

Regional nutrient budget framework for integrating livestock manure and inorganic fertilizers: a case study of Jember, Indonesia

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Abstract

Regional integration of livestock manure into inorganic fertilizer planning requires explicit accounting of crop nutrient demand, manure recoverability, nutrient retention, and plant availability. This study developed a regional nutrient budget framework for Jember Regency, Indonesia, to estimate crop nutrient demand (CND), collectable livestock manure (LM), manure-derived nutrient supply (MNS), and residual inorganic fertilizer requirement (RIFR) for nitrogen (N), phosphorus (P), and potassium (K). Regional crop and livestock data were combined with crop-specific nutrient coefficients, manure excretion rates, dry matter fractions, collection efficiencies, nutrient concentrations, retention factors, and plant-availability coefficients. The selected crops required an estimated 32,478.0 Mg N, 5,770.8 Mg P, and 26,613.6 Mg K yr⁻¹. Collectable LM was estimated at 221,268.5 Mg dry matter yr⁻¹, providing approximately 1,087.0 Mg N, 775.5 Mg P, and 2,012.2 Mg K yr⁻¹ as plant-available nutrients. Crediting these nutrients produced estimated potential reductions in inorganic fertilizer requirement of approximately 3.35% for N, 13.44% for P, and 7.56% for K. Under the enhanced manure redistribution scenario, the modeled reductions increased to approximately 5.19% for N, 20.83% for P, and 11.72% for K. Sensitivity analysis identified crop nutrient requirement coefficients and target yield as the most influential crop-side parameters, while collection efficiency and plant availability were important manure-side determinants. The framework provides a transparent and reproducible basis for nutrient-specific regional fertilizer planning; however, the estimates should be interpreted as planning values rather than field-level fertilizer recommendations, with local implementation requiring additional soil, manure, spatial, and economic information.

KEYWORDS

circular nutrient management, crop–livestock integration, livestock manure, nutrient budgeting, residual fertilizer requirement

1. INTRODUCTION

Sustaining crop productivity while improving nutrient-use efficiency remains a central challenge in intensive agricultural systems. Crop production depends on adequate nitrogen (N), phosphorus (P), and potassium (K) inputs (Ma et al., 2024), yet fertilizer management is often based on generalized recommendations rather than on explicit accounting of crop nutrient demand, nutrient supply, and locally available organic resources. Heavy dependence on inorganic fertilizers (IFs) can maintain productivity, but fertilizer inputs that are poorly synchronized with crop demand may reduce nutrient-use efficiency and increase nutrient surplus (NS) (Singh et al., 2025). Long-term field evidence has shown that crop yield and economic benefits increase only up to an appropriate N rate, whereas excessive N inputs can increase nitrate accumulation, ammonia volatilization, and nitrous oxide emissions (Li et al., 2024). Fertilizer planning therefore requires a shift from input-oriented recommendations toward nutrient accounting that distinguishes nutrient demand from the different nutrient sources available to meet that demand.

Clear conceptual separation among crop nutrient removal, crop nutrient demand, and fertilizer requirement is particularly important for nutrient-budget analysis. Crop nutrient removal refers to nutrients exported from the field in harvested products, whereas crop nutrient demand represents the amount of nutrient associated with a specified production target under the assumptions used in the accounting framework. Fertilizer requirement is a different quantity because it represents the portion of crop nutrient demand that remains to be supplied after crediting relevant nutrient sources. Within the present regional framework, crop nutrient demand (CND) is estimated from crop area, target yield, and crop-specific nutrient requirement/removal coefficients and is therefore used as a production-linked planning demand rather than a direct field fertilizer recommendation. Residual inorganic fertilizer requirement (RIFR) subsequently represents the

portion of this modeled demand remaining after manure-derived nutrient supply is credited. Because soil nutrient supply and other field-specific nutrient sources are not fully represented, RIFR should be interpreted as a regional planning estimate rather than as a complete agronomic fertilizer prescription.

Mixed crop–livestock regions provide an important opportunity to close nutrient loops through livestock manure (LM) recycling. LM contains N, P, K, secondary nutrients, micronutrients, and organic carbon and can therefore contribute to soil fertility while partially replacing IFs. Previous studies reported that partial substitution of chemical fertilizers with organic fertilizers improved crop productivity and reduced selected nutrient-loss pathways under specific soil and crop conditions (Chen et al., 2025; Han et al., 2024; Wu et al., 2024). Nevertheless, LM cannot be treated as equivalent to IFs on a simple mass basis because its fertilizer value depends on nutrient concentration, moisture content, storage conditions, decomposition stage, nutrient losses during handling, and the fraction of nutrients that becomes plant-available during the relevant cropping period. Organic N released from manure is particularly less immediate and more variable than mineral N supplied through IFs. Quantitative manure crediting therefore requires estimation not only of total manure production but also of the fraction that can be collected, retained during management, and made available to crops.

Agricultural activities in Jember are distributed across lowland, upland, and peri-urban landscapes, with food crops, estate crops, horticultural crops, and livestock production occurring within the same regional system. This spatial coexistence creates potential nutrient flows from livestock units to crop fields (Maurya et al., 2024), but such flows contribute to fertilizer planning only when manure resources and crop nutrient demand are quantified within a common accounting structure. Rice- and maize-based systems generally require substantial nutrient inputs, while horticultural and estate crops often involve more intensive nutrient management

(Zingore et al., 2022). Manure generated by cattle, goats, sheep, poultry, and other livestock can contribute organic nutrients, but its effective fertilizer value is constrained by collection efficiency, storage losses, composting practices, transport feasibility, application timing, and nutrient availability (Jayasinghe et al., 2023). Jember therefore provides a relevant crop–livestock system in which regional nutrient flows can be evaluated quantitatively rather than treating fertilizer demand and manure management as separate components.

Previous nutrient-budget approaches have provided important methods for quantifying nutrient inputs, outputs, balances, surpluses, and potential environmental losses, particularly for N (Apeh et al., 2024; Dell et al., 2022). Such approaches are valuable for identifying nutrient accumulation or depletion but do not necessarily translate recoverable manure resources directly into nutrient-specific adjustments of residual IF requirements. Likewise, plot-level manure–mineral fertilizer experiments have clarified crop responses to substitution rates, nutrient uptake, soil fertility, and environmental losses. Kadam et al. (2024), for example, demonstrated that combining manure with moderate mineral N could maintain productivity while avoiding the larger reactive N losses associated with excessive fertilizer input. Plot-scale substitution experiments, however, do not generally account simultaneously for regional livestock manure recoverability, nutrient retention during handling, first-season plant availability, spatial distribution of crop demand, and the residual fertilizer requirement after nutrient-specific manure crediting.

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The methodological contribution of the present study therefore extends beyond applying a nutrient

budget to a previously understudied location. The proposed regional nutrient budget framework (NBF) integrates five linked components within a single accounting structure: (i) crop-specific CND; (ii) collectable LM after accounting for manure production and collection efficiency; (iii) retained and first-season plant-available manure-derived nutrient supply (MNS) for N, P, and K; (iv) nutrient-specific conversion of MNS into RIFR; and (v) scenario analysis representing progressively improved manure collection, nutrient retention, and redistribution. This structure differs from nutrient-balance approaches that primarily quantify inputs, outputs, or surpluses and from substitution experiments that evaluate fixed manure–fertilizer treatments. The framework instead asks how much recoverable and plant-available manure nutrient can realistically be credited against modeled regional crop demand and how management improvements alter the remaining requirement for IFs.

This study aimed to develop and apply a regional NBF for integrating livestock manure and inorganic fertilizers in Jember, Indonesia. Specifically, the study aimed to: (i) estimate the potential plant-available supply of N, P, and K from collectable LM; (ii) quantify CND for selected crop production systems; (iii) compare MNS with CND on a nutrient-specific basis; and (iv) determine RIFR under alternative manure-recycling scenarios. The primary scientific question was: to what extent can recoverable, retained, and plant-available manure nutrients reduce nutrient-specific residual inorganic fertilizer requirements at the regional scale, and how are these reductions affected by improvements in manure collection, handling, and redistribution? We hypothesized that explicit accounting for manure recoverability, nutrient retention, and plant availability would reduce estimated RIFR in a nutrient-specific manner and that progressively improved manure management would further increase the potential manure nutrient credit. The resulting framework was intended as a regional planning tool for linking crop and livestock nutrient

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2. MATERIALS AND METHODS

2.1 Study area

This study was conducted in Jember Regency, East Java, Indonesia, a major agricultural region where crop production and livestock farming occur within the same rural landscape. The regency was selected because it represents a mixed crop-livestock system with diverse food crops, estate crops, horticultural crops, and livestock activities.

Such a production structure provides a suitable case for evaluating whether livestock manure (LM) can be quantitatively integrated into inorganic fertilizer (IF) planning. The analysis was conducted at the regency scale, with crop and livestock data aggregated from administrative units where official data were available. Jember was treated as a regional nutrient system in which crop nutrient demand (CND), manure-derived nutrient supply (MNS), nutrient surplus (NS), and residual inorganic fertilizer requirement (RIFR) were linked through a nutrient budget framework (NBF).

