Smart-eco farming villages for low carbon sustainability: evidence from an Indonesian living lab

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Abstract. Decarbonizing smallholder agriculture rarely hinges on a single technology; it depends on whether farmers can reorganize everyday routines without increasing production risk. We report monitored evidence from the Tawangargo Smart-Eco Farming Village (TAMENG) program in East Java, Indonesia (2022-2026), a CSR-supported community living lab initiated by PT Petrokimia Gresik. Using an embedded qualitative case study complemented by descriptive monitoring records, we trace two linked intervention packages: (i) circular management of horticultural residues into liquid organic fertilizer (POC) and livestock feed concentrate (wafer) and (ii) precision irrigation (drip systems and growth-stage scheduling). Program logs indicate that ≈1,095 tons of organic residues are processed annually, yielding ≈39.4 tons/year of POC and supporting a program-estimated mitigation of ≈555 tCO2-e/year through avoided unmanaged decomposition and partial substitution of upstream inputs. Irrigation pilots report water-use reductions up to 65%, with practical co-benefits for pumping time and input-related energy demand. We also describe the governance mechanisms that sustained adoption Agronova Vision as a cross-group platform and a Resource Center (P4S Ngudi Kaweruh) that anchors training, quality assurance, and replication. The case suggests that village-scale CSA living labs can connect solid-waste resource utilization with water efficiency and livelihood resilience, while keeping emissions claims transparent and conservative.

1 Introduction

Food systems are increasingly asked to deliver more output while operating under tighter environmental and economic constraints [1–3]. For horticultural smallholders, climate variability (shifting onset of rainy seasons, heat stress, and pest outbreaks) meets an input-intensive production model in which water management, fertilizer choice, and residue handling carry both cost and emissions implications. Climate-Smart Agriculture (CSA) is

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often used as a practical umbrella for responding to this tension by pursuing productivity, adaptation/resilience, and mitigation where feasible [2,4].

In Indonesia, CSA uptake is shaped by uneven access to services and inputs and by highly diverse farm contexts. In intensive horticulture areas, farmers frequently rely on non-subsidized synthetic fertilizers and pesticides, while organic residues are not always managed as resources. These realities make village-scale approaches attractive, because they can combine technical trials with collective routines and local institutions that reduce adoption risks.

This study draws on the Tawangargo Smart-Eco Farming Village (TAMENG) program in East Java, Indonesia, implemented from 2022 to 2026 as a community living lab. We ask: (1) How do circular waste-to-resource routines (organic waste processed into liquid fertilizer and feed concentrate) and precision water management translate into monitored low-carbon and resource-efficiency outcomes? (2) Which governance features help implementation and support replication? By answering these questions, the paper contributes evidence that is directly relevant on solid waste pollution control and resource utilization, environmental monitoring and management, and sustainable development, while also noting the energy co-benefits associated with water and input efficiency. Fig 1 illustrates how living-lab governance in the TAMENG program enables circular and climate-smart interventions, producing low-carbon, water-efficiency, and livelihood outcomes.

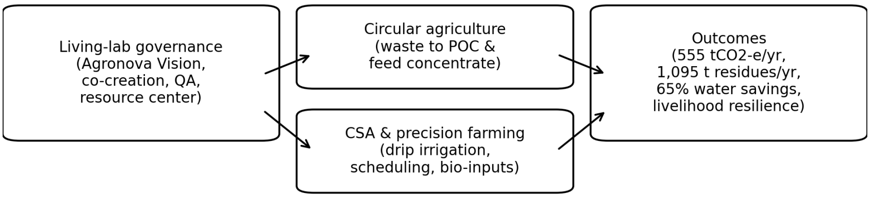

Fig 1. Living-lab governance enables CSA and circular waste-to-resource interventions, producing low-carbon, water-efficiency, and livelihood outcomes

2 Background and related work

2.1 CSA and the environment-energy nexus

CSA is typically discussed through three linked objectives: productivity, adaptation/resilience, and mitigation. Recent syntheses show that combinations of soil fertility management, diversified cropping, and water-saving irrigation can reduce climate-related production risks and stabilize incomes, although outcomes depend strongly on context, enabling services, and how performance is monitored [2,4]. From an environment–energy standpoint, the most immediate co-benefits often come from reduced pumping and fewer input deliveries when irrigation and fertilization are better targeted.

