

A Regenerative Business Ecosystem for Village-Scale Waste Autonomy

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Abstract. Unmanaged waste and limited landfill capacity increase the need for source-based, community-scale solutions, particularly in agrarian villages where waste management intersects with synthetic fertilizer dependence and soil degradation. This paper proposes a digital-governance and MRV-enabled Regenerative Business Ecosystem (RBE) to achieve zero waste outflow by integrating material, value, and information flows at village scale. The embedded case is Batur Village (Getasan, Semarang Regency), which operates a 3R waste facility and the Hijao App for pickup scheduling, recordkeeping, and incentives. Using Design Science Research (DSR) with an embedded case study, we develop three artefacts: (1) an RBE with nutrient (organics → compost → farmland), energy (selected fractions → pyrolysis → internal energy use), and recycling (valuable inorganics → offtakers) loops; (2) a digital governance blueprint covering source-separation rules, quality control, safety procedures, incentives and benefit-sharing, and role-based accountability; and (3) an MRV specification linking data capture, verification, audit trails, and KPI dashboards. The baseline indicates an intake of ~4 t/day with capacity constraints creating processing backlogs, motivating a scaling-oriented design. Scalability is examined through scenario assessment toward a 10 t/day inter-village service concept using capacity projections and market assumptions, with results presented as output and value potential.

1 Introduction

Unmanaged waste remains a major obstacle to sustainable development in Indonesia. The National Waste Management Information System reports that 65.7% of national waste generation (± 25.33 million tons/year) is still inadequately handled [1]. This service gap correlates with environmental and health impacts, increased greenhouse gas emissions, and the loss of potential economic value from waste [2]. Open burning of household waste and agricultural residues is still common in various regions, further worsening environmental degradation [3]. Amid the limited capacity of landfills, source reduction and strengthening community-based management, including minimizing residual waste leaving the village, are becoming increasingly urgent.

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In agrarian rural areas, waste problems are directly tied to the economic sustainability of production. Input cost pressures, climate risks, and limited market access weaken the resilience of farming households [4]. The dominance of synthetic fertilizers and the minimal integration of locally sourced organic fertilizer maintain a vulnerable production pattern [5], while excessive use of chemical fertilizers contributes to soil degradation and long-term declines in productivity [6]. Therefore, processing organic fractions into compost has the potential to provide dual benefits: reducing residual waste while restoring nutrient cycles for soil regeneration.

This study focuses on Batur Village (Getasan, Semarang Regency), which has been operating a 3R waste facilities, separation facilities, household sorting bins, and collection and recording services through the Hijao App. In the pilot phase, the system handled about 4,000 kg/day with a relatively balanced composition of organic and inorganic waste; however, limited capacity meant that daily service coverage from 18 villages only reached about 5 villages, resulting in a processing backlog. The waste-to-value pathway has been implemented through compost production, channeling valuable inorganic materials to off-takers, and small-scale pyrolysis for certain fractions [7]. Even so, the ecosystem has not yet been fully orchestrated, from standards for segregated supply, quality control and safety SOPs, financing schemes, incentives and benefit-sharing, to auditable MRV (measurement-reporting-verification).

To address these gaps, this research formalizes and refines the design of a Regenerative Business Ecosystem (RBE) based on digital governance and MRV to integrate nutrient loops (compost), energy (pyrolysis with feedstock control and safety SOPs), and recycling toward the target of zero waste outflow, while designing cross-village service scale-up based on the pilot baseline to overcome capacity limitations and backlogs.

2 Literature Review

Table 1 summarizes the synthesis of waste-to-value/RBE literature and digital governance-MRV in the context of villages based on 3R waste facilities. This synthesis highlights the gap in end-to-end integration (technology-governance-financing-incentives) and serves as the basis for designing the operational ecosystem and readiness for service escalation across villages.

Table 1. Literature Synthesis and Research Gap

Literature area	Dominant focus	Gap	This paper's contribution
RBE / circular / regenerative	Value-from-waste principles & system sustainability [8]	Not yet operational at village scale based on a 3R waste facility	Designs a 3R waste facility-based RBE toward zero waste outflow
Organics → compost	Composting as organic waste valorization	Compost offtake and incentives are not yet integrated	Nutrient loop + supply governance and benefit distribution
Selected fractions → pyrolysis	Local energy recovery [7]	QC/ feedstock management and safety are often separated from governance	Energy loop with QC, safety, and accountability prerequisites
Digital platform	Collection/ pickup, recordkeeping, incentives [9]	Data auditing and the incentive-performance linkage remain weak	Role-based workflow + MRV-linked incentives
Digital governance	Transparency and accountability [10]	Benefit-sharing and financing are not made explicit	Governance blueprint: rules, RACI, benefit-sharing, OPEX

