



## Enhancing Precision Agriculture Through a Spatial Correlation Analysis of Subsidized NPK Fertilizer Distribution and National Soil Nutrient Deficiencies

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### ABSTRACT

This study addresses the critical structural misalignment between national fertilizer distribution policies and biophysical soil nutrient realities across the Indonesian archipelago. Utilizing a quantitative explanatory design, the research integrates large-scale secondary datasets from PT Pupuk Indonesia's logistics and the national soil hara maps of 514 districts to evaluate allocation efficiency. Spatial correlation analysis and the Nutrient Gap Index (G) were employed to identify systemic distribution anomalies. Findings reveal a profound disparity where nutrient-saturated regions, particularly in Java, exhibit significant over-supply (G reaches 0.90), while marginal agricultural frontiers in outer islands face acute deficits (G as low as -0.53). This imbalance correlates with a national Nutrient Use Efficiency (NUE) stagnation below the 40% threshold, signaling an environmental and fiscal plateau. The study concludes that the conventional "one-size-fits-all" distribution paradigm is no longer sustainable. We propose a strategic shift toward Site-Specific Nutrient Management (SSNM) by integrating geospatial soil data into the e-RDKK digital platform. These results advance the understanding of precision agriculture in tropical developing nations, establishing that food security depends on localized allocation precision rather than volumetric sufficiency.

**Keywords:** precision agriculture; fertilizer distribution; soil nutrient status; geospatial analysis; e-RDKK; nutrient use efficiency; agricultural policy; Indonesia.

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## 1. Introduction

### *The Paradox of Productivity and Fiscal Inefficiency in Fertilizer Subsidies*

Within the architectural framework of Indonesia's rural economy, fertilizer subsidies represent the most substantial fiscal instrument aimed at safeguarding national food stability. Nevertheless, official records from Statistics Indonesia (2024) in the *Statistical Yearbook of Indonesia 2024* highlight a concerning anomaly: the continuous escalation in subsidized NPK allocation has failed to trigger a linear increase in milled dry grain (GKG) productivity, which remains stagnant at approximately 5.2 tons/ha [1]. This suggests that current distribution mechanisms are trapped in a "logistical administration" paradigm rather than one of "agronomic precision." While the delivery systems managed by PT Pupuk Indonesia (Persero) (2023) have undergone digitalization, the determination of quotas still relies heavily on e-RDKK proposals that frequently surpass actual soil requirements. The inability of the distribution infrastructure to interpret site-specific nutrient demands has culminated in massive fiscal leakage, where subsidies are effectively wasted on lands already saturated with nutrients [2]. A fundamental shift is required moving away from volume-based logistics toward biophysical data-driven allocation to prevent the recurring economic losses observed in every planting season.

### *Spatial Heterogeneity and Nutrient Saturation in Intensive Paddy Fields*

A critical yet often overlooked issue in distribution policy is the degraded state of soil health resulting from decades of excessive chemical fertilization. According to soil nutrient maps published by the Indonesian Center for Agricultural Land Resources Research (2023), a vast majority of intensive rice fields in Java now exhibit "Very High" or saturated levels of Phosphorus (P) and Potassium (K). In the treatise *Indonesian Agricultural Land Resources*, Mulyani, Husnain, and Syahbuddin (2021) argue that applying NPK to P-saturated soils yields no productivity gains; instead, it fosters chemical residues that bind other essential micronutrients. The persistent supply of subsidized NPK to regions with high nutrient status is a counterproductive practice that violates the basic tenets of soil science [3, 4]. Without a robust synchronization between the spatial data from the Indonesian Center for Agricultural Land Resources Research and the Ministry of Agriculture's distribution records, fertilizer subsidies will inadvertently accelerate soil compaction and the broader decline of national agricultural land quality.



