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Synergizing Soil Restoration and Circular Economy: Integrated Application of Nano-particle Enhanced Compost (NEC) and Husk Charcoal

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ABSTRACT

The progressive decline in rice productivity, currently reaching 7–8 tons/ha in Klaseman Village, is primarily attributed to soil fertility degradation resulting from the intensive and long-term application of inorganic chemical fertilizers. This environmental challenge necessitates a strategic technology transfer to remediate soil health and enhance farmer self-sufficiency through sustainable practices. This community service initiative aimed to elevate the technical proficiency and managerial capacity of the "Gotong Royong I" Farmer Group in the production and systematic application of Nano-particle Enhanced Compost (NEC). Utilizing a participatory approach, the program integrated theoretical socialization, hands-on manufacturing practice, and intensive field mentoring on a 0.5-hectare demonstration plot involving 25 participants. Empirical results demonstrate that 100% of the participants achieved mastery in independent NEC production, successfully generating 400 kg of the enhancer. Field implementation facilitated a 50% reduction in conventional chemical fertilizer dosage while yielding superior vegetative growth and improved soil vitality compared to control plots. Ultimately, this program effectively bridges the gap between laboratory innovation and community adoption, establishing a circular economy model that supports long-term agricultural sustainability.

Keywords: Nano-particle Enhanced Compost (NEC), Training, Application, Farmer Group, Soil Fertility

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INTRODUCTION

The situation analysis commences with the upstream agricultural sector, represented by the "Gotong Royong I" Farmer Group, which comprises 25 active members facing critical challenges in soil fertility and production efficiency. The existing cultivation system is heavily dependent on synthetic chemical fertilizers, which has led to severe soil compaction and a degradation of the land's biological carrying capacity. Quantitative data before the intervention indicate that rice productivity in this group was stagnant at 5–6 tons per hectare of Harvested Dry Grain (GKP), a figure significantly below the variety's genetic potential, which can reach 7–8 tons per hectare. Consequently, this inefficiency in input usage has resulted in high production costs, causing the farmers' net income to plateau at approximately IDR 31,250,000 per hectare per season, leaving them vulnerable to market price fluctuations and fertilizer scarcity. Conversely, the downstream sector is represented by the Karang Taruna (Youth Organization) of Klaseman Village, comprising 20 productive-age youths who were previously categorized as an economically non-productive group. The situational analysis reveals a paradox where abundant local resources are treated as waste rather than economic assets. Specifically, the village produces tons of rice husk waste per harvest season, yet 100% of this biomass has historically been untreated, typically burned in open fields or dumped, thereby causing environmental pollution. From an economic perspective, the organization had zero business units, produced zero commercial products, and generated IDR 0 in independent revenue before the program, relying entirely on voluntary contributions or village funds due to a lack of sociopreneurial skills and access to waste-processing technology.

This comprehensive analysis identifies a critical disconnect between the upstream and downstream sectors, where the agricultural waste from the upstream is treated as a pollutant rather than a resource for the downstream. The degraded soil in the upstream sector requires organic amendments to restore fertility, while the downstream sector possesses the raw material (husks) to produce these amendments but lacks the technology to process them. Therefore, this program is designed to bridge this gap by empowering youth to process waste into bio-products used by farmers, thereby establishing a sustainable circular economy that addresses both ecological degradation and economic stagnation in Klaseman Village. Agriculture, particularly rice cultivation, plays a pivotal role in the livelihoods of the Klaseman Village community in Gending District, Probolinggo Regency, where approximately 90% of the 115 hectares of agricultural land is devoted to rice cultivation. Despite significant agricultural potential, the village faces serious challenges due to a drastic decline in productivity, which has reportedly fallen to 7–8 tons per hectare in recent decades. This decline directly affects farmers' incomes and the competitiveness of local agricultural products, while simultaneously hindering the transition toward sustainable agriculture (Wihardjaka et al., 2022; Kurniawati et al., 2023). The priority problems faced by the partners are identified across the upstream and downstream sectors. In the upstream sector, the "Gotong Royong I" Farmer Group is experiencing significant productivity losses, primarily due to soil fertility and quality degradation resulting from unsustainable intensive farming practices and an over-reliance on inorganic chemical fertilizers, such as Urea and NPK, applied at high doses. Research indicates that excessive use of chemical fertilizers damages soil microflora and pollutes the environment, exacerbating soil conditions by rendering the land saturated and deficient in organic matter (Hashim et al., 2023; Ojobor & Egbuchua, 2020). Consequently, the soil composition is no longer optimal for plant growth, rendering the land incapable of supporting maximum production (Gamage et al., 2021; Gong et al., 2021). Simultaneously, in the downstream sector, the Karang Taruna group faces challenges regarding the accumulation of untreated rice husk waste and a lack of economic productivity. Current studies emphasize the urgent need for new approaches to soil management, including adopting farming practices that prioritize long-term fertility (Kadir & Harsani, 2023).