2.2 Circular agriculture and organic waste resource utilization

Circular agriculture focuses on closing nutrient and biomass loops by turning residues into useful inputs, thereby reducing informal disposal and dependence on purchased products [5]. However, the net climate benefit is not automatic: biological processing can generate CH_4 and N_2O if moisture, aeration, and feedstock mixes are poorly managed [6]. Evidence on adoption also highlights that farmers' willingness to substitute inputs depends on consistent product quality, traceability, and credible performance information [7,8].

2.3 Living labs and implementation mechanisms

In village-scale sustainability programs, “living lab” is less a label than a working arrangement: solutions are tested in the same fields and organizations that will carry them forward. Prior studies suggest living labs are most effective when they build collective capabilities (skills, shared routines, and local repair capacity), clarify roles and benefit-sharing, and maintain monitoring that is credible enough to guide decisions and secure legitimacy [9,10].

For circular residue systems, this matters because logistics (collection, sorting, transport), operating discipline (SOPs, hygiene, batch control), and user acceptance (willingness to apply waste-derived inputs) are shaped by local norms and incentives, factors that cannot be solved through technology alone.

2.4 Precision irrigation and water-energy co-benefits

Precision irrigation is a prominent CSA lever because it links adaptation to measurable resource savings. Reviews of drip and scheduling approaches report improvements in water-use efficiency and reduced environmental footprints when irrigation is integrated with agronomic management and monitoring [11]. In parallel, recent work shows that the carbon footprint of irrigation pumping can be substantial, making water management an energy-relevant mitigation opportunity in many settings [12].

In practice, adoption can stall when equipment, data, or maintenance requirements exceed local capacity. Programs therefore tend to perform better when they sequence trials, invest in local maintenance skills, and document benefits using simple before/after metrics that farmers recognize as meaningful.

3 Case study context and methods

3.1 Program context and living-lab design

TAMENG (2022-2026) operates in Tawangargo Village, Malang Regency, East Java, an intensive horticultural area where seasonal uncertainty, pest pressure, and input price volatility are persistent concerns. Although the village sits within PT Petrokimia Gresik’s broader distribution area for subsidized fertilizer, horticultural farmers face limited access to subsidy allocations that prioritize certain staple commodities. As a result, many farmers depend on non-subsidized synthetic inputs, which increases production costs and can exacerbate longer-term soil quality concerns [13].

From the outset, the village was positioned as a living lab: interventions were designed to be tried, adjusted, and institutionalized through participatory learning rather than delivered as one-off input support. Agronova Vision functions as an umbrella institution integrating farmer groups, youth, women’s groups, and ruminant livestock actors, while the P4S Ngudi Kaweruh Resource Center provides training infrastructure and supports an exit strategy aimed at community continuity beyond company facilitation [13,14].

3.2 2 Research design, data sources, and analysis

We applied an embedded qualitative case study design, supported by descriptive quantitative monitoring data. The empirical base was assembled from (i) program documents and implementation notes, (ii) routine monitoring records (2022–2025) such as residue processing logs and output records for POC and wafer feed, (iii) laboratory certificates for liquid organic fertilizer batches, (iv) irrigation pilot notes comparing water use before and after drip installation and scheduling adjustments, (v) basic economic monitoring (group revenues and employment), and (vi) institutional documentation (P4S certification, visitor logs, and local recognition) [13].

The GHG mitigation figure reported here follows an avoided-emissions logic documented in program monitoring: it combines avoided unmanaged residue decomposition with partial substitution effects linked to local input production. To reduce over-claiming, assumptions were kept conservative and checked against relevant IPCC inventory guidance where applicable [1,3], and we treat the estimate as an internal program calculation rather than a full life-cycle assessment.