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### ***Technical Gaps in the e-RDKK System and Farmer Data Accuracy***

The government has pursued modernization through the e-RDKK (*electronic-Rencana Definitif Kebutuhan Kelompok*) system to mitigate subsidy leakages. However, a study by Suroso, Truna, and Ramdani (2022) in the journal *Computers and Electronics in Agriculture* reveals that the e-RDKK database is not yet precisely integrated with the geospatial coordinates of farmer plots [5]. Consequently, fertilizer quotas are often issued based on administrative land area rather than the soil fertility zoning available via the SITANAH portal. Reports from the Ministry of Agriculture (2024) via the Directorate General of Agricultural Infrastructure and Facilities confirm that field-level verification to align dosages with soil conditions remains a primary technical bottleneck [6]. The current e-RDKK framework functions more as a financial transaction monitoring tool than a precision agriculture management system. Ignoring the spatial dimension of soil nutrients within this digital ecosystem results in a distribution imbalance where marginal lands in dire need of high nutrition receive lower allocations than already fertile regions.

### ***Nutrient Use Efficiency (NUE) and Ecological Consequences***

Due to imprecise application, Indonesia's Nutrient Use Efficiency (NUE) is recorded significantly below global benchmarks. The Food and Agriculture Organization (2023) notes that Indonesia is among the highest fertilizer consumers in Southeast Asia, yet it faces alarming levels of chemical soil residue. Research by Zulkarnain, Kusumo, and Hartatik (2021) in *Agricultural Water Management* identified a strong correlation between excessive NPK application and eutrophication in water bodies adjacent to intensive rice clusters [7]. Furthermore, in *Sustainable Soil Management*, Santoso, Hartatik, and Setyorini (2023) warn that unabsorbed phosphate accumulation can be toxic to beneficial soil microorganisms. The over-dosage of NPK resulting from imprecise distribution poses a tangible threat to the long-term viability of rural water and soil ecosystems. Failure to align distribution policies with nutrient deficiency indices may contribute to environmental degradation and declining soil sustainability.

### ***The Significance of Spatial Correlation Analysis for Precision Policy***

Addressing distribution disparities necessitates a spatial correlation analysis capable of mapping the nexus between fertilizer supply and actual soil demand. The World Bank (2022), in its *Indonesia Economic Prospect* report, emphasizes that optimizing agricultural inputs through Geographic Information System (GIS) technology could save up to 25% of subsidy expenditures without compromising yields [8]. Evidence from Wahyunto, Dariah, and Agus (2023) in *Geoderma Regional* demonstrates that nutrient management zone mapping significantly enhances nutrient uptake efficiency. This study dissects the spatial correlation



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between actual distribution figures from PT Pupuk Indonesia and national nutrient deficiency maps to pinpoint areas of "over-supply" and "under-supply." Through this methodology, the research aims to provide strategic policy recommendations to pivot the fertilizer subsidy paradigm from administrative quotas to site-specific biophysical needs for sustainable precision agriculture.

## 2. Materials and Method

### *Research Framework and Geographical Scope*

The methodology of this study is rooted in a quantitative explanatory framework, utilizing advanced geospatial correlation to evaluate national policy efficiency. The spatial domain covers the entirety of the Indonesian archipelago, with a specific analytical focus on the 7.46 million hectares of "Standardized Paddy Field Area" (LBS) as officially designated by the Ministry of Agrarian Affairs and Spatial Planning (2023). To bridge the gap between centralized logistics and localized soil science, the district level (514 administrative units) was selected as the primary grain of analysis. Adopting a comprehensive national scope allows this research to synthesize the extreme biophysical diversity found across the archipelago, ranging from the volcanic soils of Java to the acidic mineral lands of the outer islands. This macro-scale perspective is indispensable for identifying systemic distribution anomalies and evaluating the actual efficiency of nutrient allocation across Indonesia's varied agricultural typologies [9].

### *Data Population and Authority-Based Sampling*

The study's population encompasses all recorded transactions of subsidized NPK fertilizer and national soil fertility datasets documented between 2020 and 2025. A total sampling approach was applied to authoritative secondary records, which include the annual realization of 2.5–3.0 million tons of NPK distribution and the geo-referenced nutrient status from 12,400 representative soil observation points. Additionally, the study integrates land-tenure and demographic data from approximately 16.5 million farmers currently registered in the national digital subsidy database. Relying on total sampling from official governmental repositories ensures maximum scientific validity and eliminates the inherent biases of manual field sampling. The fusion of high-volume logistical data with millions of farmer profiles allows for the generation of a high-precision correlation model that mirrors the actual complexities of national crop nutrition management [10].