To address these interconnected issues, this program proposes an integrated solution that converts downstream waste into upstream inputs. As a viable solution, technological innovations such as Nano-particle Enhanced Compost (NEC) have been identified as a promising alternative for soil remediation and improved fertilization efficiency. NEC is an organic-based compost fertilizer that utilizes nanoparticle engineering to facilitate a slow and controlled release of nutrients, thereby enhancing nutrient use efficiency compared to conventional fertilizers (Sholihah et al., 2023; Sung et al., 2023). Research has demonstrated that the application of compost enriched with nanoparticles, such as ZnO, significantly increases nutrient uptake and rice grain yields (Gao et al., 2024; Farooq et al., 2021). Furthermore, the use of nanosilica has been shown to improve crop quality and increase the profitability of rice farming enterprises (Mohamed et al., 2023; Zhang et al., 2024). The plan to implement NEC in Klaseman Village, **which was facilitated by the KOSABANGSA Community Service Grant**, aims to empower the "Gotong Royong I" Farmer Group to independently produce and apply NEC, which is expected to be a pivotal step in breaking the cycle of dependency on chemical fertilizers while simultaneously restoring soil fertility (Srisawat et al., 2024). This strategy is designed not only to enhance agricultural productivity but also to boost farmers' income and assist them in transitioning toward more sustainable agricultural practices (Win et al., 2022; Xu et al., 2024).

THEORETICAL FRAMEWORK

Soil Degradation and Chemical Fertilizer Dependency The fundamental premise of this study addresses the critical issue of soil degradation caused by unsustainable agricultural practices. Theoretical literature confirms that excessive use of inorganic chemical fertilizers severely disrupts the soil's ecological balance. Research indicates that such practices damage soil microflora and contaminate the surrounding environment, thereby exacerbating soil deterioration by making the land saturated and deficient in essential organic matter (Hashim et al., 2023; Ojobor & Egbuchua, 2020). Consequently, the soil composition fails to maintain optimal conditions for plant growth, rendering the land incapable of supporting maximum agricultural production (Gamage et al., 2021; Gong et al., 2021). Contemporary studies emphasize the urgent necessity for novel soil management approaches, particularly those that prioritize long-term fertility restoration over short-term gains (Kadir & Harsani, 2023). Nano-particle Enhanced Compost (NEC) Technology. To mitigate these challenges, this program relies on the Nano-particle Enhanced Compost (NEC) technology. NEC is theoretically defined as an organic-based compost fertilizer that utilizes nanoparticle engineering to facilitate the slow, controlled release of nutrients (Nurhidayati et al., 2024). This mechanism significantly enhances nutrient use efficiency compared to conventional fertilizers (Sholihah et al., 2023; Sung et al., 2023). The integration of nanotechnology into organic composting serves as a sophisticated remediation strategy that improves soil health while ensuring sustained nutrient availability.