Qualitative materials were coded thematically to identify adoption drivers, governance arrangements, inclusion mechanisms, and operational practices (e.g., SOP discipline, traceability). Quantitative figures were summarized descriptively and triangulated across records. Because substitution claims depend on product performance, quality assurance (batch SOPs, traceability, and periodic lab testing) was treated as a core analytical theme [13].

4 Results

4.1 Circular waste-to-resource pathways

Monitoring records indicate that TAMENG processed approximately 1,095 tons of organic agricultural residues per year through controlled biological processing and short-cycle logistics. Primary outputs were liquid organic fertilizer (POC) and livestock feed concentrate (wafer), both intended to reduce dependence on external inputs. Recorded POC output was approximately 39.4 tons/year, supported by laboratory testing and routine batch SOPs [13].

The environmental logic is straightforward but operationally demanding by diverting residues from unmanaged disposal reduces methane generation and enables nutrient recycling, provided that moisture, aeration, and feedstock mixes are managed to limit CH4 and N2O during treatment [6]. In TAMENG, source separation and basic traceability were monitored to reduce contamination and maintain product consistency [13].

4.2 Estimated GHG mitigation

Based on its internal monitoring approach, TAMENG reports an estimated mitigation of approximately 555 tCO2-equivalent per year. This figure reflects avoided residue mismanagement emissions and partial displacement of upstream emissions through locally produced fertilizer and feed substitution [14]. Consistent with the circular agriculture literature, the magnitude of mitigation depends on baseline disposal practices and the extent to which waste-derived products actually substitute purchased inputs [5].

4.3 Precision irrigation and water-energy co-benefits

Drip irrigation and growth-stage-based scheduling reduced water consumption by up to 65% relative to baseline farmer practice, according to pilot records [13]. Reduced water demand also lowered the frequency and duration of pumping in participating plots, implying energy savings and indirect emissions reduction. These water–energy co-benefits are consistent with the broader evidence base on irrigation efficiency and pumping-related footprints [11,12,15].

4.4 Livelihood outcomes, resilience, and diffusion

Program records describe a shift toward higher cropping intensity and lower perceived climate risk among participating farmers. For certain horticultural plots, reported harvest frequency increased from around 3-4 cycles/year to 14-18 cycles/year, with 40-80 kg per harvest cycle recorded in pilots [13]. While these figures cannot be attributed causally without a control group, they indicate that improved water control and input routines were associated with more stable production schedules.

Economic monitoring indicates expansion of collective income streams through Agronova Vision (reported revenue around IDR 76,680,000/month) and local job creation (about 35 productive-age jobs at roughly IDR 3,000,000/month) [13]. Program documentation also records direct engagement of vulnerable groups, including women farm laborers and village youth, through processing, operations, and field demonstrations [13].

Learning and diffusion were anchored by the Resource Center and P4S certification, which created a visible demonstration site and routine training calendar. Visitor logs report 494 visitors (2024) and 397 (2025), suggesting growing demand for peer learning and replication support beyond the village [13].

4.5 Sustainability and impact monitoring synthesis

To synthesize multi-dimensional effects beyond single indicators, TAMENG applied the Sustainability Compass to classify and value outcomes across economic, social, well-being, and environmental dimensions. Internal monitoring indicates the economic dimension dominated (86.68%, valued at IDR 4.078 billion), followed by social (11.56%, IDR 544.59 million), well-being (1.12%, IDR 52.7 million), and environment (0.63%, IDR 29.64 million) [13]. In program logic, strengthening farm economics and collective enterprise was treated as the entry point for sustaining broader social and environmental practices at household and group levels.

The program also applied The Impact Compass, reporting an internal Impact Potential Score of 243 based on criteria such as value to society, efficacy, impact magnitude, sociability, mission alignment, and ESG relevance [13]. We use these frameworks as descriptive monitoring tools rather than as causal proof. Table 1 presents a summary of key monitored indicators and outcome valuations across economic, social, well-being, and environmental dimensions, while Table 2 details the program's product outputs and associated circular value pathways from waste-to-fertilizer and feed conversion.

Table 1. Summary of key monitored indicators and outcomes.