MRV	Performance measurement/reporting [10]	Verification and audit trails are not yet operational	Auditable MRV + KPI dashboard
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3 Research Methodology

This study uses Design Science Research (DSR) with an embedded case study to design an operational artifact for waste management in agrarian villages [11]. The setting is Batur Village, Getasan District, Semarang Regency, with the 3R waste facility serving as the management hub and the Hijao App as a platform for pickup services and participation incentives. The actors include the village government, 3R waste facility managers, households, farmers/farmer groups, and inorganic material offtaker partners. This study applies DSR to design artifacts: RBE, a governance blueprint, and MRV. The artifacts were demonstrated through pilot implementation in Batur Village. Scalability assessment used scenario analysis based on pilot baseline, capacity projections, and market assumptions, so findings are indicative and require further evaluation. The DSR stages are summarized as follows:

- Problem identification: mapping existing processes and main gaps (segregated supply, QC/safety, financing, incentives/benefit-sharing, as well as auditable MRV requirements).
- Requirements: formulation of design needs to achieve zero waste outflow (regulations, roles/accountability, incentives, and verifiable KPIs).
- Design artifacts: development of (i) RBE design (nutrient–energy–recycling loop), (ii) digital governance blueprint (rules, RACI, incentives, benefit-sharing, QC/safety), and (iii) MRV architecture and platform workflow (recording–verification–reporting).
- Demonstration: demonstration in a pilot through key operational scenarios (deposit/pickup → weighing → verification → processing → benefit distribution → reporting).
- Scalability assessment (ex-ante): analysis of service escalation scenarios based on pilot baseline, projection of processing capacity, and market/output absorption assumptions, to identify prerequisites and scalability risks.

Data were collected through interviews, observations, and documents (SOPs/ regulations/ records), as well as operational data from the 3R waste facility. Analysis was carried out by mapping material–value flows, actor–role mapping, and governance gap analysis to determine design requirements and develop artifacts operationally.

4 Case Context

Batur Village, Getasan District, Semarang Regency, Indonesia, operates a 3R waste facility for sorting and processing waste, with sorting facilities (conveyor) and household-level shorting bins. Waste collection occurs periodically through pick-up services and recording via the Hijao App. The pilot phase handles 4,000 kg/day with balanced organic and inorganic fractions; however, limited operational capacity means only 5 of 18 villages receive daily service, creating a processing backlog. Management routes include organic processing using composters (maggot and drum), channeling valuable inorganic fractions to offtakers, and small-scale pyrolysis (± 5 kg/batch; ± 1.5 hours) as proof of concept. This context serves as the minimum system boundary to design end-to-end integration of 3R facility operations, digital governance, and MRV within RBE framework, including capacity enhancement to reduce backlog and support service escalation.

5 Proposed Framework

This study proposes a Regenerative Business Ecosystem (RBE) framework based on digital governance and MRV to achieve zero waste outflow through the integration of material, value, and information flows at the village scale. This section presents artifacts at the requirements-workflow level (minimum specifications) so that the system implemented in the pilot phase can be stabilized and prepared for service escalation. Figure 1 provides a detailed illustration of the proposed framework.

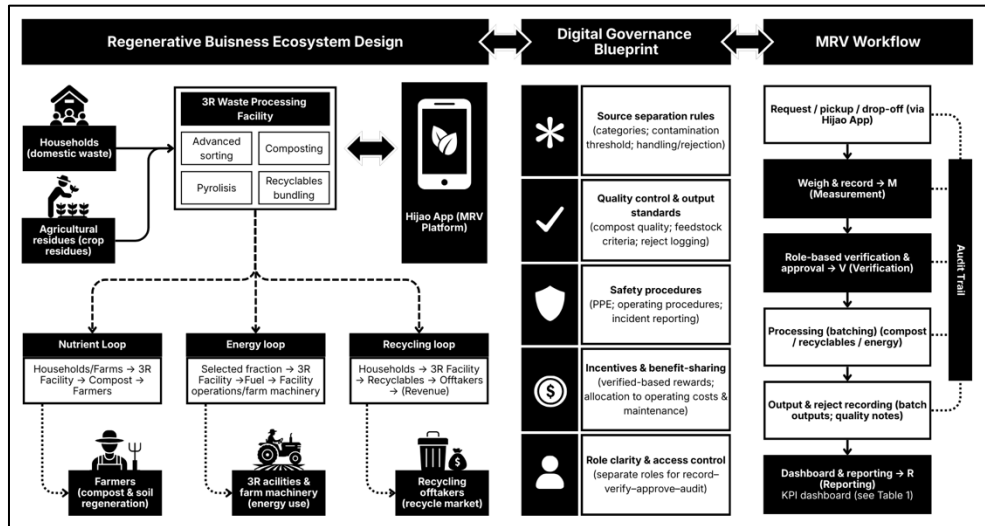


Fig. 1. Integrated framework for a village-scale Regenerative Business Ecosystem (RBE)

