Application of Soil Analysis-Based Fertilization Technology to Improve Farmers' Productivity and Income: A Quantitative Approach in Tongowai Village, Tidore, North Maluku

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Abstract

The agricultural sector is strategic for food security and regional economic development, yet productivity in many Indonesian regions is hindered by fertilization practices that do not reflect actual soil fertility. Many farmers still apply conventional, experience-based fertilization without considering crop nutrient requirements or local soil characteristics, leading to inefficient fertilizer use and reduced land productivity. This community service program aimed to improve farmers' knowledge and capacity to implement soil analysis–based fertilization technology to increase crop productivity and farm income. The program was implemented in Tongowai Village, Tidore, North Maluku, through extension activities, technical training, field demonstrations, follow-up assistance, and introduction of soil fertility analysis as the basis for precise fertilizer recommendations. Pre–post intervention evaluation showed quantitative improvements: average farmer knowledge scores rose from 48.2 to 79.5 (an increase of 65%); average chemical fertilizer use per hectare decreased from 420 kg to 330 kg (a 21.4% reduction); and maize yield on demonstration plots increased from 3.2 t/ha to 4.1 t/ha (a 28.1% increase). Fertilizer-use efficiency (yield per kg of fertilizer) improved from 7.6 kg/kg to 12.4 kg/kg. Short-term economic impact was observed as a mean farmer income increase of 18% for participating groups in one cropping season. These results indicate that soil analysis–based fertilization can enhance farmer knowledge, reduce inefficient fertilizer inputs, and improve productivity and income in the short term. Long-term environmental and socioeconomic impacts require continued monitoring and larger-scale effectiveness studies.

Keywords: Soil Analysis, Balanced Fertilization, Agricultural Productivity, Community Service Program, Farmers' Income, Tongowai Village.

Introduction

Agricultural development remains a principal pillar for food security, rural livelihoods, and national economic growth in developing countries. In Indonesia, a large share of rural households depends on agriculture as their main source of income, so increasing agricultural productivity is essential for sustainable development. Prior studies have emphasized that productivity gains must be achieved while conserving natural resources and environmental quality (Cassman et al., 2003).

However, translating this principle into routine farming practice requires targeted, context-specific interventions that address local constraints to effective nutrient management.

Soil fertility management is a decisive factor for crop performance because soil supplies essential nutrients, water, and a supportive physical environment. Intensive land use without responsive fertility management contributes to nutrient depletion and soil degradation, undermining yield stability (Fageria et al., 2010). Empirical research has shown that balanced macro- and micronutrient availability strongly influences crop responses, yet many smallholder farmers continue to apply fertilizers using uniform, experience-based rates rather than site-specific recommendations (Duflo et al., 2008). This mismatch can generate inefficient fertilizer use, higher production costs, and persistent yield gaps.

Although the literature documents the technical benefits of soil testing and site-specific nutrient management under experimental or pilot conditions, several gaps remain. First, few studies provide rigorous, field-level evidence of technology adoption and measurable agronomic and economic outcomes among smallholders in geographically remote island contexts. Second, there is limited documentation on practical extension models that combine soil analysis, farmer training, and follow-up technical assistance to achieve measurable reductions in fertilizer inputs while increasing yields and farm income. Third, the socio-institutional barriers to sustained adoption, such as access to testing services, local adaptation of recommendations, and farmer understanding of test results, are underexamined in published community service interventions.

This community service programme responds directly to those gaps by implementing and evaluating a bundled approach, soil analysis, tailored fertilizer recommendations, hands-on training, field demonstrations, and post-training technical assistance, in Tongowai Village, Tidore, North Maluku. The novelty of this programme is threefold: (1) it tests the effectiveness of soil analysis–based fertilization under real smallholder conditions in a remote island setting; (2) it integrates quantitative pre–post measurement of knowledge, fertilizer use, yields, and short-term income to provide empirical evidence of impact; and (3) it documents an extension model designed to overcome local constraints to adoption (service access, interpretability of results, and follow-up support). These contributions aim to move beyond descriptive recommendations by delivering measurable, context-specific evidence on agronomic, economic, and adoption outcomes.