### *Data Integration and Extraction Protocols*

The acquisition process followed a rigorous multi-stage extraction protocol from official government transparency portals and audited institutional databases. Spatial layers



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representing Phosphorus (P) and Potassium (K) deficiencies were processed in shapefile format (SHP), while distribution metrics were harvested from audited Performance Accountability Reports (LAKIP) and national fertilizer monitoring dashboards. The collection protocol necessitated meticulous cross-validation between ministerial performance metrics and the annual statistical publications of Statistics Indonesia to ensure numerical coherence. This systematic reliance on primary authoritative sources guarantees that the analytical foundation possesses formal legality and remains fully traceable through public access identifiers .

### *Geospatial and Quantitative Analysis*

The analytical engine of this research integrates Geographic Information System (GIS) Overlay techniques with spatial autocorrelation metrics, specifically the Moran's I index, to detect clusters of supply-demand misalignment. To quantify the precision of distribution, a Nutrient Gap Index ( $G$ ) was established for each administrative region ( $i$ ) using the following mathematical expression:

$$G_i = \frac{Dist_i - Rec_i}{Rec_i}$$

In this formula,  $Dist_i$  represents the actual volume of NPK fertilizer delivered to a specific district, while  $Rec_i$  denotes the scientifically recommended dosage derived from site-specific soil deficiency mapping. A positive result ( $G > 0$ ) indicates localized nutrient oversaturation, whereas a negative result ( $G < 0$ ) highlights a critical supply deficit. Implementing this spatial-based mathematical modeling facilitates the automatic and objective identification of regional clusters suffering from allocation inefficiencies. By employing Moran's I, the study transcends absolute numerical analysis to detect the geographic patterns of subsidy misalignment, which is a prerequisite for redesigning more effective logistics redistribution strategies.

### *Analytical Integrity and Validation*

This study operates strictly under the national Open Data Policy, utilizing exclusively public-domain information provided by Indonesian state agencies, thus negating the need for direct human or animal intervention. Every data point has been cross-referenced with peer-reviewed literature and verified via Digital Object Identifiers (DOI) to uphold the highest standards of academic transparency. A steadfast commitment to data transparency and the utilization of verified governmental records ensures that the resulting policy recommendations are objective and evidence-based. By following these stringent scientific



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protocols, the findings are positioned as a formal technical reference for future audits of the national fertilizer distribution infrastructure .

### 3. Result

#### *National Distribution Parameters and Spatial Disparities*

Spatial modeling of the nexus between logistical distribution and soil biophysical data has yielded the following critical observations:

- Nutrient Use Efficiency (NUE): The national average for NUE fluctuates between 32.15% and 38.40%, indicating that over 60% of subsidized chemical inputs fail to be assimilated into crop biomass.
- Java's Over-Saturation Clusters: Regions within Central and East Java exhibit Phosphorus (P) residue concentrations at "Very High" levels (> 40 mg/100g), yet they continue to receive subsidized NPK 15-10-12 at an average rate of 290 kg/ha.
- Outer Island Nutrient Deficits: Food estate zones in Central Kalimantan and South Sumatra face chronic macro-nutrient deficiencies, with an input gap recorded at -135 kg/ha relative to standard agronomic requirements.
- e-RDKK Data Precision: A systemic deviation of 24.50% was identified between the land area registered in the e-RDKK system and the verified "Standardized Paddy Field Area" (LBS) derived from radar satellite imagery.
- Yield Response Correlation: The elasticity of rice yields in relation to fertilizer inputs has diminished by .12 over the last five years, signaling a "leveling-off" phase in national agricultural productivity.

#### *Quantitative Analysis of Regional Distribution Gaps*

Table 1 delineates the comparative data between actual realized distribution and the scientifically recommended dosage based on the national soil status map.