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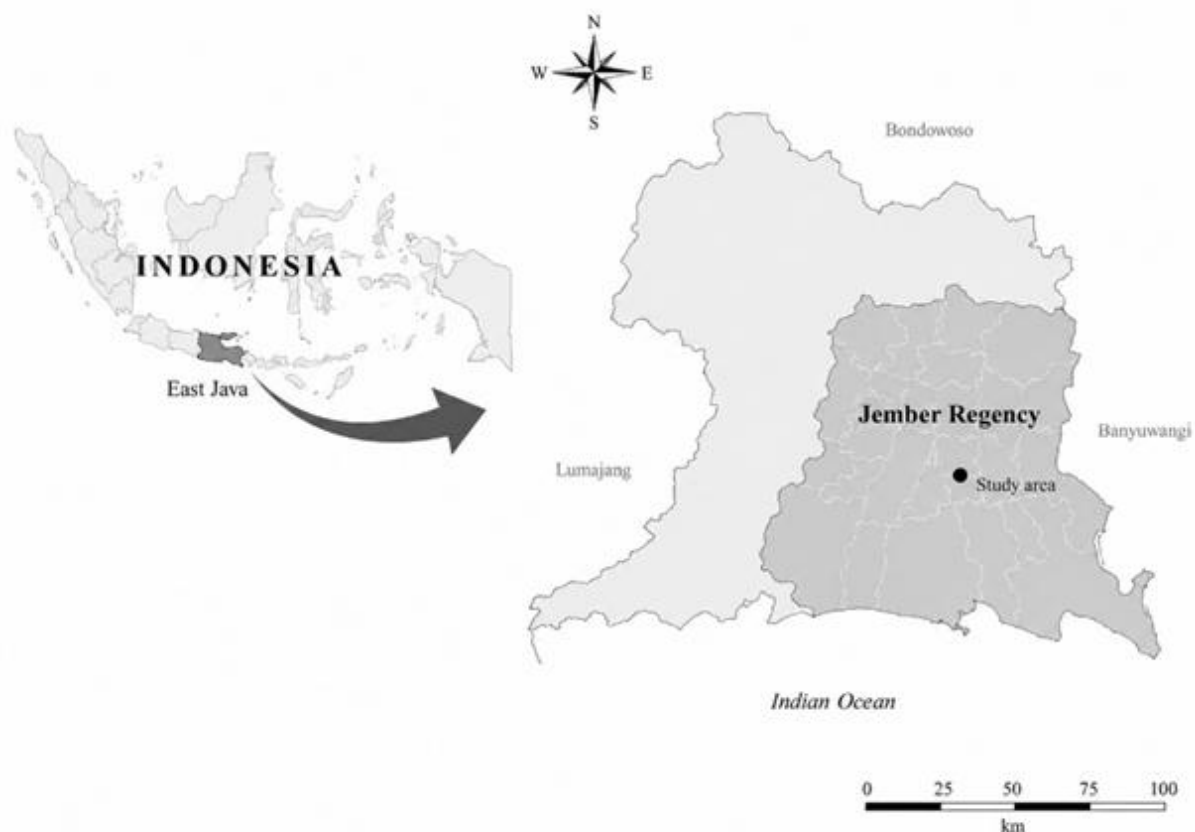


Figure 1. Location of study research Jember Regency, East Java, Indonesia

2.2 Nutrient budget framework and data sources

The study used a quantitative regional nutrient budget framework (NBF) to integrate livestock manure (LM) with inorganic fertilizers (IFs). The analytical sequence comprised four linked steps: (i) estimation of crop nutrient demand (CND) for the selected crop systems; (ii) estimation of collectable LM from the selected livestock categories; (iii) conversion of collectable LM into plant-available manure-derived nutrient supply (MNS) for nitrogen (N), phosphorus (P), and potassium (K); and (iv) calculation of the residual inorganic fertilizer requirement (RIFR) after crediting MNS. Nutrient balance (NB) and nutrient surplus (NS) were subsequently evaluated under alternative manure-recycling scenarios. This structure ensured that manure was treated as a nutrient-specific resource rather than as a uniform substitute for IFs.

The quantitative calculations reported in this revision were based on traceable secondary regional statistics and literature- or guideline-derived coefficients. Regional crop and livestock statistics were standardized to the 2024 reference year. The principal official source was Jember Regency in Figures 2025, published by BPS-Statistics Jember Regency (Catalogue No. 1102001.3509; Publication No. 35090.25001), which reports 2024 regional statistics. Variables used from official statistics included harvested area, crop production, crop productivity, and livestock population. Manure-accounting procedures were parameterized following the structure of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Chapter 10 (Eggleston et al., 2006) (Eggleston et al., 2006) together with crop- and manure-specific coefficients used in the original calculation dataset. The exact source, unit, baseline value, and analytical role of each input are summarized in Table S1.

No undocumented primary observations were used as numerical inputs to Eqs. (1)-(10) in the revised description. Consequently, the results should be interpreted as a secondary-data benchmark analysis unless a separately documented

field survey is provided. Any primary survey used in the final manuscript should report the survey period, sampling frame, sample size, locations, variables measured, data-collection instrument, and the procedure used to validate manure handling, collection, composting, or farmer fertilizer use. All inputs were harmonized before calculation. Crop area was expressed in hectares (ha), crop yield in megagrams per hectare (Mg ha^{-1}), collectable manure in megagrams of dry matter per year (Mg DM yr^{-1}), and nutrient flows in kilograms or megagrams of elemental nutrient per year ($\text{kg nutrient yr}^{-1}$ or $\text{Mg nutrient yr}^{-1}$). Fertilizer application rates were expressed in kilograms of fertilizer per hectare ($\text{kg fertilizer ha}^{-1}$). Nutrient quantities were reported as elemental N, P, and K. Values reported as P_2O_5 and K_2O were converted to elemental P and K using factors of 0.4364 and 0.8301, respectively.

2.3 Selection of crop and livestock categories

Crop categories were selected to represent the major food, estate, industrial, and horticultural systems included in the regional benchmark dataset. The selected crops were lowland rice, maize, sugarcane, cassava, tobacco, and red chili. Selection considered harvested area, production scale, economic relevance, nutrient demand, and the availability of a consistent production basis for the 2024 reference year. Each crop was treated as a nutrient-demanding unit, and CND was estimated separately for elemental N, P, and K because nutrient removal patterns and manure-derived nutrient credits differ among nutrients.

Livestock categories were selected according to population size, manure production potential, and their relevance to manure recovery in mixed crop-livestock systems. The categories comprised beef cattle, dairy cattle, goats, sheep, native chickens, broiler chickens, laying hens, and ducks. Category-specific manure excretion rates, DM fractions, collection efficiencies, nutrient concentrations, retention factors, and plant-availability factors were applied. This classification allowed the NBF to estimate collectable and plant-available manure

nutrients rather than assuming that all excreted manure was recoverable or agronomically available.

2.4 Estimation of crop nutrient demand

Crop nutrient demand was estimated for each crop and nutrient using harvested area, target yield, and nutrient requirement or nutrient removal coefficients. The target yield was derived from observed productivity or locally relevant attainable yield, depending on data availability. The CND was calculated as Eq. (1)

$$\text{CNDC}_j = \text{Ac} \times \text{Yc} \times \text{NRC}_{c,j} \quad (1)$$

Where "CNDC_j" are crop nutrient demand of crop *c* for nutrient *j* (kg nutrient yr⁻¹). *Ac* are harvested area of crop *c* (ha). *Yc* are target yield of crop *c* (Mg ha⁻¹). *NRC_{c,j}* are nutrient removal coefficient of crop *c* for nutrient *j* (kg nutrient Mg⁻¹ yield). Total crop nutrient demand (TCND) was calculated by summing CND across all selected crops Eq. (2)

$$\text{TCND}_j = \sum \text{CND}_j \quad (2)$$

Where "TCND_j" are total crop nutrient demand for nutrient *j* (kg nutrient yr⁻¹). $\sum$ "CND_j" are sum of nutrient demand from all selected crops. The CND estimation followed a nutrient removal-based budgeting approach, where nutrient demand was derived from crop yield and nutrient requirement coefficients. This approach is consistent with nutrient budget studies that compare crop nutrient demand or nutrient outputs with nutrient inputs from fertilizer and organic amendments.

2.5 Estimation of manure availability and manure-derived nutrient supply

Livestock manure availability was estimated from livestock population, manure excretion rate, dry matter fraction, and collection efficiency. The calculation distinguished total manure production from collectable manure because manure losses may occur through grazing, unmanaged disposal, scattered manure, household use, and limited collection infrastructure. The estimation of LMA

was adapted from livestock population and manure management approaches used in IPCC guidelines for manure-related nutrient and emission inventories (Eggleston et al., 2006). The LMA was calculated as Eq. (3).

$$\text{LMA}_i = \text{LP}_i \times \text{ER}_i \times 365 \times \text{DM}_i \times \text{CE}_i \quad (3)$$

Where "LMA_i" are annual collectable livestock manure from livestock category *i* (kg dry matter yr⁻¹). *LP_i* are population of livestock category *i* (head). *ER_i* = fresh manure excretion rate of livestock category *i* (kg head⁻¹ d⁻¹). 365 are number of days in one year. *DM_i* = dry matter fraction of manure from livestock category *i*. *CE_i* are manure collection efficiency of livestock category *i*. *i* are livestock category.

Manure-derived nutrient supply was estimated by converting LMA into plant-available N, P, and K. The calculation accounted for nutrient concentration, nutrient retention during storage or composting, and plant-available nutrient fraction. This approach was adapted from manure nutrient accounting methods that consider manure excretion, manure management losses, and manure nutrients available for application to managed soils (Eggleston et al., 2006). The MNS was calculated Eq. (4)

$$\text{MNS}_{i,j} = \text{LMA}_i \times \text{NC}_{i,j} \times \text{RF}_{i,j} \times \text{AF}_{i,j} \quad (4)$$

Where "MNS_{i,j}" are plant-available nutrient supply from livestock category *i* for nutrient *j* (kg nutrient yr⁻¹). *LMA_i* are annual collectable livestock manure from livestock category *i* (kg dry matter yr⁻¹). *NC_{i,j}* are nutrient concentration of nutrient *j* in manure from livestock category *i* (kg nutrient kg⁻¹ dry matter). *RF_{i,j}* are nutrient retention factor after manure storage or composting. *AF_{i,j}* are plant-availability factor of nutrient *j* during the crop growth period.

Total manure-derived nutrient supply (TMNS) was calculated by summing MNS from all livestock categories Eq. (5)

$$\text{TMNS}_j = \sum \text{MNS}_{i,j} \quad (5)$$

Where "TMNS_j" are total manure-derived nutrient supply for nutrient *j* (kg nutrient yr⁻¹). Σ "MNS_{i,j}" are sum of plant-available nutrient supply from all livestock categories. This approach avoided a direct equal-mass or equal-N substitution assumption and treated LM as a variable nutrient source whose fertilizer value depends on manure quality, handling, and nutrient availability.