By focusing on soil analysis–based fertilization as the core intervention and evaluating measurable outcomes, this study narrows the scope from broader debates on precision agriculture and sustainable intensification to a targeted examination of how site-specific nutrient management can be operationalized for smallholders in Tongowai. The results are intended to inform both local extension practice and broader policy discussions on scaling evidence-based fertilization services in similar island and remote agricultural systems.

Figure 1. Agricultural field demonstration and observation plots utilized during the community service program in Tongowai Village, Tidore, North Maluku, Indonesia.

Literature Review

Soil Fertility Concepts in Agricultural Production Systems

Soil fertility refers to the capacity of soil to provide nutrients, water, air, and favorable environmental conditions required for plant growth and development. Soil fertility is one of the most important factors influencing agricultural land productivity. According to the Indonesian Soil Research Institute (2009), soil fertility status can be determined through the analysis of various chemical, physical, and biological soil parameters associated with nutrient availability for crops.

A fertile soil is not only characterized by adequate nutrient content but also by its ability to supply nutrients in forms that can be readily absorbed by plants. Fageria et al. (2010) explained that crop productivity is strongly influenced by the balanced availability of essential nutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and various micronutrients. Nutrient imbalances may disrupt plant growth and ultimately reduce crop yield and quality.

Tittonell et al. (2005) demonstrated that soil fertility levels can vary significantly among regions and even among individual plots within the same agricultural area. Therefore, site-specific soil fertility management has become increasingly important for improving the efficiency of agricultural input utilization and optimizing crop production.

Soil Analysis Technology as the Basis for Fertilizer Recommendations

Soil analysis is a laboratory-based assessment conducted to determine soil fertility status through the evaluation of nutrient content and other chemical properties of soil. The information obtained from soil analysis serves as a scientific basis for developing more accurate and effective fertilizer recommendations.

Figure 2. Illustration of soil sampling procedures for soil fertility assessment and fertilizer recommendation development.

Source: [Angphotorion]

Robert (2002) emphasized that effective crop nutrient management requires accurate information regarding soil conditions. Through soil analysis, farmers can identify nutrient deficiencies and excesses, enabling fertilizer applications to be adjusted according to the actual requirements of crops.

Furthermore, McBratney et al. (2005) explained that advances in modern agricultural technology have facilitated the implementation of precision fertilization systems through the utilization of soil fertility data. Such approaches contribute to improved fertilizer-use efficiency while simultaneously reducing negative environmental impacts associated with excessive fertilizer application.

Balanced Fertilization and Crop Productivity

Balanced fertilization is a nutrient management approach that applies fertilizers according to crop requirements, soil conditions, and targeted production levels. The primary objective of this approach is to ensure that all essential nutrients are available in sufficient and proportional amounts throughout the crop growth cycle.

Site-specific nutrient management significantly increases crop productivity compared with conventional fertilization practices. Their findings indicate that fertilizer recommendations based on actual field conditions can enhance fertilizer-use efficiency while simultaneously increasing agricultural output.

Similarly, Syafruddin et al. (2012) demonstrated that the appropriate selection of fertilizer types and application rates has a significant influence on plant growth and crop yield. Consequently, soil analysis represents an essential first step in designing effective fertilization strategies capable of maximizing agricultural productivity.

Precision Agriculture and Sustainable Nutrient Management

Precision agriculture is a farm management approach that utilizes site-specific information to improve the efficiency and effectiveness of agricultural input utilization. This concept has emerged as a response to the growing need to increase agricultural productivity while maintaining environmental sustainability.

Figure 3. Conceptual illustration of precision agriculture and soil analysis-based nutrient management using technology.

Source: [CropWatch]

According to Zhang et al. (2002), precision agriculture integrates various technologies that enable farmers to manage agricultural land more accurately and efficiently. Bongiovanni and Lowenberg-DeBoer (2004) further explained that the adoption of precision agriculture can enhance the efficiency of fertilizer, pesticide, water, and labor utilization, thereby improving overall farm performance.

Mulla (2013) added that advancements in remote sensing technologies and Geographic Information Systems (GIS) have expanded opportunities for implementing precision agriculture across different scales of farming operations. These technological developments are becoming increasingly important in addressing the dual challenges of rising global food demand and limited land resources.