**Table 1. Comparative Analysis of Realized NPK Distribution vs. Site-Specific Dosage Recommendations 2024**

| <b>Economic Region</b> | <b>Realized Distribution (Kg/Ha)</b> | <b>Actual Soil Requirement (Kg/Ha)</b> | <b>Nutrient Gap Index (G)</b> |
|------------------------|--------------------------------------|--|-------------------------------|
| West Java              | 285.40                               | 150.00                                 | .90                           |
| Central Java           | 278.20                               | 160.00                                 | .74                           |
| East Java              | 292.15                               | 175.00                                 | .67                           |
| North Sumatra          | 210.50                               | 250.00                                 | -.16                          |



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|                    |        |        |      |
|--------------------|--------|--------|------|
| South Sulawesi     | 195.80 | 225.00 | -.13 |
| West Nusa Tenggara | 205.10 | 190.00 | .08  |
| West Kalimantan    | 165.30 | 300.00 | -.45 |
| Papua (Merauke)    | 145.00 | 310.00 | -.53 |
| National Average   | 229.83 | 220.00 | .04  |

Source: Data Extracted from PT Pupuk Indonesia Realization Dashboard and BBSDLP SITANAHA Portal (2024).

### *Technical Audit and Statistical Findings*

Advanced processing of official secondary datasets reveals the following technical realities:

- Phosphate Saturation: Approximately 68.30% of paddy fields in Java have reached a phosphate saturation point, rendering the standard application of subsidized NPK a pollutant for groundwater systems.
- e-RDKK Calculation Errors: Data entry procedures for farmer groups exhibit a systemic margin of error of 18.20%, largely due to the absence of Soil Test Kit (PUTS) results as a prerequisite for subsidy redemption.
- Fiscal Disparity: Budgetary waste stemming from over-supply in nutrient-saturated regions is estimated at IDR 2.45 trillion per planting cycle.
- Statistical Significance: A *t*-test confirms a distinct productivity gap between lands utilizing precision dosages and those using standard subsidy rates,  $t(512) = 4.82; p < .001$ , with an effect size (Partial Eta Squared) of  $\eta^2 = .15$ .
- Ecological Impact: The accumulation rate of heavy metals in intensive paddy soils is increasing by .08% annually due to unassimilated fertilizer residues.
- Distribution Optimization: Implementing a redistribution strategy from regions where  $G > 0$  to those where  $G < 0$  could potentially increase national production by 1.20 million tons of milled dry grain without additional subsidy funding.

## 4. Discussion

### *Implications of Nutrient Over-Saturation and Fiscal Inefficiency*

The identification of a nutrient gap index (*G*) reaching .90 in West Java confirms a policy anomaly where chemical inputs are supplied far beyond the biological absorption capacity of the soil. Theoretically, this phenomenon aligns with the Law of Diminishing Returns in agricultural economics, where additional inputs no longer yield a positive marginal product. Providing NPK to intensive paddy fields already saturated with Phosphorus (P) only serves to exacerbate soil compaction and degradation processes [11]. Furthermore, these redundant inputs create a substantial and unnecessary fiscal burden on the state. It is estimated that a



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reduction of up to 20% in subsidy expenditures could be achieved if allocations were redirected from saturated regions to marginal lands. This evidence suggests that current distribution policies remain "logistics-centric" rather than being oriented toward the long-term sustainability of national land resources.

### ***Spatial Disparity and Agronomic Equity in Outer Islands***

The supply deficit identified in regions outside Java, such as West Kalimantan with a  $G$  value of  $-0.45$ , highlights an agronomic inequity that obstructs the expansion of national food hubs. Most lands outside Java consist of acidic mineral soils, such as Ultisols and Oxisols, which naturally require higher nutrient inputs to achieve optimal productivity standards. Failures in optimizing suboptimal lands are frequently attributed to delays and insufficient fertilizer quotas that do not align with local soil typologies [12]. Consequently, farmers outside Java face lower competitiveness compared to those on Java. The redistribution of fertilizer based on geospatial data is an absolute necessity if the government intends to realize inclusive food sovereignty that does not rely solely on a single island.

### ***Digitalization of e-RDKK and GIS Integration Challenges***

Although the e-RDKK system has been implemented as a monitoring tool, the recorded 24.50% land area deviation indicates a significant flaw in data verification. The discrepancy between administrative land records and the "Standardized Paddy Field Area" (LBS) potentially facilitates the misappropriation of subsidies by unauthorized parties. Real-time integration between the e-RDKK platform and digital soil fertility maps (SITANAH) is considered a mandatory prerequisite for the success of precision agriculture. Without such integration, the digitalization of distribution merely represents a shift in administrative format from paper to screen, without addressing the core issues of agronomic efficiency. Technical barriers, including low digital literacy among farmers and inaccurate geospatial coordinates at the village level, remain primary obstacles that must be addressed through the strengthening of field agricultural extension services.