2.6 Inorganic fertilizer supply, nutrient balance, and residual fertilizer requirement

Nutrient supply from IFs was estimated from fertilizer application rates and nutrient contents. The analysis included the main fertilizers used in local cropping systems, such as urea, ZA, NPK compound fertilizers, SP-36, and KCl, depending on data availability. The inorganic fertilizer nutrient supply (IFNS) was calculated as Eq. (6).

$$\text{IFNS}_{f,j} = \text{FR}_f \times \text{FC}_{f,j} \quad (6)$$

Where "IFNS_{f,j}" are nutrient supply from fertilizer type *f* for nutrient *j* (kg nutrient ha⁻¹). FR_f are application rate of fertilizer type *f* (kg fertilizer ha⁻¹). FC_{f,j} are nutrient concentration of nutrient *j* in fertilizer type *f* (kg nutrient kg⁻¹ fertilizer). *f* are fertilizer type. Total inorganic fertilizer nutrient supply (TIFNS) was calculated by summing nutrient supply from all fertilizer types Eq. (7)

$$\text{TIFNS}_j = \Sigma \text{IFNS}_{i,j} \quad (7)$$

Where "TIFNS_j" are total nutrient supply from IFs for nutrient *j* (kg nutrient ha⁻¹ or kg nutrient yr⁻¹). Σ "IFNS_{i,j}" are sum of nutrient supply from all fertilizer types. Nutrient balance was calculated by comparing nutrient inputs from TMNS and TIFNS with TCND. This calculation was adapted from the apparent nutrient surplus approach, where nutrient surplus is estimated as nutrient input minus nutrient output or demand (Gao et al., 2021; Zhu et al., 2021; Miao et al., 2023; Li et al., 2024). The NB was calculated Eq. (8)

$$\text{NB}_j = (\text{TMNS}_j + \text{TIFNS}_j) - \text{TCND}_j \quad (8)$$

Where "NB_j" are nutrient balance for nutrient *j* (kg nutrient yr⁻¹). TMNS_j are total manure-derived nutrient supply for nutrient *j* (kg nutrient yr⁻¹). TIFNS_j are total inorganic fertilizer nutrient supply for nutrient *j* (kg nutrient yr⁻¹). TCND_j are total crop nutrient demand for nutrient *j* (kg nutrient yr⁻¹). Positive NB values indicate potential NS, whereas negative NB values indicate nutrient deficit.

Residual inorganic fertilizer requirement was calculated to determine the amount of IF still needed after accounting for TMNS. The RIFR was calculated as Eq. (9)

$$\text{RIFR}_j = \text{TCND}_j - \text{TMNS}_j \quad (9)$$

Where "RIFR_j" are residual inorganic fertilizer requirement for nutrient *j* (kg nutrient yr⁻¹). TCND_j are total crop nutrient demand for nutrient *j* (kg nutrient yr⁻¹). TMNS_j are total manure-derived nutrient supply for nutrient *j* (kg nutrient yr⁻¹).

Negative RIFR values were interpreted as potential NS rather than as negative fertilizer requirements. The residual nutrient requirement was then converted into fertilizer product equivalents using fertilizer nutrient concentration Eq. (10).

$$\text{FE}_{f,j} = \frac{\text{RIFR}_j}{\text{FC}_{f,j}} \quad (10)$$

Where "FE_{f,j}" are fertilizer product equivalent required from fertilizer type *f* for nutrient *j* (kg fertilizer yr⁻¹). RIFR_j are residual inorganic fertilizer requirement for nutrient *j* (kg nutrient yr⁻¹). FC_{f,j} are nutrient concentration of nutrient *j* in fertilizer type *f* (kg nutrient kg⁻¹ fertilizer).

2.7 Manure recycling scenarios and sensitivity analysis

Scenario analysis was used to examine how progressively greater manure recovery and utilization could alter RIFR while maintaining the benchmark nutrient-accounting balance. The scenarios represented predefined planning conditions rather than solutions from a formal optimization algorithm. S0 represented baseline IF

supply without manure nutrient credit. S1 represented current collectable LM with IF adjusted to RIFR. S2 represented improved manure collection and was operationalized as an effective MNS equal to 1.25 times the S1 baseline MNS. S3 represented improved manure handling or composting with greater effective nutrient retention and was operationalized as 1.45 times baseline MNS. S4 represented enhanced manure redistribution across crop systems according to CND and RIFR and was operationalized as 1.55 times baseline MNS. The same multiplier was applied to N, P, and K within each scenario, after which nutrient-specific RIFR and NB were recalculated. These multipliers reproduce the scenario outputs reported in the Results and make the scenario calculations explicit and repeatable.

A one-at-a-time sensitivity analysis was conducted to determine how variation in major input parameters affected the NBF outputs. Each parameter was varied around its baseline value while all other parameters were held constant. The tested ranges were $\pm 15\%$ for crop nutrient requirement/removal coefficients, $\pm 10\%$ for target yield, $\pm 10\%$ for livestock population, $\pm 20\%$ for manure excretion rate, $\pm 15\%$ for DM fraction, $\pm 25\%$ for manure collection efficiency, $\pm 20\%$ for manure nutrient concentration, $\pm 15\%$ for nutrient retention factor, $\pm 25\%$ for plant-availability factor, and $\pm 20\%$ for manure redistribution efficiency. These ranges were treated as scenario perturbations for robustness testing rather than as statistical confidence intervals. Sensitivity was evaluated from the resulting changes in TCND, TMNS, RIFR, NB, and NS, allowing the analysis to identify which assumptions exerted the greatest influence on regional nutrient-budget estimates.

2.8 Data analysis and visualization

Descriptive statistics were used to summarize crop area, crop production, livestock population, LMA, CND, TMNS, RIFR, NB, and NS. Scenario comparisons were conducted by calculating absolute and percentage changes in IF requirements relative to the baseline scenario. Correlation or

regression analysis was applied when sufficient subdistrict-level data were available to evaluate relationships among livestock density, CND, MNS, and NB. Spatial visualization was performed using geographic information system software when administrative-level data were available. Maps were used to display CND, MNS, NB, and RIFR across subdistricts. The framework outputs were presented as nutrient flow tables, nutrient balance diagrams, scenario comparison graphs, and spatial distribution maps. All calculations used consistent nutrient units, and all assumptions were documented to ensure transparency and reproducibility.

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3. RESULT AND DISCUSSION

3.1 Baseline crop–livestock system, regional nutrient demand t

The benchmark crop–livestock system in Jember was characterized by the coexistence of large-scale crop production and diverse livestock populations (Table 1). Lowland rice occupied the largest harvested area, covering approximately 165,000 ha and producing 1.02 million Mg of grain annually, followed by maize with 60,000 ha and annual production of 420,000 Mg. Sugarcane generated the largest production mass among the selected estate crops, reaching approximately 1.05 million Mg yr⁻¹ from 14,000 ha, whereas cassava, tobacco, and red chili represented smaller but nutritionally distinct production systems. The livestock component was numerically dominated by poultry, particularly broiler and native chickens, while beef cattle represented the principal large-ruminant population and the largest potential source of collectable manure. This coexistence of nutrient-demanding crops and manure-producing livestock indicates substantial potential for internal nutrient recycling, although the effective fertilizer value of

manure depends on collection, handling, nutrient retention, and spatial accessibility.

Table 1. Baseline crop–livestock characteristics in Jember used for benchmark nutrient budgeting

Component	Category	Selected commodity/ livestock	Harvested area or population	Production or baseline indicator	Average yield	Analytical role in the NBF
Crop system	Food crop	Lowland rice	165,000 ha	1,020,000 Mg grain yr ⁻¹	6.18 Mg ha ⁻¹	Major driver of N, P, and K demand because of large harvested area
		Maize	60,000 ha	420,000 Mg grain yr ⁻¹	7.00 Mg ha ⁻¹	Secondary food crop with high N demand
	Estate crop	Sugarcane	14,000 ha	1,050,000 Mg cane yr ⁻¹	75.00 Mg ha ⁻¹	High biomass crop with substantial K demand
	Food/industrial crop	Cassava	6,000 ha	138,000 Mg fresh root yr ⁻¹	23.00 Mg ha ⁻¹	Root crop contributing mainly to K removal
	Estate crop	Tobacco	10,500 ha	16,800 Mg cured leaf yr ⁻¹	1.60 Mg ha ⁻¹	High-value crop with high nutrient demand per unit yield
	Horticultural crop	Red chili	3,000 ha	36,000 Mg fresh fruit yr ⁻¹	12.00 Mg ha ⁻¹	Representative horticultural crop with intensive fertilizer use
Livestock system	Ruminant	Beef cattle	285,000 head	High manure biomass potential	—	Main source of collectable livestock manure

	Small ruminant	Dairy cattle	2,500 head	High manure excretion per head	—	Localized but nutrient-rich manure source
		Goats	125,000 head	Moderate manure biomass potential	—	Important household-scale manure source
		Sheep	85,000 head	Moderate manure biomass potential	—	Complementary manure source in mixed farms
	Poultry	Native chickens	1,650,000 birds	Diffuse manure source	—	Low collection efficiency but widely distributed
		Broiler chickens	5,200,000 birds	High manure nutrient concentration	—	Important source of nutrient-dense poultry manure
		Laying hens	520,000 birds	High nutrient concentration in manure	—	Potential source of N- and P-rich manure
		Ducks	180,000 birds	Moderate manure potential	—	Minor manure source relative to chickens

Note: Values represent the finalized baseline inputs used in the regional nutrient budget analysis. Crop and livestock data were derived from the official and literature-based sources specified in the Methods and Table S1 of the parameterization section.