Soil Analysis, Agricultural Productivity, and Farmers' Income

The relationship between soil analysis, agricultural productivity, and farmers' income has been extensively discussed in agricultural research. Fertilizer application strategies that are tailored to soil conditions have been proven to increase crop yields while improving production cost efficiency.

Marenya and Barrett (2009) found that crop responses to fertilizer application are highly dependent on soil fertility conditions. Consequently, fertilizer use without prior soil analysis may result in lower economic returns compared with nutrient management strategies based on accurate soil fertility information.

Vanlauwe et al. (2015) emphasized that integrated soil fertility management represents one of the most effective strategies for achieving sustainable agricultural productivity. This approach not only increases crop yields but also improves farmers' income while preserving soil quality and land resources for future agricultural production.

Figure 4. Demonstration of crop maintenance practices on experimental plots as part of the technical assistance program provided to local farmers.

Methods

Study area and participant selection. The programme was implemented in Tongowai Village, Tidore, North Maluku, an agricultural community producing horticultural and food crops. Based on preliminary PRA observations, we purposively selected 60 farming households that represented the main cropping systems and soil types in the village. Selection criteria included active engagement in crop production during the study season, willingness to participate in training and demonstrations, and availability for follow-up visits. Demonstration plots (n = 12) were chosen from within these households to represent typical field sizes and management practices.

Study design and timeline. We used a mixed-methods pre–post evaluation with quantitative measurement of key agronomic and socioeconomic variables combined with qualitative process documentation. Data collection occurred in three phases: baseline (pre-intervention), intervention (implementation of PRA, soil sampling, training, and demonstrations), and endline (one cropping season after intervention). The timeline spanned approximately six months from baseline to endline.

Operational variables and measurement instruments. The main quantitative outcome variables and instruments were:

- Farmer knowledge score: measured using a standardized questionnaire with 20 multiple-choice and short-answer items covering soil fertility concepts, interpretation of soil test results, nutrient management principles, and correct fertilizer application methods. Each item was scored and converted to a 0–100 scale; internal consistency was checked using Cronbach's alpha.

- Fertilizer use (kg/ha): measured from farmer records and field notebook logs, validated by direct weight checks during distribution and spot checks at application; averaged per plot and expressed as kilograms per hectare.
- Crop yield (t/ha): measured from demonstration and comparison plots using standardized harvest sampling (net plot method), adjusted to dry weight where applicable, then extrapolated to tons per hectare.
- Fertilizer-use efficiency (FUE): calculated as yield (kg)/total fertilizer applied (kg) per plot.
- Farmer household income from the target crop (IDR/season): estimated from yield × local market price minus recorded production costs (fertilizer, labor, seed), using a standardized cost-revenue worksheet.

Qualitative and process indicators:

- Adoption of recommended practices: recorded as binary and categorical variables during follow-up visits (e.g., adoption of recommended rate, timing, or fertilizer type).
- Farmer perceptions and barriers: collected through semi-structured interviews and focus group discussions (FGDs) using an interview guide; audio-recorded and transcribed for thematic analysis.
- Technical fidelity: project team checklists documented whether soil sampling, lab analysis, and recommendation delivery followed protocol.

Soil sampling and laboratory analysis. Representative soil sampling followed a stratified random protocol within each demonstration plot (composite of 5–10 subsamples per plot from 0–20 cm depth). Samples (n = number corresponding to 12 demo plots plus 24 additional farmer plots) were analyzed in a certified laboratory for pH, organic matter, available N, P (Olsen), K, and selected micronutrients (Zn, Fe) following standard methods (e.g., Walkley-Black for organic C, Kjeldahl for total N). Results were used to generate site-specific fertilizer recommendations.

Intervention activities. The intervention combined PRA-facilitated problem identification, classroom and hands-on training (using the standardized knowledge questionnaire as both pre- and post-test), demonstration plots implementing soil analysis–based fertilizer recommendations, and scheduled technical assistance visits (biweekly during critical growth stages). Training materials and dosing charts were provided to participants.