5.1 RBE Design: three loops and actor configuration

RBE in Batur Village is designed as three loops centered around the 3R waste facility as a hub (supply consolidation, advanced sorting, and valorization processes):

- Nutrient loop: household organic waste/agricultural residues → processing at a 3R waste facility → compost → distribution to farmers/farmer groups for soil regeneration.
- Energy loop: selected fractions (generally inorganic) → pyrolysis → energy products for internal needs (3R waste facility and/or community agricultural machinery), with the prerequisite of feedstock control and safety SOPs.
- Recycling loop: valuable inorganic materials → aggregation/packaging → offtaker → revenue to support OPEX and incentives.

Institutionally, the 3R waste facility operator acts as the orchestrator of operations and services; the village government/Environmental Agency serves as an enabler through local regulations, guidance, and infrastructure support; while households, farmers, and offtakers are the actors who supply inputs and absorb outputs. This configuration is designed to link valorization with service and financing mechanisms, so that processing backlogs can be reduced by controlling inflows and increasing capacity.

5.2 Digital Governance Blueprint

The governance blueprint establishes minimum rules to ensure that the loop runs consistently, safely, and fairly, especially under limited capacity conditions and during cross-village escalation. Its main components include: (i) segregated supply rules (material categories, contamination thresholds, rejection/handling mechanisms); (ii) QC and output standards (compost quality; suitability of pyrolysis feedstock; rejection recording); (iii) safety SOPs (PPE, operating procedures, incident reporting—especially for thermal processes); (iv) incentives and benefit-sharing tied to verified contributions and allocated for operators, OPEX, and maintenance funds; and (v) RACI and role-based access rights to separate input, verification, approval, and audit functions. This blueprint is positioned as a rule-set that can be gradually adopted according to organizational readiness and operational capacity.

5.3 MRV dan workflow platform

MRV is designed to ensure the system's performance is measurable—reported—verified and auditable under realistic operational loads. The implementation utilizes existing features of the Hijao App (collection/recording/reward) and adds the minimum MRV elements: core data (material type, weight, source, time, operator), contamination/reject indicators, batch process and output recording (compost/energy if available), as well as incentive transactions and benefit allocation. The role-based verification mechanism ensures that weighing data and quality are approved by officers/verifiers before being recorded by the manager, supported by minimum evidence (e.g., batch/QR number or weighing proof) according to capacity. All data changes are recorded as an audit trail for quality control and anomaly tracking. The KPI dashboard presents operational summaries (3R waste facility), governance summaries (village administration), and monitoring (Environmental Agency), including service indicators (e.g., SLA/backlog) to manage processing queues. The proposed minimum MRV KPIs are summarized in Table 2.

Table 2. MRV KPIs, Data Sources, and Responsible Parties

MRV KPI	Operational definition (brief)	Primary data source	Frequency	Owner (R/A)
Serviced intake	kg of waste entering the system (weighed/recorded)	TPS scale records + Hijao App logs	Weekly	Weighing staff / TPS manager
Sorting compliance	% transactions meeting sorting standard (\leq contamination threshold)	Verification form + transaction logs	Monthly	Verifier / TPS manager
Contamination/rejects	% weight rejected or reworked due to contamination	QC log + batch recap	Weekly	QC staff / TPS manager
Diversion rate	% intake diverted from off-site disposal (compost + recycling + energy)	Output recap + residual records	Monthly	TPS manager / Village gov.
Compost output	kg compost produced (verified batches)	Compost batch log	Weekly	Compost operator / TPS manager
Compost uptake	% compost distributed/used by farmers	Distribution log + recipient proof	Monthly	TPS manager / Farmer group lead
Recyclables revenue	IDR from sales to offtakers	Receipts/invoices + sales recap	Monthly	Treasurer / TPS manager

Service performance (SLA)	% pickups completed on time	App scheduling & completion logs	Weekly	App admin / TPS manager
Processing backlog	Intake minus processed volume (kg/day or “days of backlog”)	Intake vs output recap	Weekly	TPS manager / Village gov.
Energy output	Volume produced and internal use	Production/use log	Monthly	Thermal operator / TPS manager