The estimated annual nutrient demand of the selected crops reached 32,478.0 Mg N, 5,770.8 Mg P, and 26,613.6 Mg K ([Table 2](#)). Lowland rice accounted for 62.8% of the total estimated N demand, followed by maize at 28.5%. Together, these two cereal crops represented 91.3% of regional N demand within the benchmark crop portfolio. Lowland rice also accounted for approximately 61.9% of estimated P demand and 57.5% of estimated K demand, while maize contributed approximately 29.1% and 28.4%, respectively. Their dominant contribution reflected the combined effects of large production volumes and relatively high nutrient-removal requirements. The distribution of total crop nutrient demand among the major crop groups is illustrated in [Figure 2](#). Food crops accounted for approximately 91.12% of the combined N, P, and K demand, whereas estate crops and horticultural crops contributed approximately 8.3% and 0.5%, respectively. This distribution confirms that the regional nutrient budget was strongly controlled by food-crop production,

particularly lowland rice and maize. Consequently, changes in their harvested area, target yield, or nutrient-removal coefficients would have a disproportionate influence on the total crop nutrient demand calculated for Jember.

Table 2. Estimated N, P, and K demand of selected crops in Jember based on benchmark crop production data

Selected crop	Production basis	Nutrient coefficient			Estimated demand			Share of total N demand (%)
		N (kg N Mg ⁻¹)	P (kg P Mg ⁻¹)	K (kg K Mg ⁻¹)	N (Mg N yr ⁻¹)	P (Mg P yr ⁻¹)	K (Mg K yr ⁻¹)	
Lowland rice (Mg grain yr ⁻¹)	1,020,000	20.0	3.5	15.0	20,400.0	3,570.0	15,300.0	62.8
Maize (Mg grain yr ⁻¹)	420,000	22.0	4.0	18.0	9,240.0	1,680.0	7,560.0	28.5
Sugarcane (Mg cane yr ⁻¹)	1,050,000	1.4	0.3	2.0	1,470.0	315.0	2,100.0	4.5
Cassava (Mg fresh root yr ⁻¹)	138,000	4.0	0.7	5.2	552.0	96.6	717.6	1.7
Tobacco (Mg cured leaf yr ⁻¹)	16,800	40.0	5.0	45.0	672.0	84.0	756.0	2.1
Red chili (Mg fresh fruit yr ⁻¹)	36,000	4.0	0.7	5.0	144.0	25.2	180.0	0.4
Total					32,478.0	5,770.8	26,613.6	100.0

Note: N, P, and K demand values are expressed as elemental nutrients. Crop-specific nutrient requirement/removal coefficients correspond to the finalized parameter values documented in the Methods and were applied consistently across the regional nutrient budget calculations.

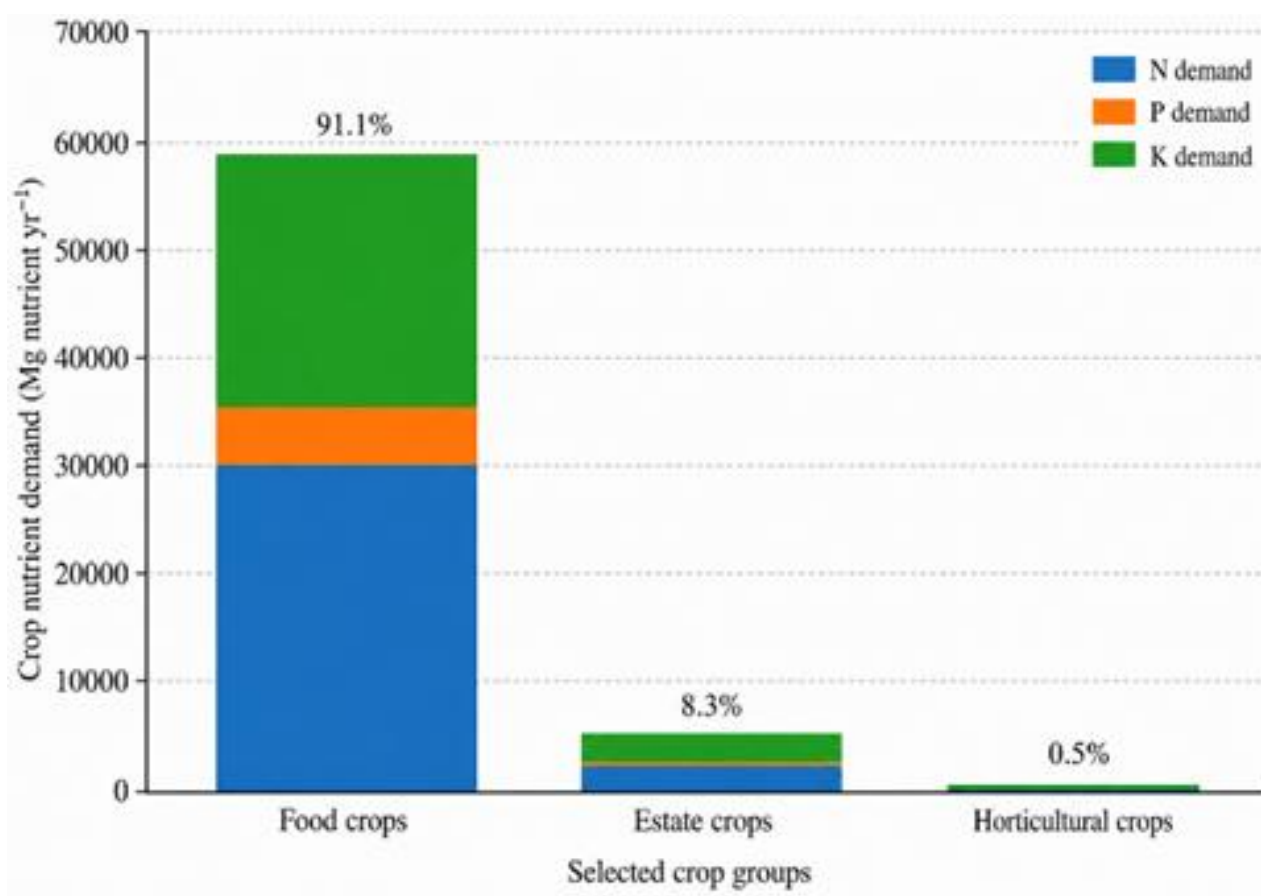


Figure 2. Contribution of selected crop groups to total CND.

The remaining crops contributed smaller but compositionally different shares of nutrient demand. Sugarcane required an estimated 1,470.0 Mg N, 315.0 Mg P, and 2,100.0 Mg K yr⁻¹, indicating a comparatively strong K requirement associated with its high biomass production. Tobacco accounted for only 2.1% of total N demand but had relatively high nutrient-removal coefficients per unit of cured-leaf production. Cassava also contributed proportionally more to K demand than to N and P demand, consistent with the substantial removal of K through harvested roots. Red chili contributed the smallest share at the regional scale because of its limited production area, although its intensive fertilizer use may remain important within localized horticultural systems. These crop-specific patterns demonstrate that regional fertilizer planning should consider not only total nutrient demand but also differences in

nutrient composition, crop distribution, and production scale.

The concentration of nutrient demand in a limited number of crops has important implications for regional nutrient management. Large cereal systems provide the greatest opportunity for reducing inorganic fertilizer use in absolute terms, but they may also create substantial nutrient surpluses when fertilizer inputs are not synchronized with crop uptake. Regional nutrient budgets are commonly used to distinguish nutrient deficits from potential surpluses by comparing inputs with crop demand or nutrient outputs (Tamagno et al., 2022). Nevertheless, the reliability of these budgets depends strongly on the quality of crop-production data, nutrient-removal coefficients, and assumptions concerning nutrient availability.

The coexistence of high crop nutrient demand and large livestock populations further emphasizes the need to evaluate manure and inorganic fertilizers within the same accounting framework. Adding manure without reducing inorganic fertilizer inputs may increase nutrient accumulation, whereas assigning manure an appropriate nutrient credit can lower residual fertilizer requirements. Previous evidence has shown that manure combined with moderate inorganic fertilizer inputs can maintain productivity while avoiding the higher nutrient losses associated with excessive mineral fertilizer application (Li et al., 2024). For Jember, the baseline crop–livestock structure therefore provides a clear basis for estimating collectable manure and plant-available manure-derived nutrients before calculating the remaining inorganic fertilizer requirement.

These results should, however, be interpreted as a regional nutrient-removal benchmark rather than as field-level fertilizer recommendations. Crop nutrient demand was estimated from production and nutrient requirement or removal coefficients and did not explicitly include soil nutrient supply, residual soil fertility, crop-residue recycling, biological N fixation, atmospheric deposition, irrigation-water inputs, or fertilizer-recovery efficiency (Bhattacharyya et al., 2021). Aggregated annual values also do not capture temporal differences between nutrient release from manure and crop nutrient uptake (Zhang et al., 2021). Site-specific fertilizer recommendations would therefore require soil testing, locally validated nutrient coefficients, and explicit consideration of nutrient availability and environmental loss pathways.

Crop nutrient demand was estimated from production and nutrient requirement or removal coefficients and did not explicitly include soil nutrient supply, residual soil fertility, crop-residue recycling, biological

N fixation, atmospheric deposition, irrigation-water inputs, or fertilizer-recovery efficiency

3.2 Manure availability, manure-derived nutrient supply

The benchmark livestock population generated an estimated 1,933,806.5 Mg of fresh manure annually, which corresponded to 221,268.5 Mg dry matter (DM) yr^{-1} of collectable livestock manure availability (LMA) after accounting for manure-specific DM fractions and collection efficiencies (Table 3). Beef cattle were the dominant source, contributing 168,520.5 Mg DM yr^{-1} or 76.16% of total collectable LMA. Broiler chickens provided the second-largest contribution at 28,470.0 Mg DM yr^{-1} or 12.87%. Goats, sheep, native chickens, laying hens, dairy cattle, and ducks individually contributed between 0.31% and 4.08%. Beef cattle and broiler chickens therefore accounted for approximately 89.03% of the estimated collectable manure resource, indicating that improvements in manure recovery from these two livestock categories would have the greatest influence on regional manure availability.