Indicator	Baseline / prior condition	TAMENG monitoring result
Organic residues processed (tons/year)	Unmanaged residues often left to decay or disposed informally	≈1,095 tons/year processed into liquid organic fertilizer and feed concentrate pathways
Liquid organic fertilizer output	Reliance on synthetic inputs	≈39.4 tons/year liquid organic fertilizer output (lab-validated)
Estimated GHG reduction (tCO_2e/year)	-	≈555 tCO_2e/year avoided/offset (program estimate)
Water use (precision irrigation)	Conventional watering with limited scheduling control	Up to 65% reduction in water consumption in drip irrigation pilots
Feed concentrate/wafer output	Limited integration of crop-livestock systems	Wafer feed concentrate produced from suitable organic fractions; supports ruminant integration and input substitution

Cropping intensity	≈3-4 harvest cycles/year (traditional schedule)	≈14-18 harvest cycles/year; 40-80 kg per harvest cycle reported in pilots
Collective group revenue	Fragmented individual sales; limited value-added income	Agronova Vision revenue ≈ IDR 76,680,000/month; trial harvest revenue ≈ IDR 68,200,000/season
Inclusion (direct participation)	Participation often limited by informal norms and time constraints	Program records include participation of women farm laborers (42) and village youth (35) in operations, processing, and learning activities
Learning diffusion	Ad hoc training; limited demonstration sites	Resource Center visitors: 494 (2024), 397 (2025); P4S certification and local recognition

Table 2. TAMENG product outputs and circular value pathways (waste-to-fertilizer and feed).

Product/output	Primary function	Monitoring evidence and notes
Liquid organic fertilizer (POC)	Substitute/augment synthetic fertilizers; improve nutrient cycling	≈39.4 tons/year output; supported by lab certificate and batch SOPs
Feed concentrate/wafer	Valorize suitable organic fractions for ruminant feed	Supports integrated crop-livestock system; reduces feed purchase dependence

5 Discussion

The TAMENG case shows how circular routines can turn an environmental burden (horticultural residues) into productive assets, provided that logistics and process control are treated as seriously as the technology itself. In this setting, the most plausible pathways are waste diversion (reducing unmanaged decomposition) and substitution (reducing reliance on purchased fertilizer and feed), which also reduces upstream burdens linked to mineral fertilizer production [5].

Precision irrigation delivered clear water savings in monitored pilots and plausibly reduced pumping time, which is an energy-relevant co-benefit. The practical challenge is continuity: maintaining emitters, schedules, and farmer confidence requires routine maintenance skills and simple monitoring so that benefits do not erode over time or trigger rebound effects [11,12].

Institutional design mattered for feasibility. Agronova Vision created a venue for co-creation, SOP discipline, and benefit-sharing across groups, while the Resource Center lowered transaction costs for training and replication. For external credibility, especially when reporting emissions figures, clear system boundaries and transparent assumptions are essential, alongside basic standards for product quality and traceability [3,7,9].

6 Limitations and future research

This case study has three main limitations. First, we do not have a counterfactual control group, so improvements in yield, incomes, or land-retention behavior cannot be attributed causally to TAMENG. Second, the mitigation figure is a monitored program estimate rather than a full life-cycle assessment; future work should expand boundaries to include additional pathways such as nutrient runoff and soil carbon dynamics. Third, scaling conditions are context-specific: governance capacity, market access, and consistent quality assurance will shape whether similar circular systems perform as intended.

7 Conclusion

This study provides monitored case evidence that a Smart-Eco Farming Village model can connect waste pollution control and water efficiency with low-carbon objectives when CSA is implemented as a living lab. In TAMENG, approximately 1,095 tons/year of residues were processed into liquid organic fertilizer and feed concentrate, with a program-estimated mitigation of about 555 tCO2-e/year and water savings up to 65% in precision irrigation pilots.

Beyond technical outputs, the case highlights the enabling role of inclusive local institutions and learning infrastructure (Agronova Vision and the Resource Center/P4S). These mechanisms helped translate circular and precision practices into livelihood gains and a visible pathway for replication.

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