Efficacy of Nanoparticles in Crop Productivity. Empirical evidence from recent research underpins the efficacy of nanoparticle application in enhancing crop performance. Studies demonstrate that the application of compost enriched with nanoparticles, such as Zinc Oxide (ZnO), results in a significant increase in nutrient uptake and rice grain yields (Gao et al., 2024; Farooq et al., 2021). Furthermore, the specific use of nanosilica has been proven to improve harvest quality and increase the overall profitability of rice farming enterprises (Mohamed et al., 2023; Zhang et al., 2024). These findings provide the scientific basis for the technical intervention implemented in this community service program. Sustainable Agriculture and Socio-Economic Empowerment The implementation of NEC is also grounded in the broader theories of sustainable agriculture and economic empowerment. The framework posits that breaking the cycle of dependency on chemical fertilizers is a prerequisite for restoring soil fertility (Srisawat et al., 2024). This strategy is projected not only to increase agricultural productivity but also to boost farmers' income, thereby facilitating a successful transition toward more sustainable agricultural practices (Win et al., 2022; Xu et al., 2024).

METHODS

The implementation of this community service activity utilized a Participatory Action Research approach designed to actively involve two primary strategic partners in an integrated upstream and downstream framework throughout the 2025 fiscal year. The problem-solving framework was executed systematically to address specific priority issues within the agricultural supply chain. The upstream phase focused on the "Gotong Royong I" Farmer Group to resolve the critical problem of

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soil degradation and productivity stagnation caused by excessive chemical fertilizer use. The solution in this sector was the transfer of Nanoparticle Enhanced Compost (NEC) technology, which included technical training in fermentation and the direct application of the product on a 0.5-hectare demonstration plot. This upstream intervention aimed to restore soil fertility and demonstrate a concrete increase in rice productivity to the target of 7 tons per hectare. Simultaneously, the methodology addressed the downstream sector by engaging the Karang Taruna Youth Organization of Klaseman Village to resolve issues of unmanaged rice husk waste and the lack of economic activities among the youth. The solution implemented was the introduction of biomass conversion technology to transform waste into charcoal briquettes. This stage involved installing production machinery, including disk mills and briquette molders, followed by intensive training in production operations. To ensure economic viability, the downstream activities were supplemented with capacity-building in digital marketing and financial management, which was conducted specifically in November 2025. The final phase of the method focused on program sustainability through the establishment of a Joint Business Group (KUB) and the official handover of Standard Operating Procedures, along with an equipment grant to ensure post-program independence for both partners.

RESULTS AND DISCUSSION

The implementation of the community service program in Klaseman Village generated comprehensive data across two strategic sectors: the upstream agricultural sector, managed by the "Gotong Royong I" Farmer Group, and the downstream economic sector, managed by the "Karang Taruna" Youth Organization. The results presented below detail the quantitative and qualitative achievements achieved during the program's execution, focusing on capacity building, technology adoption, and initial economic outputs.

Upstream Sector Results: Capacity Building and Agronomic Performance

The intervention in the upstream sector primarily targeted the technical transformation of the "Gotong Royong I" Farmer Group. The initial baseline assessment revealed a significant psychological barrier among the farmers, characterized by deep-seated skepticism toward organic amendments. This mindset was historically shaped by the rapid visual effects of inorganic fertilizers, often referred to as the "green in three days" effect, leading to a perception that organic methods were laborious and slow to yield results. To address this challenge, the program executed a three-phase training curriculum based on andragogy principles covering the Awareness Phase, the Hands-on Practice Phase, and the Technology Adoption Phase. The results of this phased intervention were highly effective. Attendance data confirmed that 25 core farmers, representing 100% of the participant target, fully participated in the training series. The most critical result in the technology adoption phase was the successful dismantling of the mental barrier regarding the labor-intensive nature of organic production. By introducing the Chopper Machine and Disk Mill through the equipment grant, farmers witnessed that the raw material grinding process could be completed in minutes rather than hours. Consequently, the primary quantitative indicator of success in the upstream sector was achieving production independence. Post-training monitoring revealed that the farmer group successfully produced 400 kg of solid Nano-particle Enhanced Compost (NEC) independently without the direct supervision of the mentoring team. This output served as the material foundation for the subsequent field application.