Livestock population alone did not determine the fertilizer value of manure because manure excretion rate, DM content, collection efficiency, nutrient concentration, storage retention, and first-season plant availability differed among livestock categories. The use of these correction factors is consistent with manure-accounting approaches that distinguish total manure production from the fraction that can realistically be collected and applied to agricultural land (Yu et al., 2024). This distinction is important because manure lost during grazing, unmanaged disposal, storage, or handling cannot be credited against crop fertilizer requirements (Wavhal et al., 2025). Consequently, the estimated collectable LMA represents a more operational nutrient resource than total fresh manure production.

Table 3. Estimated fresh manure production and collectable livestock manure availability by livestock category in Jember.

Livestock category	Population	Fresh manure excretion rate (kg head ⁻¹ d ⁻¹)	Dry matter fraction	Collection efficiency	Estimated fresh manure production (Mg yr ⁻¹)	Estimated collectable LMA (Mg DM yr ⁻¹)	Share of total LMA (%)
Beef cattle	285,000	15.00	0.18	0.60	1,560,375.0	168,520.5	76.16
Dairy cattle	2,500	25.00	0.16	0.75	22,812.5	2,737.5	1.24
Goats	125,000	1.20	0.30	0.55	54,750.0	9,033.8	4.08
Sheep	85,000	1.00	0.30	0.55	31,025.0	5,119.1	2.31
Native chickens	1,650,000	0.08	0.30	0.25	48,180.0	3,613.5	1.63
Broiler chickens	5,200,000	0.10	0.25	0.60	189,800.0	28,470.0	12.87
Laying hens	520,000	0.10	0.25	0.65	18,980.0	3,084.3 Mg	1.39
Ducks	180,000	0.12	0.25	0.35	7,884.0	689.9	0.31
Total					1,933,806.5	221,268.5	100.00

Note: LMA = livestock manure availability; DM = dry matter. Estimates were calculated using the finalized livestock population, manure excretion, DM fraction, and collection-efficiency parameters reported in the Methods.

The collectable manure resource supplied an estimated 1,087.0 Mg N, 775.5 Mg P, and 2,012.2 Mg K yr⁻¹ after nutrient-retention and plant-availability factors were applied ([Table 4](#)). Beef-cattle manure provided the largest amount of each nutrient, supplying 591.5 Mg N, 409.5 Mg P, and 1,375.1 Mg K yr⁻¹. It accounted for 54.42% of total manure-derived N supply. Broiler manure supplied a further 336.3 Mg N, 251.1 Mg P, and 370.3 Mg K yr⁻¹ and contributed 30.94% of total manure-derived N. Together, beef cattle and broiler chickens

therefore represented 85.36% of the estimated plant-available N derived from livestock manure. The remaining livestock categories made smaller individual contributions, although goat, sheep, native-chicken, and laying-hen manure may remain locally important where these livestock populations are spatially concentrated. The distribution of combined manure-derived N, P, and K among livestock categories is presented in [Figure 3](#). Beef-cattle manure accounted for approximately 61.3% of the combined nutrient supply, followed by broiler

manure at 24.7%. Goats contributed approximately 4.4%, laying hens 2.8%, native chickens 2.7%, sheep 2.5%, dairy cattle 1.1%, and ducks 0.5%. The greater proportional contribution of broiler manure to nutrient supply than to collectable manure mass

reflected the higher nutrient concentrations assigned to poultry manure. Thus, livestock categories producing the greatest manure biomass were not necessarily identical to those providing the highest nutrient supply per unit of manure.

Table 4. Estimated plant-available N, P, and K supply from collectable livestock manure in Jember.

Livestock category	Collectable LMA (Mg DM yr ⁻¹)	Concentration			Estimated MNS			Share of total MNS-N (%)
		N (kg kg ⁻¹ DM)	P (kg kg ⁻¹ DM)	K (kg kg ⁻¹ DM)	N (Mg N yr ⁻¹)	P (Mg P yr ⁻¹)	K (Mg K yr ⁻¹)	
Beef cattle	168,520.5	0.018	0.0045	0.012	591.5	409.5	1,375.1	54.42
Dairy cattle	2,737.5	0.020	0.0050	0.014	10.7	7.4	26.1	0.98
Goats	9,033.8	0.022	0.0060	0.016	41.7	29.3	98.3	3.84
Sheep	5,119.1	0.022	0.0060	0.016	23.7	16.6	55.7	2.18
Native chickens	3,613.5	0.030	0.0120	0.015	36.6	27.3	39.2	3.37
Broiler chickens	28,470.0	0.035	0.0140	0.018	336.3	251.1	370.3	30.94
Laying hens	3,084.3	0.038	0.0150	0.018	39.6	29.1	40.1	3.64
Ducks	689.9	0.030	0.0120	0.015	7.0	5.2	7.5	0.64
Total	221,268.5	—	—	—	1,087.0	775.5	2,012.2	100.00

Note: MNS = manure-derived nutrient supply; LMA = livestock manure availability; DM = dry matter. Estimated MNS values represent plant-available nutrient supply after considering nutrient retention and plant-availability factors. For this benchmark calculation, ruminant manure was assumed to have lower first-season N availability than poultry manure, while P and K were assumed to have relatively higher availability than organic N.

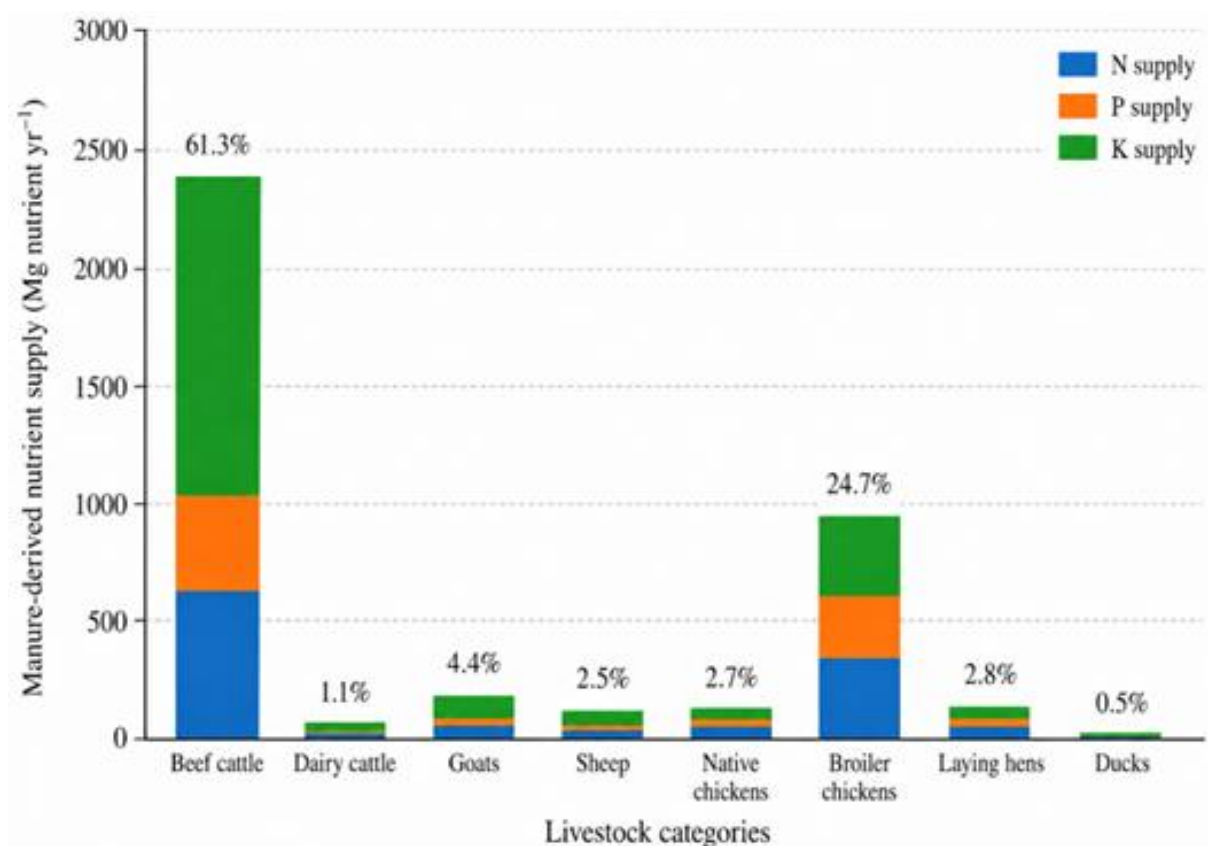


Figure 3. Relative contribution of livestock categories to the combined manure-derived N, P, and K supply in Jember.

The nutrient profile of the collectable manure was dominated by K, followed by N and P. Potassium represented approximately 51.9% of the combined plant-available N, P, and K supply, compared with 28.1% for N and 20.0% for P. This pattern partly reflected the comparatively high availability assigned to manure-derived K and P, whereas a smaller fraction of organic N was assumed to become available during the first growing season. Nitrogen in livestock manure is distributed among mineral and organic forms, and its agronomic value depends strongly on manure type, storage conditions, application timing, and mineralization (Bohoussou et al., 2023). Manure should therefore not be treated as directly equivalent to inorganic fertilizer on either a fresh-mass or total-N basis. Regional and global nutrient-budget studies likewise emphasize that manure nutrient credits

must account for recoverability and availability rather than relying solely on total excretion (Guejjoud et al., 2025). The contrasting contributions of ruminant and poultry manure have practical implications for regional nutrient recycling. Beef-cattle manure provided the largest resource because of its high total biomass, whereas broiler manure provided a disproportionately large nutrient contribution because of its higher nutrient density. Poultry manure may consequently reduce transport requirements per unit of nutrient supplied, although its concentrated N and P contents may also increase the risk of nutrient accumulation when application is not matched to crop demand. By contrast, the larger mass and lower nutrient concentration of cattle manure may create greater collection, storage, and transport constraints. Evidence from manure-amendment studies

indicates that manure can partially replace mineral fertilizer, but its benefits depend on appropriate nutrient crediting and synchronized application; adding manure without reducing mineral fertilizer may instead increase nutrient surpluses and reactive N losses (Ren et al., 2022).