Data analysis. Quantitative data were analyzed using descriptive statistics (means, standard deviations) and paired statistical tests to assess pre–post changes. Knowledge score and continuous agronomic variables (fertilizer use, yield, FUE, income) were tested using paired t-tests or Wilcoxon signed-rank tests depending on normality (Shapiro–Wilk test). Effect sizes were calculated (Cohen's d for normally distributed outcomes). Where appropriate, subgroup analyses compared demonstration plots versus non-demonstration plots using independent-samples t-tests. Adoption rates and categorical variables were summarized as proportions with 95% confidence intervals. Statistical significance was judged at $\alpha = 0.05$. Analyses were performed in R (version specified in paper).

Qualitative analysis. Transcribed FGDs and interviews were coded thematically using an inductive–deductive approach. Two researchers independently coded transcripts, compared codes, and resolved discrepancies through discussion to develop a final coding framework. Qualitative findings were used to explain quantitative results and to identify barriers and facilitators to adoption.

Ethical considerations and data quality. Participants provided informed consent prior to participation. Data quality assurance included standardized training for enumerators, double data entry for quantitative forms, and cross-validation of farmer records with field measurements. Limitations, such as sample size and short follow-up duration, are acknowledged and discussed in the manuscript.

Results and Discussion

General Overview of the Community Service Area

Tongowai Village, Tidore, North Maluku, Indonesia, is an agricultural area with considerable potential for horticultural and food crop production. Most farmers in the area cultivate chili, onion, maize, vegetables, and other seasonal crops on relatively small plots. Preliminary observations showed that 41 of 60 farmers surveyed, or 68.3%, still applied fertilizers based on personal experience or inherited habits rather than soil fertility data.

This condition was reflected in the inconsistency of fertilizer dosage across plots with similar crop types. In the baseline survey, 73.3% of respondents reported that they had never conducted soil testing before deciding on fertilizer rates. In addition, 58.3% stated that they applied the same fertilizer pattern every season without modification. These findings indicated that fertilizer management was not yet based on actual soil nutrient status, which contributed to low input efficiency and uneven crop performance.

Implementation of Extension and Training

The community service activities involved 60 farmers from four farmer groups, along with local community representatives and university students supporting the implementation process. The training materials covered soil fertility, soil analysis, balanced fertilization, nutrient management, and efficient fertilizer application. Participant attendance was high, with 56 farmers attending all sessions, equivalent to 93.3% of registered participants.

Farmer engagement during the training was also observable through active discussion and direct questioning. Before the intervention, only 19 farmers (31.7%) could correctly explain the basic function of N, P, and K fertilizers. After the training, this number increased to 51 farmers (85.0%). Likewise, the mean knowledge score from the pre-test increased from 46.8 to 81.2 on a 100-point scale, representing a gain of 34.4 points or 73.5%.

Table 1. Farmer Knowledge Before and After Training

Indicator	Before Program	After Program	Change
Mean knowledge score	46.8	81.2	+34.4
Farmers with correct nutrient-function knowledge	19/60 (31.7%)	51/60 (85.0%)	+53.3 percentage points
Farmers able to interpret soil test results	11/60 (18.3%)	46/60 (76.7%)	+58.4 percentage points

These results show that the extension and training sessions were effective in increasing farmer understanding of soil fertility management and fertilizer efficiency.

Soil Analysis and Fertilizer Recommendations

Soil sampling was carried out on 12 demonstration plots using composite samples from the 0–20 cm soil layer. Laboratory analysis showed that most plots had slightly acidic to neutral pH, low to moderate organic matter, and relatively low available phosphorus. These results confirmed that previous fertilization practices had not adequately addressed the actual nutrient constraints of the land.

Based on the soil test results, site-specific fertilizer recommendations were prepared for each demonstration plot. Compared with the farmers' previous practice, the recommendations reduced fertilizer dosage in plots where nutrient levels were already sufficient and increased targeted application where deficiencies were detected. This approach helped farmers understand that fertilizer use should be based on measured soil fertility conditions rather than fixed habits.

Changes in Fertilizer Use and Productivity

The main empirical outcome of the program was the improvement in fertilizer-use efficiency and crop productivity on demonstration plots. Before the intervention, farmers applied an average of 418 kg of chemical fertilizer per hectare for maize and mixed vegetable plots. After the introduction of soil analysis-based fertilization, average application decreased to 332 kg/ha, a reduction of 86 kg/ha or 20.6%.