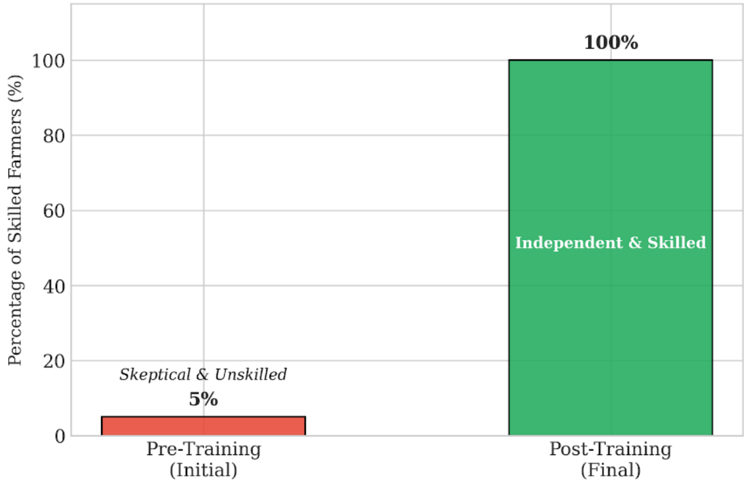

Figure 1. Farmers from "Gotong Royong I" Group actively operate the Chopper Machine during the NEC production training session

Source: Authors' analysis based on pre- and post-training survey data.

Following the production phase, the field results were observed in a 0.5-hectare demonstration plot owned by a group member. The specific objective was to test the efficacy of NEC while reducing chemical dependency. The implementation result showed a successful reduction of inorganic chemical fertilizers, specifically Urea and NPK, by 50% in the demonstration plot area compared to the control plots. This 50% reduction was a deliberate outcome of the bridging strategy, designed to mitigate farmers' fear of crop failure while gradually introducing organic inputs. Despite the significant reduction in chemical inputs, the vegetative data collected from the demonstration plot showed superior agronomic performance compared to the full-chemical control plots. Visual observations confirmed three distinct improvements in the NEC-treated rice plants. First, the leaf color in the demonstration plot was darker green, indicating higher chlorophyll content and more efficient photosynthetic processes. Second, the number of productive tillers per clump was visually higher in the demonstration plot, serving as a primary indicator for increased panicle formation and potential grain yield. Third, the plants exhibited more uniform growth patterns, suggesting that soil nutrient availability was evenly distributed following compost application.

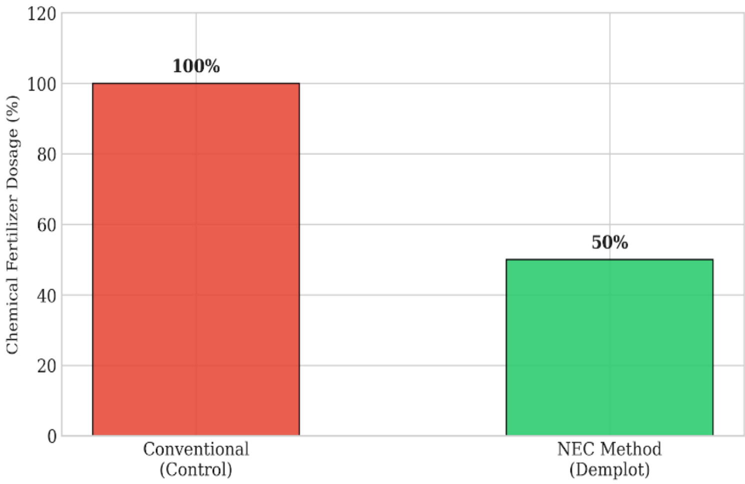

Figure 2. Comparative Analysis of Chemical Fertilizer Reduction between Conventional Practices and NEC Implementation

Source: Authors' analysis based on pre- and post-training survey data.

