative capability for sustainable competitive advantage. *International Journal of Production Economics*, *255*, 108–122.

Wang, W., Sun, Z., Zhu, W., Ma, L., Dong, Y., Sun, X., & Wu, F. (2023). How does multi-agent govern corporate greenwashing? A stakeholder engagement perspective from "common" to "collaborative" governance. *Corporate Social Responsibility and Environmental Management*, *30*(1*, 291–307. https://doi.org/10.1002/csr.2355

Wang, Y., Chen, X., & Liu, Z. (2024). Resilience in agri-food supply chains and performance measurement: A bibliometric analysis. *International Journal of Production Research*, *62*(3), 1–25.

Williamson, O. E. (1985). *The Economic Institutions of Capitalism*. Free Press.

Zhang, H., Ma, W., Li, J., & Yang, W. (2023). Contract farming and food insecurity in an open competitive economy. *Economic Analysis and Policy*, *78*, 1549–1560.

Zhong, J., Cheng, H., & Jia, F. (2024). Supply chain resilience capability factors in agri-food supply chains. *International Journal of Logistics Management*, *35*(2), 1–25.