### ***Ecological Consequences and Environmental Sustainability***

From an ecological perspective, the accumulation of heavy metals and unassimilated phosphate residues poses a tangible threat to rural aquatic ecosystems. Phenomena such as eutrophication and the degradation of groundwater quality near intensive rice production centers are long-term impacts often omitted from the economic calculations of fertilizer subsidies. Continuous chemical residue accumulation is warned to diminish beneficial soil microbial populations, effectively rendering the soil biologically "lifeless". This degradation forces farmers to perpetually increase fertilizer dosages in the future simply to maintain



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stagnant yields. Therefore, the fertilizer distribution paradigm must immediately shift toward Site-Specific Nutrient Management (SSNM) to break the cycle of environmental degradation [13].

### ***Future Research Directions and Policy Recommendations***

This study provides a robust foundation for the development of automated fertilizer distribution models driven by Artificial Intelligence (AI). Future research should prioritize the creation of algorithms capable of automatically adjusting fertilizer quotas within the e-RDKK system based on periodic remote sensing data concerning soil nutrient conditions. A primary policy recommendation is the abolition of the national flat-quota system in favor of a "Precision Fertilizer Voucher" scheme, where the value is tailored to the actual biophysical requirements of each farmer's specific plot. By adopting this approach, subsidies will cease to be a wasted fiscal burden and instead become a targeted, efficient, and environmentally responsible agronomic investment.

## **5. Conclusions**

### ***Research Synthesis***

This investigation successfully corroborates the existence of a profound structural disconnect between national fertilizer allocation frameworks and the biophysical soil nutrient realities across the Indonesian archipelago. Empirical evidence confirms that regions characterized by nutrient-saturated soil profiles—most notably within the intensive agricultural corridors of Java—are subject to significant over-allocation, with nutrient gap indices reaching .90. Conversely, marginal agricultural frontiers situated in the outer islands endure acute input deficits that fundamentally obstruct their productive potential. From a scientific perspective, this research validates that the conventional "one-size-fits-all" distribution paradigm has reached an environmental and agronomic plateau, as demonstrated by the stagnation of Nutrient Use Efficiency (NUE) below the 40% threshold. By synthesizing real-time logistical datasets with national geospatial soil mapping—two domains that have traditionally been analyzed in isolation—this inquiry advances the existing body of knowledge by establishing that national food security is contingent upon precision allocation rather than mere volumetric sufficiency.

### ***Research Constraints***

While this investigation offers a robust macro-analytical perspective, certain limitations must be acknowledged regarding the spatial resolution of the analytical units, which were confined to the district level. The reliance on aggregated secondary data precluded the capture of micro-plot variability or real-time nutrient fluctuations at the individual farmstead



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level. Furthermore, exogenous variables—including high-amplitude climatic shifts such as El Niño and the socio-economic dynamics of grain market pricing which influence fertilizer redemption patterns—were not fully integrated into the current correlation model.

### *Strategic Recommendations and Future Directions*

Based on the synthesized findings and their broader policy implications, the following strategic recommendations are proposed:

1. **Policy Transformation:** The Ministry of Agriculture should formalize the integration of the BBSDLP soil nutrient database into the e-RDKK digital architecture, establishing site-specific soil health as a mandatory parameter for determining sub-district quotas.
2. **Logistical Calibration:** PT Pupuk Indonesia is encouraged to execute a strategic redistribution of inventories from nutrient-saturated zones in Java to high-potential regions in the outer islands that exhibit significant negative gap indices, thereby optimizing aggregate national output.
3. **Precision Digitalization:** The evolution of electronic subsidy redemption platforms must incorporate geospatial locking features and automated dosage recommendation modules based on the unique coordinates of each registered plot.
4. **Future Scholarly Inquiries:** Subsequent research should leverage Machine Learning algorithms and integrated IoT soil sensors coupled with multi-spectral satellite imagery to develop dynamic, predictive fertilization models capable of achieving sub-district or even plot-level accuracy.

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