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Figure 3. Visual Comparison of Vegetative Growth: The NEC Demplot (Left) Exhibits Darker Green Leaves and More Tillers Compared to the Control Plot (Right).
Source: Documentation by Author

Downstream Sector Results: Institutional Establishment and Production Metrics

In the downstream sector, the results focused on activating the "Karang Taruna" Youth Organization. Before the intervention, this partner had no business units and possessed unexploited agricultural waste. The primary institutional outcome was the successful formation of one Joint Business Group (KUB) immediately following the Appropriate Technology training. This KUB was established with a specific management structure to oversee the husk charcoal and briquette business unit, marking the transition of the partner from a social organization to a productive economic entity. The technical training provided to 20 youth members covered the entire production cycle from the economic valuation of waste to the operation of pyrolysis drum kilns and disk mills. The adoption of this technology yielded immediate quantitative results in production capacity. While the initial proposal targeted a production rate of 10 kg per day, the KUB's actual production capacity stabilized at 15-20 kg of husk charcoal powder per day within the first month of operation. This result exceeded the initial target significantly, driven by members' enthusiasm and the user-friendly nature of the granted technology.

Figure 4. Members of the newly formed KUB Karang Taruna are processing rice husks into charcoal powder using the granted Pyrolysis technology
Source: Documentation by Author

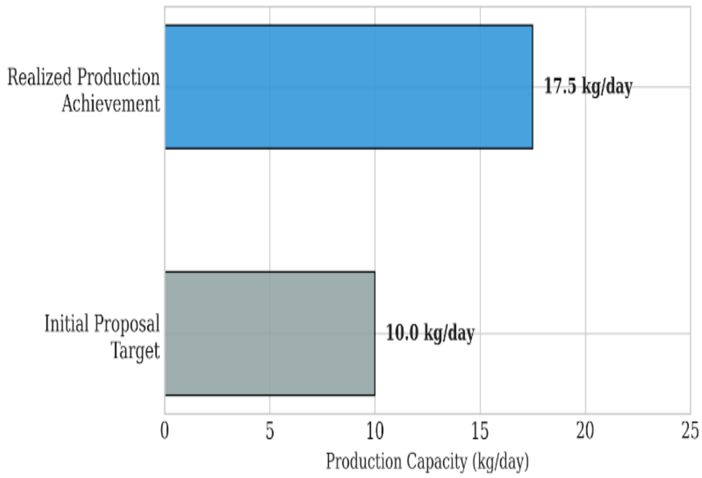

Figure 5. Production Performance Analysis: The KUB successfully exceeded the initial target of 10 kg/day, achieving a stable output of 15-20 kg/day.
Source: Authors' analysis based on pre- and post-training survey data.

In terms of economic results, the KUB successfully achieved market validation through initial sales. By the time of the 80% progress report, the partner had sold 50 kg of husk charcoal powder to the local market. Market identification results indicated that buyers comprised three segments: local farmers seeking planting media, ornamental plant hobbyists, and local agricultural shops. Although the nominal revenue was in the early stages, the achievement of these first sales provided tangible proof that the waste-to-wealth model was operationally viable.

The discussion interprets the empirical results presented above through the theoretical frameworks of sustainable agriculture, nanotechnology in soil science, and the circular economy. It analyzes how the specific methods applied effectively resolved the priority problems identified at the onset of the program.

Analysis of Upstream Soil Restoration and Nanotechnology Efficacy

The success of the NEC application in the upstream sector can be scientifically attributed to mechanisms of nanoparticle engineering that enhance Nutrient Use Efficiency (NUE). The observed reduction in chemical fertilizer usage by 50% without compromising plant growth confirms that nanoparticles in the compost, specifically Zinc Oxide and Silica derived from husk charcoal, play a crucial role in optimizing nutrient uptake. When plants absorb nutrients more efficiently due to improved soil structure and NEC's slow-release mechanisms, the need for chemical fertilizers can be reduced without sacrificing the nutrients plants require (Sholihah et al., 2023; Sung et al., 2023). The theoretical definition of NEC as an organic-based compost that utilizes nanoparticle engineering to facilitate slow, controlled nutrient release is supported by field evidence gathered in this program. The darker green leaves observed in the demonstration plot suggest enhanced nitrogen uptake and chlorophyll synthesis, likely facilitated by the improved cation exchange capacity of the soil amended with NEC. Research has demonstrated that the application of compost enriched with nanoparticles such as ZnO significantly increases nutrient uptake and rice grain yields (Gao et al., 2024; Farooq et al., 2021). Additionally, the use of nano-silica, which is abundant in the downstream partner's husk charcoal, has been shown to improve crop quality and increase the overall profitability of rice farming enterprises (Mohamed et al., 2023; Zhang et al., 2024).