The concentration of manure resources in a few livestock categories provides a practical entry point for manure–fertilizer integration in Jember. Collection infrastructure and nutrient testing could initially prioritize beef-cattle and broiler production systems because these categories dominated both collectable manure mass and manure-derived nutrient supply (Oyedun et al., 2025). However, regional availability does not ensure that manure nutrients are accessible to crops with the greatest demand. Transport distance, manure-processing capacity, seasonal application opportunities, and the spatial relationship between livestock-producing areas and crop fields must also be considered. Uncertainty remains substantial because livestock populations, excretion rates, DM fractions, nutrient concentrations, collection efficiencies, retention factors, and plant-availability coefficients were not measured consistently across all livestock systems. Although the parameters were finalized for the present regional analysis, their transfer to farm-level fertilizer recommendations remain subject to local variation in manure handling, nutrient composition, storage conditions, and spatial accessibility. Site-specific implementation would therefore benefit from complementary field surveys and manure laboratory analyses.

3.3 Nutrient balance, residual inorganic fertilizer requirement

The nutrient-balance results demonstrated that explicitly crediting manure-derived nutrients substantially affected the estimated inorganic fertilizer requirement (Table 5). Under the baseline condition, crop nutrient demand was assumed to be supplied entirely by inorganic fertilizers, corresponding to annual inputs of 32,478.0 Mg N, 5,770.8 Mg P, and 26,613.6 Mg K. Because inorganic fertilizer supply was set equal to the

estimated crop nutrient demand, the calculated nutrient balance was zero by definition. This condition therefore served as a reference for regional fertilizer planning rather than representing an observed regional nutrient balance. The manure-added condition without inorganic fertilizer adjustment retained the full baseline inorganic fertilizer input while adding the estimated plant-available nutrients from collectable manure. This condition generated potential surpluses of 1,087.0 Mg N, 775.5 Mg P, and 2,012.2 Mg K yr⁻¹. These surpluses were numerically equivalent to the estimated manure-derived nutrient supply because no reduction in inorganic fertilizer input was made. The result indicates that manure recycling alone does not necessarily improve nutrient-use efficiency when manure-derived nutrients are added in addition to existing fertilizer inputs. Failure to account for these nutrients may instead increase nutrient accumulation and the potential for losses to air and water. Nutrient-budget studies similarly emphasize the importance of evaluating nutrient inputs relative to crop removal or demand because persistent positive balances may indicate inefficient nutrient use and greater environmental pressure (Ali et al., 2024; Zhang et al., 2026).

Under the manure-credit adjustment condition, manure-derived nutrient supply was deducted from crop nutrient demand before the residual inorganic fertilizer requirement was calculated. The resulting inorganic fertilizer requirements were 31,391.0 Mg N, 4,995.3 Mg P, and 24,601.4 Mg K yr⁻¹. These adjustments reduced the estimated inorganic nutrient requirement by 3.35% for N, 13.44% for P, and 7.56% for K while maintaining a calculated nutrient balance of zero. The greater proportional reductions for P and K reflected the larger contribution of manure-derived nutrients relative to their respective crop demands. By contrast, the smaller reduction in N indicated that manure supplied a comparatively limited proportion of regional N demand, partly because only a fraction of manure N was assumed to become plant-available during the modeled growing period.

Table 5. Nutrient balance under baseline and manure-integrated conditions

Nutrient	Management condition	Total CND	MNS credit	IF nutrient supply	Total nutrient input	Nutrient balance	Balance status	IF reduction relative to baseline
N	Baseline	32,478.0	0.0	32,478.0	32,478.0	0.0	Balanced by IF input	0.00%
	Manure added without IF adjustment	32,478.0	1,087.0	32,478.0	33,565.0	+1,087.0	Potential N surplus	0.00%
	Manure-credit adjustment	32,478.0	1,087.0	31,391.0	32,478.0	0.0	Balanced after manure credit	3.35%
P	Baseline	5,770.8	0.0	5,770.8	5,770.8	0.0	Balanced by IF input	0.00%
	Manure added without IF adjustment	5,770.8	775.5	5,770.8	6,546.3	+775.5	Potential P surplus	0.00%
	Manure-credit adjustment	5,770.8	775.5	4,995.3	5,770.8	0.0	Balanced after manure credit	13.44%
K	Baseline	26,613.6	0.0	26,613.6	26,613.6	0.0	Balanced by IF input	0.00%
	Manure added without IF adjustment	26,613.6	2,012.2	26,613.6	28,625.8	+2,012.2	Potential K surplus	0.00%
	Manure-credit adjustment	26,613.6	2,012.2	24,601.4	26,613.6	0.0	Balanced after manure credit	7.56%

Note: CND = crop nutrient demand; MNS = manure-derived nutrient supply; IF = inorganic fertilizer. Values are expressed as Mg elemental nutrient yr⁻¹. “Baseline” assumes that CND is supplied entirely by IFs without manure credit. “Manure added without IF adjustment” retains the baseline IF input while adding MNS, thereby indicating the potential nutrient surplus if manure nutrients are not credited. “Manure-credit adjustment” subtracts MNS from CND to determine the residual IF requirement.

Table 6. Residual inorganic fertilizer requirement and fertilizer product equivalents after manure nutrient credit.

Nutrient	Total CND	MNS credit	RIFR after manure credit	Fertilizer product equivalent	Nutrient content used for conversion	Baseline product requirement without manure credit	Product requirement after manure credit	Potential product reduction	Reduction from baseline
N (Mg N yr ⁻¹)	32,478.0	1,087.0	31,391.0	Urea	46% N	70,604.3 Mg urea yr ⁻¹	68,241.3 Mg urea yr ⁻¹	2,363.0 Mg urea yr ⁻¹	3.35%
P (Mg P yr ⁻¹)	5,770.8	775.5	4,995.3	SP-36	36% P ₂ O ₅ = 15.71% P	36,732.4 Mg SP-36 yr ⁻¹	31,795.9 Mg SP-36 yr ⁻¹	4,936.4 Mg SP- 36 yr ⁻¹	13.44%
K (Mg K yr ⁻¹)	26,613.6	2,012.2	24,601.4	KCl	60% K ₂ O = 49.81% K	53,434.5 Mg KCl yr ⁻¹	49,394.4 Mg KCl yr ⁻¹	4,040.1 Mg KCl yr ⁻¹	7.56%

Note: RIFR = residual inorganic fertilizer requirement. The fertilizer product equivalents are benchmark calculations based on single-source fertilizer conversion: urea for N, SP-36 for P, and KCl for K. If actual fertilizer practice uses compound NPK fertilizers, ZA, or mixed fertilizer sources, product equivalents should be recalculated to avoid double counting of nutrient inputs.

The residual nutrient requirements were subsequently converted into single-fertilizer product equivalents, as presented in [Table 6](#). Without manure nutrient credit, the estimated regional requirements were equivalent to 70,604.3 Mg urea, 36,732.4 Mg SP-36, and 53,434.5 Mg KCl yr⁻¹. After manure-derived nutrients were credited, the corresponding requirements declined to 68,241.3 Mg urea, 31,795.9 Mg SP-36, and 49,394.4 Mg KCl yr⁻¹. The resulting potential annual reductions were 2,363.0 Mg urea, 4,936.4 Mg SP-36, and 4,040.1 Mg KCl. These estimates indicate that even a relatively modest manure contribution at the regional scale can translate into substantial reductions in fertilizer-product requirements when nutrient credits are incorporated systematically into fertilizer planning.

The nutrient-specific pattern further indicates that manure should not be represented by a uniform substitution ratio across N, P, and K. Manure-derived P and K contributed larger proportions of

regional demand than manure-derived N, meaning that fertilizer adjustment based solely on N could lead to excessive P or K inputs. This risk is particularly relevant where manure is repeatedly applied near livestock-producing areas without accounting for crop-specific nutrient requirements. Previous experimental evidence has shown that moderate manure substitution can maintain crop productivity while reducing dependence on synthetic fertilizers, whereas manure application without corresponding mineral-fertilizer adjustment may increase nutrient surpluses and reactive N losses (Hidalgo et al., 2025; Oyebiyi et al., 2026). Manure should therefore be credited separately for each nutrient rather than treated as a single undifferentiated fertilizer input. The manure-added condition without inorganic fertilizer adjustment increased total nutrient input above the estimated crop demand, whereas the manure-credit adjustment condition maintained the calculated nutrient balance by reducing inorganic fertilizer

inputs according to manure-derived nutrient credits. This distinction is important for circular nutrient management because the potential environmental benefit of manure recycling may be diminished when mineral fertilizer inputs remain unchanged. The regional NBF therefore provides a transparent mechanism for translating manure availability into nutrient-specific fertilizer adjustments and for identifying conditions under which potential nutrient surpluses may arise.

3.4 Scenario-based manure fertilizer optimization

The scenario analysis showed a progressive reduction in residual inorganic fertilizer requirement as manure collection, nutrient retention, and redistribution were improved (Table 7). Under the baseline scenario (S0), manure-derived nutrient supply was not credited, and the entire estimated crop nutrient demand was supplied by inorganic fertilizers. This resulted in residual requirements of 32,478.0 Mg N, 5,770.8 Mg P, and 26,613.6 Mg K yr⁻¹, which served as the reference condition for comparison with the manure-integrated scenarios. Under S1, current collectable manure was credited and inorganic fertilizer supply was adjusted to the residual inorganic fertilizer requirement. The resulting manure nutrient credits were 1,087.0 Mg N, 775.5 Mg P, and 2,012.2 Mg K yr⁻¹, reducing the residual inorganic fertilizer requirements to 31,391.0 Mg N, 4,995.3 Mg P, and 24,601.4 Mg K yr⁻¹. Relative to S0, the nutrient-specific reductions were 3.35% for N, 13.44% for P, and 7.56% for K, while the combined reduction across the three nutrients was 5.97%. S1 therefore represented the current manure-credit condition without assuming additional improvements in collection, handling, or redistribution.

