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# Integrating BioEnergi : Living Lab Renewable Energy TPST 3R Mulyoagung Sejahtera

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## Abstract

**Introduction/Main Objectives:** Integration of renewable energy systems based on biomass and biogas in the BioEnergi Living Lab project at TPST 3R Mulyoagung Bersatu. The primary aim is to develop an educational, research, and technology innovation space for renewable energy conversion through waste processing, particularly using biogas and biomass-based technologies.

**Background Problems:** Urban waste management issues require innovative solutions, particularly in the application of 3R (Reduce, Reuse, Recycle) principles. The potential for converting organic waste into renewable energy offers significant benefits, including reducing fossil fuel dependency and mitigating greenhouse gas emissions.

**Research Methods:** BPMN-based modelling which employs a community-driven Living Lab model, integrating both technological innovation (such as biodigesters, pyrolysis, and IoT) and social engagement. Involves active collaboration between universities, local communities, and government agencies to implement and monitor renewable energy conversion technologies, data collection through IoT sensors and real-time monitoring systems.

**Finding/Results:** Project successfully demonstrated the capacity of converting 15-30 tons of organic waste monthly using biodigesters and pyrolysis for up to 6 tons of plastic and 5 tons of paper. IoT-enabled systems ensured real-time monitoring of critical parameters such as gas production, reactor temperature, and safety protocols. Highlight the potential for creating a circular economy model by producing biogas, biochar, and organic fertilizers.

**Conclusion:** BioEnergi Living Lab project offers a sustainable and scalable model for waste-to-energy conversion, contributing to both energy independence and environmental sustainability. Innovative addresses urban waste management issues, community engagement and local economic growth through renewable energy-based solutions.

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**Keywords:** Green Innovation, Renewable Energy, Biogas, Waste-to-Energy, Circular Economy

# Introduction

Integration of biogas systems from waste into energy production within the framework of a circular economy presents a sustainable approach to waste management while generating renewable energy. Model emphasizes resource efficiency, waste valorization, and environmental impact reduction through innovative technologies and practices. The following sections outline the key aspects of this approach, highlighting its urgency, novelty, potential, and implications for a sustainable future. Biogas Production and Circular Economy. Anaerobic Digestion transforms organic waste into biogas, which can be utilized for energy production, minimizing carbon emissions and enhancing waste recycling (Acharya, 2020). Resource Recovery Biogas systems can produce biofertilizers and other value-added products, promoting a circular economy by reusing waste materials (Begum et al., 2024).

Potential have opportunities but policy coherence effective implementation of biogas systems requires cohesive cross-sector policies to address barriers and enhance local circular economies (Acharya, 2020). Implication technological innovations upgrading biogas to biomethane can facilitate its use as a clean fuel, in line with the principles of circular economy (Begum et al., 2024). On a local level, communities can benefit from reduced waste disposal costs, cleaner environments, and the creation of green economic. biogas systems contribute to the fight against climate change by reducing methane emissions from landfills and providing an alternative to fossil fuels. However, the successful integration of biogas systems requires coordinated efforts between policymakers, industries, and communities (Pitcairn et al, 2017). Addressing challenges such as policy coherence, technological advancements, and the need for comprehensive life cycle assessments is essential to ensure these systems deliver their full potential without unintended negative consequences. Community-based waste-to-energy models prove that organic waste can be routed through clearly defined technological pathways (e.g., biodigester, composting, pyrolysis) and governance steps, which can be explicitly represented as tasks, gateways, and roles in BPMN (Junus et al., 2025).

International Examples: Studies from the UK and Chile illustrate the potential of biogas systems in diverse contexts, highlighting the need for tailored approaches to local waste management challenges (Acharya, 2020; González et al., 2018). While the transition to a circular economy through biogas waste-to-energy systems shows promise, it is essential to consider the potential environmental impacts and resource consumption associated with these technologies (Almendrala & Evidente, 2022). Strong Green marketing management implies not only lipservice that BPMN must include activities for community outreach, education, and feedback loops to support participation in each waste-sorting and energy-use step (Putra, 2022). A comprehensive life cycle assessment is crucial to ensure that the shift does not lead to unintended consequences (González et al., 2018).

# Research Methods

Methodology BPMN-based modelling for the BioEnergi Living Lab TPST3R project follows an iterative approach, where each phase builds upon the previous one. Effective asset management requires BPMN tasks and lanes that show responsibility for maintaining reactors, sensors, and other critical infrastructure to ensure process continuity and reliability (Putra, 2024). Structure ensures continuous improvement in the technology and processes involved. Below is an outline of the iterative phases. Summarizing the iteration mechanism for the BioEnergi Living Lab TPST3R project. It includes the focus, planning, analysis, design, implementation, validation, and deliverables for each iteration phase (1, 2, and 3). he overall BioEnergi Living Lab application follows these frameworks:

- Micro level: Individual and household behavior change, skills, and direct energy benefits.

- Meso level: Community institutions like TPST3R, SMEs, and universities with integrated energy tech and decision-making.
- Macro level: City, regional, policy, and national model replication and energy strategy adoption.
- Meta level: Long-term systemic change including national standards, innovation culture, and waste perception shifts.