Furthermore, the strategy of reducing chemical dosage aligns with the concept of Integrated Soil Fertility Management. This approach effectively addresses the root cause of land degradation

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caused by excessive chemical use, as highlighted in previous studies on soil saturation and organic matter deficiency (Hashim et al., 2023; Ojobor & Egbuchua, 2020). By reintroducing organic matter in the form of NEC, the program not only provides nutrients but also restores soil microflora, enabling the land to support maximum production once again (Gamage et al., 2021; Gong et al., 2021).

Analysis of Downstream Economic Empowerment

In the downstream sector, the formation of the KUB and the achievement of initial sales validate the Waste-to-Wealth concept. The youth's ability to transform rice husk waste into marketable charcoal briquettes addresses the environmental issue of open burning while simultaneously creating economic value. This transformation supports the theoretical framework that breaking the cycle of dependency is a prerequisite for empowering rural communities (Srisawat et al., 2024).

The economic success of the Karang Taruna serves as market validation, proving that the business model is economically viable. This strategy is projected not only to increase agricultural productivity but also to boost farmers' income and help them transition towards more sustainable agricultural practices (Win et al., 2022; Xu et al., 2024). By integrating the energy of the youth with the wisdom of the farmers, the program creates a sustainable pathway for village development.

Synthesis: The Integrated Circular Economy Model

The ultimate achievement of this program is the establishment of a functional circular economy model that bridges the upstream and downstream sectors. This program created an ecosystem where the two partners mutually reinforced each other. The synergy is evident in the material flow: the upstream sector produces rice and husk waste, the downstream sector processes it into husk charcoal, and finally, the farmers purchase it back as an essential raw material for NEC production.

Figure 6. The Integrated Circular Economy Model established in Klaseman Village, connecting waste management with agricultural productivity
Source: The authors' Own conceptualization based

This integrated model shows that the waste problem in the upstream sector becomes the income solution for the downstream sector, and the downstream sector's products return as soil restoration solutions for the upstream sector. This creates positive interdependence and strengthens the overall economic and social resilience of Klaseman Village.

CONCLUSION

This community service initiative has successfully achieved its main objectives through the implementation of an integrated upstream and downstream empowerment model. Regarding the program achievements, the objective of enhancing the capacity of the "Gotong Royong I" Farmer Group was fully realized, as evidenced by 25 farmers representing 100% of the target demonstrating skilled proficiency and the capability to independently produce 400 kg of Nano-particle Enhanced Compost (NEC). The implementation of this technology on the 0.5-hectare demonstration plot proved successful, marked by a 50% reduction in chemical fertilizer use and visual observations of healthier rice growth, which effectively serves as social proof for other farmers. Simultaneously, on the downstream side, the objective of creating new entrepreneurial opportunities for the Karang Taruna was achieved through the establishment of a Joint Business Group (KUB) comprising 20 members. This group successfully adopted Appropriate Technology, achieving a production capacity of 15-20 kg of husk charcoal powder per day, surpassing the initial target, and executing initial sales of 50 kg, providing early market validation.

The broader implication of this program lies in the creation of a tangible circular-economy synergy in which the upstream partner's husk waste is processed into revenue by the downstream partner, and the processed product is purchased back as a raw material for soil restoration. This model implies that rural economic resilience can be strengthened by connecting social capital between generations and transforming waste into productive assets. Furthermore, the success of the NEC technology implies a potential shift in agricultural practices from chemical dependency toward sustainable farming without sacrificing productivity. To ensure the sustainability and optimization of these impacts, several suggestions are proposed for future implementation. First, the Farmer Group is advised to consistently apply the Standard Operating Procedures for NEC production in the subsequent planting seasons to maintain soil fertility stability. Second, it is suggested that the Karang Taruna formalize their business unit and integrate it into the Village-Owned Enterprise (BUMDes) to access better capital and legal protection. Finally, future empowerment programs are recommended to focus on the downstream processing of food products, such as certified organic rice, to further increase the added value of the commodities produced in Klaseman Village.

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