Improved manure collection efficiency under S2 increased the effective manure-derived nutrient credits to 1,358.8 Mg N, 969.4 Mg P, and 2,515.3 Mg K yr⁻¹. The corresponding residual inorganic fertilizer requirements declined to 31,119.2 Mg N,

4,801.4 Mg P, and 24,098.3 Mg K yr⁻¹, equivalent to reductions of approximately 4.18% for N, 16.80% for P, and 9.45% for K relative to S0 and an overall reduction of 7.47%. The transition from S1 to S2 indicated the importance of manure recovery because uncollected manure cannot contribute to fertilizer adjustment. Further improvement in manure handling, storage, or composting under S3 increased the effective nutrient credits to 1,576.2 Mg N, 1,124.5 Mg P, and 2,917.7 Mg K yr⁻¹. Residual inorganic fertilizer requirements consequently decreased to 30,901.8 Mg N, 4,646.3 Mg P, and 23,695.9 Mg K yr⁻¹, corresponding to reductions of 4.85%, 19.49%, and 10.96% for N, P, and K, respectively, and an overall reduction of 8.66%. These results indicated that the fertilizer value of manure depended not only on the quantity recovered but also on nutrient retention during storage and handling. Poor handling can reduce manure nutrient credit through ammonia volatilization, leaching, runoff, or uncontrolled decomposition, whereas improved composting and protected storage may increase the amount of nutrients retained for subsequent field application (Oyedun et al., 2025).

Enhanced manure redistribution under S4 produced the largest modeled reduction in inorganic fertilizer requirement among the predefined scenarios. Effective manure-derived nutrient supply reached 1,684.9 Mg N, 1,202.0 Mg P, and 3,118.9 Mg K yr⁻¹, while the respective residual inorganic fertilizer requirements declined to 30,793.1, 4,568.8, and 23,494.7 Mg yr⁻¹. Relative to S0, these values represented reductions of 5.19% for N, 20.83% for P, and 11.72% for K, with an overall reduction of 9.26%. This scenario assumed more effective allocation of manure nutrients toward crop systems with unmet nutrient demand, thereby reducing nutrient mismatch relative to less coordinated allocation. S4 should therefore be interpreted as an enhanced redistribution scenario for comparative planning rather than as a mathematically optimized solution.

Table 7. Comparison of manure recycling and inorganic fertilizer adjustment scenarios

Scenario	Scenario description	Effective MNS			RIFR			Overall IF nutrient reduction (%)	Nutrient balance status	Scenario interpretation
		N	P	K	N	P	K			
S0	Baseline IF use without manure nutrient credit	0.0	0.0	0.0	32,478.0	5,770.8	26,613.6	0.00	Nutrient demand fully supplied by IFs	Reference scenario; no manure nutrient credit
S1	Current collectable LM use with IF adjusted to RIFR	1,087.0	775.5	2,012.2	31,391.0	4,995.3	24,601.4	5.97	Balanced after manure nutrient credit	Current manure-credit condition; modest IF reduction, especially for P and K
S2	Improved LM collection efficiency with IF adjusted to RIFR	1,358.8	969.4	2,515.3	31,119.2	4,801.4	24,098.3	7.47	Balanced after improved manure recovery	Greater manure recovery increased nutrient credit; redistribution remains important
S3	Improved LM handling or composting with higher nutrient retention and IF adjusted to RIFR	1,576.2	1,124.5	2,917.7	30,901.8	4,646.3	23,695.9	8.66	Balanced under adjusted IF use	Improved nutrient retention further reduced RIFR; uniform application may still increase local P and K

										accumulation risk
S4	Enhanced manure redistribution based on CND and RIFR	1,68 4.9	1,20 2.0	3,11 8.9	30,79 3.1	4,56 8.8	23,49 4.7	9.26	More balanced nutrient allocation	Largest modeled IF reduction among predefined scenarios; lower nutrient mismatch risk

Note: Values are expressed as Mg elemental nutrient yr⁻¹. MNS = manure-derived nutrient supply; RIFR = residual inorganic fertilizer requirement; IF = inorganic fertilizer; LM = livestock manure; CND = crop nutrient demand. The total CND used in the regional calculation was 32,478.0 Mg N yr⁻¹, 5,770.8 Mg P yr⁻¹, and 26,613.6 Mg K yr⁻¹. The overall IF nutrient reduction was calculated from the total manure nutrient credit relative to total N, P, and K demand

The scenario results also revealed a consistent nutrient-specific pattern. Manure integration produced the greatest proportional reduction in P requirements, followed by K and N. This pattern reflected the relatively large manure-derived P and K credits compared with regional demand and the lower first-season availability assumed for manure N. Consequently, manure could not substitute for N, P, and K at a uniform rate. Fertilizer adjustment based solely on the N contribution of manure may leave substantial P and K inputs unaccounted for, thereby increasing the risk of nutrient accumulation under repeated application. Nutrient-specific accounting is therefore essential when manure is combined with urea, phosphate fertilizers, KCl, or compound NPK products (Li et al., 2025). The progression from S1 to S4 further indicated that manure recycling was constrained sequentially by collection, handling, and redistribution. Collection determined how much manure entered the nutrient-recycling system, handling affected how much nutrient content was retained, and redistribution determined whether those nutrients reached crop systems with corresponding demand. These components are complementary rather than interchangeable. Increasing collection without

improving storage may increase the mass of manure recovered without a proportional increase in effective nutrient value (Feng et al., 2023), whereas improving nutrient retention without appropriate allocation may intensify local P and K surpluses. Consistent with previous experimental evidence, the present results indicate that the benefits of manure-mineral fertilizer integration depend on adjusting mineral fertilizer inputs according to manure-derived nutrient credits (Ren et al., 2022).

The predefined scenarios also provide a practical sequence for regional intervention. The current manure nutrient credits represented by S1 could be incorporated into fertilizer planning using the existing collectable manure resource. Improvements in collection systems would support movement toward S2, whereas covered storage, composting facilities, and improved manure handling would be required to approach the conditions represented by S3. Implementation of S4 would additionally require spatial information on crop nutrient demand, manure supply, transport feasibility, and nutrient balances across subdistricts. This scenario therefore represents an enhanced decision-support condition for matching nutrient sources with spatially distributed crop demand

rather than a formal optimization outcome. Such spatial coordination is particularly relevant where manure availability and crop nutrient demand are geographically disconnected (Zhang et al., 2021).

3.5 Sensitivity, uncertainty, practical implications

The sensitivity analysis identified crop-side parameters as the dominant sources of variation in the regional nutrient budget framework (Table 8). Using the S1 current manure-credit scenario as the reference condition, total crop nutrient demand (CND), manure-derived nutrient supply (MNS), and residual inorganic fertilizer requirement (RIFR) were 64,862.4, 3,874.7, and 60,987.7 Mg nutrient yr⁻¹, respectively. A ±15% perturbation in crop nutrient requirement coefficients changed total RIFR by approximately ±9,729.4 Mg yr⁻¹, whereas a ±10% perturbation in target yield changed RIFR by approximately ±6,486.2 Mg yr⁻¹. These were the largest modeled responses among the tested parameters, indicating that uncertainty in crop nutrient demand propagates strongly into estimates of regional fertilizer requirement. The effect was

particularly relevant for rice and maize because these crops accounted for the largest share of regional nutrient demand.

Among manure-side parameters, collection efficiency and the plant-availability factor produced the largest changes in effective MNS, with modeled deviations of approximately ±968.7 Mg yr⁻¹ under the tested ±25% perturbations. Manure excretion rate, manure nutrient concentration, and redistribution efficiency produced changes of approximately ±774.9 Mg yr⁻¹ under ±20% perturbations, whereas livestock population, dry-matter fraction, and nutrient-retention factor produced smaller responses within their specified ranges. These results indicate that the fertilizer credit assigned to manure depends not only on livestock population but also on how much manure is recoverable and how much of its nutrient content is retained and becomes available to crops. This interpretation is consistent with evidence that manure recovery, nutrient composition, handling, and first-season availability strongly influence the agronomic value of manure (Álvarez Salas et al., 2024; Mancho et al., 2023).

Table 8. One-at-a-time sensitivity analysis of key parameters used in the regional nutrient budget framework

Parameter tested	Reference condition/ value	Sensitivity range	Primary affected output	Estimated lower output	Estimated upper output	Change from reference	Sensitivity level	Interpretation for the NBF
Crop nutrient requirement coefficient	Final crop-specific coefficient (100%)	−15% to +15%	Total CND and RIFR	55,258.3 Mg RIFR yr ⁻¹	74,717.1 Mg RIFR yr ⁻¹	±9,729.4 Mg yr ⁻¹	Very high	Crop-specific nutrient coefficients exerted the largest influence on estimated fertilizer requirement .

Target crop yield	Reference yield used in CND calculation	−10% to +10%	Total CND and RIFR	54,501.5 Mg RIFR yr ^{−1}	67,473.9 Mg RIFR yr ^{−1}	±6,486.2 Mg yr ^{−1}	Very high	Yield variation strongly affected total nutrient demand, particularly for rice and maize.
Livestock population	Reference livestock population	−10% to +10%	Total MNS and RIFR	3,487.2 Mg MNS yr ^{−1}	4,262.2 Mg MNS yr ^{−1}	±387.5 Mg yr ^{−1}	Mode rate	Livestock population affected manure nutrient credit, but less strongly than crop-side parameters.
Manure excretion rate	Reference ER by livestock category	−20% to +20%	Total LMA, MNS, and RIFR	3,099.8 Mg MNS yr ^{−1}	4,649.6 Mg MNS yr ^{−1}	±774.9 Mg yr ^{−1}	High	Variation in ER altered manure availability and MNS, particularly for livestock categories contributing large manure quantities.
Dry matter fraction	Reference DM fraction by manure type	−15% to +15%	Collectable LMA and MNS	3,293.5 Mg MNS yr ^{−1}	4,455.9 Mg MNS yr ^{−1}	±581.2 Mg yr ^{−1}	Mode rate	DM variation affected conversion from fresh manure to dry manure and therefore estimated nutrient supply.