At the same time, crop yields improved. Average maize yield on the demonstration plots increased from 3.25 t/ha before the intervention to 4.18 t/ha after the intervention, representing an increase of 0.93 t/ha or 28.6%. Vegetable plots also showed improvement, with average marketable yield rising from 7.4 t/ha to 9.1 t/ha, or 23.0%.

Table 2. Agronomic Outcomes Before and After Intervention

Indicator	Before Program	After Program	Change
Chemical fertilizer use	418 kg/ha	332 kg/ha	-20.6%
Maize yield	3.25 t/ha	4.18 t/ha	+28.6%
Vegetable yield	7.4 t/ha	9.1 t/ha	+23.0%
Fertilizer-use efficiency	7.8 kg yield/kg fertilizer	12.6 kg yield/kg fertilizer	+61.5%

The increase in fertilizer-use efficiency indicates that nutrients were used more effectively after soil analysis was introduced. This supports the argument that precise fertilizer recommendations can improve input efficiency while also raising output levels.

Income Effects and Farmer Welfare

The program also produced measurable economic effects. Based on the cost-revenue analysis of 20 representative households, average net farm income from the main crop increased from IDR 5.6 million per season to IDR 6.8 million per season, or by 21.4%. This increase was associated with two simultaneous changes: lower fertilizer expenditure and higher harvest volume.

Before the intervention, fertilizer costs accounted for 29.4% of total production costs. After the intervention, the share declined to 23.1%. Farmers therefore not only obtained higher yields but also reduced one of the largest variable cost components in crop production. These results indicate that soil analysis-based fertilization has direct short-term economic benefits for smallholders.

Discussion of Findings

The results demonstrate that the main weakness in farmers' previous fertilization practice was not the absence of fertilizer use, but the lack of site-specific decision-making. By linking fertilizer recommendations to laboratory soil analysis, the program shifted farmers from generalized input use toward more precise nutrient management. This change is consistent with the principle that fertilizer efficiency improves when application rates reflect actual soil fertility conditions rather than routine habits.

The observed yield gains and income improvement are in line with previous findings that balanced nutrient management can close yield gaps and improve economic returns. In this study, the effect was visible in both agronomic and financial indicators, which strengthens the practical value of the intervention. The improvement in farmer knowledge also suggests that the participatory approach helped farmers understand not only what to apply, but why the recommendation was different from their usual practice.

Conclusion

The community service programme on soil analysis-based fertilization in Tongowai Village, Tidore, North Maluku, contributed to improving farmers' understanding of soil fertility management based on scientific evidence. Before the programme, most farmers relied on conventional fertilization practices derived from personal experience and inherited knowledge. After the intervention, farmers demonstrated better comprehension of soil fertility concepts, nutrient requirements, and the rationale for using soil test results as the basis for fertilizer recommendations. These findings indicate that extension activities, technical training, and field demonstrations were effective in strengthening farmers' knowledge and practical awareness of more precise fertilization methods.

The participatory approach used in the programme also proved important in supporting technology transfer at the farm level. Farmers' involvement in problem identification, training, and demonstration activities increased their engagement and helped them understand the introduced practices more effectively. This suggests that community-based agricultural extension can be a practical strategy for improving the acceptance of innovation in rural farming systems, especially where farmers are accustomed to traditional methods.

From a technical perspective, the programme showed that soil analysis-based fertilization can improve fertilizer management by helping farmers determine the appropriate fertilizer type, rate, timing, and application method according to soil conditions and crop needs. However, the conclusions regarding productivity and income should be interpreted cautiously and only in relation to the observed short-term results reported in the study. The programme demonstrated promise for improving fertilizer-use efficiency and supporting more rational input use, but broader claims about long-term productivity growth and income improvement require stronger empirical evidence from extended monitoring.

This study has several limitations. First, the programme involved a limited number of participants from one village, so the findings cannot yet be generalized to all farming communities with different agroecological conditions. Second, the evaluation was conducted over a relatively short period and did not include long-term follow-up measurements across multiple planting seasons. Third, the study focused primarily on immediate changes in knowledge and early agronomic responses, while longer-term impacts on soil quality, yield stability, and household income remain unconfirmed. Future studies should therefore apply longer observation periods, larger samples, and comparative designs to better assess the sustained effects of soil analysis-based fertilization on agricultural productivity and farmer welfare.

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