6 Pilot Demonstration and Ex-ante Scalability Assessment

The Desa Batur 3R waste facility pilot operates with collection via the Hijao App, organic processing (maggot cultivation and drum composter), distribution of valuable inorganic waste to offtakers, and small-scale pyrolysis as proof of concept. The baseline shows an intake of 4,000 kg/day with a balanced organic–inorganic composition. However, sorting capacity remains limited, so from 18 villages in the service area, daily coverage reaches only 5 villages, with waste forming a backlog. These findings show the key issue is capacity management (inflow-SLA-backlog) and the need for supply standardization to maintain performance as load increases. Scalability is assessed through scenario analysis toward a target of 10 tons/day with planned capacity of 5 tons/day for rapid composter and 5 tons/day for pyrolysis. Based on yields and projected prices, this scenario yields potential gross value of Rp 41.09 million/day from compost and pyrolysis outputs. This value is indicative (not including CAPEX/OPEX and risks), so main prerequisites for escalation include contamination control, SOPs for thermal process safety, output uptake assurance, and minimum MRV to monitor SLA/backlog and accountability for incentive-sharing (Table 2). A summary of scenarios is presented in Table 3.

Table 3. Pilot baseline vs. escalation scenario (ex-ante)

Dimension	Pilot (existing)	Scale-up (ex ante)
Throughput	±4,000 kg/day	10,000 kg/day
Service coverage	18 villages; daily effective coverage ≈5 villages; processing backlog	Cross-village/subdistrict service via a hub-based model (3R waste facility)
Organics pathway	Black soldier fly larvae (maggot) + drum composter	Rapid composter, 5 t/day
Inorganics pathway	Valuable recyclables → offtakers	Remains → offtakers (with supply QC)
Energy pathway	Pyrolysis PoC, 5 kg/batch (±1.5 hours)	Pyrolysis, 5 t/day; fuel/wax + substitution gas
Key outputs	Compost + sale of recyclables; energy as PoC	Compost ≈3,500 kg/day; fuel ≈1,500 L/day; wax ≈1 t/day
Economic value potential	-	Gross value ≈ IDR 41.09 million/day (indicative)
Scaling prerequisites	Reduce contamination; manage backlog; recording burden	QC & safety SOP; output offtake; MRV for SLA/backlog and accountability

7 Results & Discussion

This study produced three integrated artifacts: (i) a Regenerative Business Ecosystem (RBE) design based on a 3R waste facility with three loops (nutrient–energy–recycling), (ii) digital governance specifications (supply rules, QC/output standards, safety SOPs, incentives, RACI and access rights), and (iii) MRV specifications (core data, role-based verification, audit trail, KPI dashboard). These artifacts consolidate existing components into an orchestratable

system, linking material flows with value flows (incentives, OPEX financing, maintenance) and information flows to strengthen backlog control, supply quality, and accountability.

The main contribution bridges the gap between technical waste-to-value pathway and governance mechanisms for sustainability. Contamination control and standardization reduce compost quality degradation risk; RACI and verification limit moral hazard; while service KPIs enable capacity management for pilot constraints. Implementation faces trade-offs: reducing contamination requires education and disincentives that may trigger resistance; MRV must prioritize viable data to avoid increased recording burdens; thermal operations require SOP discipline, material control, and risk management; and financial sustainability depends on guaranteed uptake of outputs, making market networks and distribution mechanisms essential.

This design can serve as foundation for village regulations to establish sorting standards, service SLAs, incentive schemes, and MRV reporting mandates. The design affirms the 3R waste facility operator as service orchestrator while increasing transparency of financing. At regional level, the hub-and-spoke scheme enables the Batur 3R waste facility to serve surrounding villages, requiring QC standardization, safety, and MRV data interoperability to prevent backlog increase or benefit distribution conflicts.

8 Conclusion & Future Work

This study formalizes and refines the pilot waste management system of Batur Village into an RBE framework based on digital governance and MRV to achieve zero waste outflow and service escalation readiness. The main contributions of this research are: (1) the design of an RBE based on a 3R waste facility with three integrated loops (nutrient–energy–recycling); (2) minimum specifications for digital governance that ensure supply quality, safety, incentives, and benefit-sharing through clear division of roles; and (3) minimum auditable MRV specifications to monitor service performance (including SLA/backlog) and support accountability in benefit distribution.

Further research is needed to: (i) conduct a structured field evaluation of the effectiveness of governance and MRV (including implementation tests for verification modules and audit trail on the platform); (ii) measure the agronomic impact of increased compost use, such as changes in chemical fertilizer use and soil quality indicators; and (iii) empirically test inter-village scaling scenarios, including capacity needs, logistics, financing, and MRV data interoperability mechanisms for hub-and-spoke operations.

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