Manure collection efficiency	Reference collection efficiency	−25% to +25%	Collectable LMA, MNS, and RIFR	2,906.0 Mg MNS yr ^{−1}	4,843.4 Mg MNS yr ^{−1}	±968.7 Mg yr ^{−1}	High	Collection efficiency strongly affected the quantity of manure entering the nutrient-credit calculation.
Manure nutrient concentration	Reference N, P, and K concentrations	−20% to +20%	MNS-N, MNS-P, MNS-K, and RIFR	3,099.8 Mg MNS yr ^{−1}	4,649.6 Mg MNS yr ^{−1}	±774.9 Mg yr ^{−1}	High	Nutrient concentration directly affected manure-derived nutrient supply; local manure analyses would further refine site-specific application.
Nutrient retention factor	Reference retention factor after handling	−15% to +15%	Effective MNS and RIFR	3,293.5 Mg MNS yr ^{−1}	4,455.9 Mg MNS yr ^{−1}	±581.2 Mg yr ^{−1}	Mode rate	Retention during storage and handling affected the amount of manure nutrient available for fertilizer credit.
Plant-availability factor	Reference first-season availability factor	−25% to +25%	Plant-available MNS and RIFR	2,906.0 Mg MNS yr ^{−1}	4,843.4 Mg MNS yr ^{−1}	±968.7 Mg yr ^{−1}	High	Plant availability strongly influenced the manure nutrient fraction that

								could be credited against IF demand.
Manure redistribution efficiency	Reference redistribution efficiency used in the model	-20% to +20%	Effective MNS utilization and local NB	3,099.8 Mg effective MNS yr ⁻¹	4,649.6 Mg effective MNS yr ⁻¹	±774.9 Mg yr ⁻¹	High	Redistribution efficiency influenced whether manure nutrients reached crop areas with corresponding nutrient demand.

Note: CND = crop nutrient demand; LMA = livestock manure availability; MNS = manure-derived nutrient supply; RIFR = residual inorganic fertilizer requirement; NBF = nutrient budget framework; ER = manure excretion rate; DM = dry matter; NB = nutrient balance. The reference condition corresponds to S1 in Section 3.4 (current collectable LM with IF adjusted to RIFR), for which total CND, MNS, and RIFR were 64,862.4, 3,874.7, and 60,987.7 Mg nutrient yr⁻¹, respectively. Sensitivity values were generated by varying one parameter at a time while holding all other parameters constant. The tested ranges are deterministic model perturbations rather than statistical confidence intervals. Sensitivity levels are descriptive rankings of the modeled response within the specified ranges.

The sensitivity analysis should be interpreted as a deterministic robustness assessment rather than a probabilistic uncertainty analysis. Each parameter was varied independently while all other inputs were held constant; therefore, the reported ranges quantify the responsiveness of the NBF to specified parameter changes and do not represent statistical confidence intervals. Interactions among uncertain parameters were not evaluated. Consequently, the ranking in [Table 8](#) reflects relative model sensitivity within the tested ranges rather than statistical significance. This distinction is important because crop nutrient coefficients, manure nutrient concentrations, collection efficiencies, nutrient retention, and first-season availability may vary spatially and seasonally.

Each parameter was varied independently while all other inputs were

held constant; therefore, the reported ranges quantify the responsiveness of the NBF to specified parameter changes and do not represent statistical confidence intervals.

For regional planning, the results identify the parameters for which improved local information would most strongly refine model outputs. Priority should be given to crop nutrient coefficients and yield estimates on the crop-demand side, and to manure nutrient concentration, collection efficiency, and plant-availability factors on the manure-supply side. These additional data would refine site-specific implementation rather than indicate that the regional dataset used in the present analysis was incomplete. The operational sequence of the framework is summarized in [Figure 4](#). Crop

nutrient demand and manure-derived nutrient supply are quantified first, after which nutrient-specific manure credits are used to calculate residual N, P, and K fertilizer requirements (Xu et al., 2026). Potential nutrient surpluses and spatial mismatch between manure production and crop demand can then be evaluated to inform collection, processing, transport, and redistribution strategies (Muntwyler et al., 2026). The framework can therefore support site-specific manure–fertilizer integration, reduced inorganic fertilizer dependence, and lower nutrient-mismatch risks, although implementation must also

consider transport costs, infrastructure, farmer adoption, and nutrient losses during storage and application.

Priority should be given to crop nutrient coefficients and yield estimates on the crop-demand side, and to manure nutrient concentration, collection efficiency, and plant-availability factors on the manure-supply side

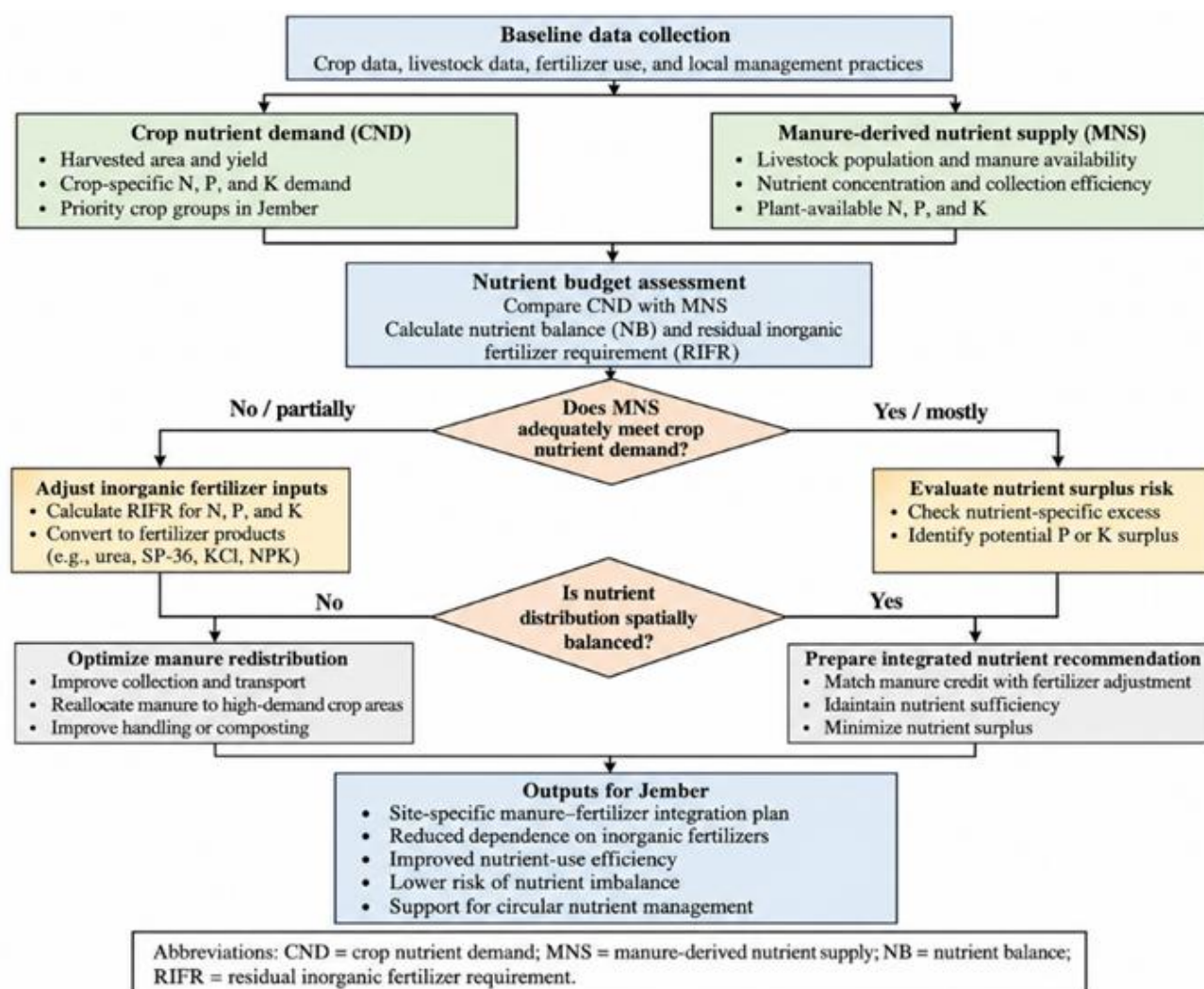


Figure 4. Decision framework for manure–fertilizer integration in Jember

4. CONCLUSION

The regional nutrient budget framework demonstrated the potential contribution of livestock manure to inorganic fertilizer planning in Jember. The selected crops required an estimated 32,478.0 Mg N, 5,770.8 Mg P, and 26,613.6 Mg K yr⁻¹, while collectable livestock manure supplied approximately 1,087.0 Mg N, 775.5 Mg P, and 2,012.2 Mg K yr⁻¹ as plant-available nutrients. Crediting these nutrients resulted in estimated reductions in inorganic fertilizer requirement of 3.35% for N, 13.44% for P, and 7.56% for K. Improved manure collection, handling, nutrient retention, and redistribution further reduced residual fertilizer requirements.

The framework provides a transparent basis for nutrient-specific manure crediting at the regional planning level; however, these outputs should not be interpreted as field-level fertilizer dosage recommendations. Their operational application requires additional validation using locally measured soil nutrient supply, manure composition, spatial crop–livestock distribution, transport constraints, and economic feasibility. Future research should therefore prioritize field validation, multi-season monitoring, and spatially explicit manure-allocation analysis to evaluate nutrient-use efficiency, logistical feasibility, and environmental trade-offs under different manure-management strategies.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Adi Septa Hidayat: Funding acquisition, Conceptualization. Wulan Triminarwati: Conceptualization, Funding acquisition, Writing – original draft, Supervision. Ratmi Rosilawati: Writing – original draft, Writing – review & editing.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The author declares no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available by request.

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