Figure1. Iteration Living Lab TPST 3R Mulyoagung Bersatu

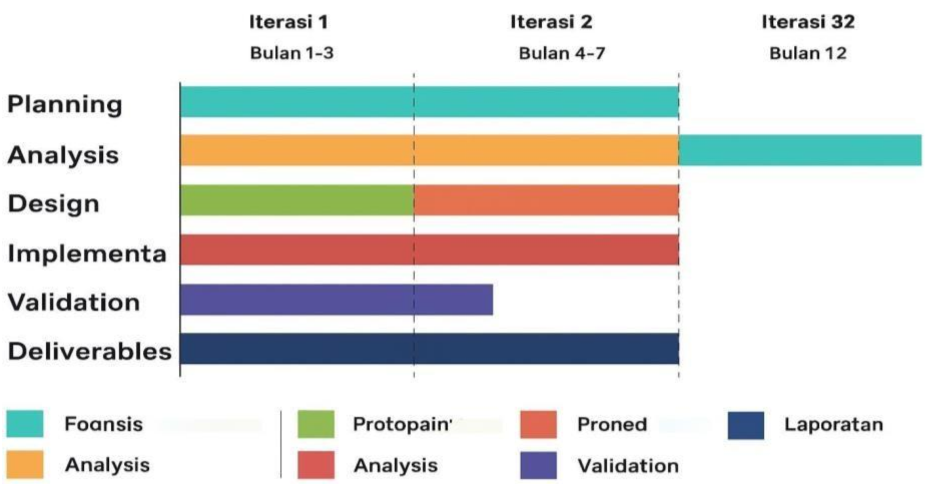



Table 1. Iteration Reseach Methode  BioEnergi Living Lab TPST3R project based

| Iteration Stage | Focus | Planning |
|---|---|---|
| Iteration 1 (Months 1-3) | Initial mapping, prototype development | Define focus on waste processing scale, baseline values, prototype needs |
| Iteration 2 (Months 4-7) | Optimize biodigester, pyrolysis, IoT | Target performance improvements, improvement planning |
| Iteration 3 (Months 812) | Scale up, full system integration | Develop scaling and replication plans |

Source : Team Reseacher Addopt Maroua et al., 2020; Gudek, 2019)., 2025

This iterative and multi-level approach drives continuous improvement, community involvement, and scalable impact for sustainable waste-to-energy solutions under the BioEnergi Living Lab TPST3R project.

## Discussion

TPST 3R Mulyoagung Bersatu currently focuses on traditional 3R-based waste management, so its main orientation is reducing waste volume rather than maximizing its energy value. The high proportion of residual waste (>10%), low community participation (<50%), limited economic returns, and non-digital monitoring system indicate that the potential for converting waste into renewable energy is still underutilized and not yet scientifically measured in a systematic way (Szyba & Mikulik, 2022). Environmental management accounting suggests that BPMN should model data-capture and reporting activities that trace costs, benefits, and environmental performance along the waste-to-energy process at TPST 3R Mulyoagung Bersatu (Putra et al., 2025). These conditions highlight the urgency of science- and technology-based strengthening, for example through biodigester and pyrolysis technologies integrated with digital monitoring, to transform waste into higher-value, efficient, and sustainable renewable energy while simultaneously increasing transparency, accountability, and long-term community benefits.

Table 2. Root Cause TPST 3R Mulyoagung Bersatu

| Main Effect (Problem) | Cause Category | Root Cause |
|---|---|---|
| | Technology & Infrastructu | - Dependence on conventional grid electricity |
| | People & Social Behavior | - Lack of integrated waste-to-energy technologies |
| | Process & Governance | - Limited and fragmented recycling system |
| | | - Low community participation in waste sorting |
| | | - Limited number of trained personnel in energy t- echnologies |
| Renewable energy potential from waste not utilized optimally; low added value output | | - Weak coordination among actors in the waste–energy sector |
| | | Inadequate monitoring of energy output and residual waste |
| | | Limited funding for green energy innovation No economic incentives to adopt or develop innovation |
| | Economy & Supporting Policies | - Operational dependence on routine government/organizational budget |

Source : Team Reseacher, 2025

Table 3. Implementation BioEnergi Living Lab TPST3R Project Based

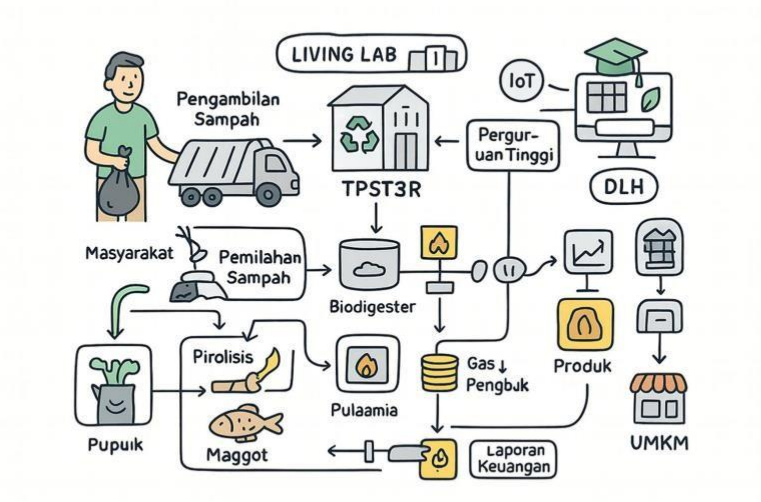
| Iteration Stage | Analysis | Design | Implementation | Validation | Deliverables |
|---|---|---|---|---|---|
| Iteration 1 (Months 1-3) | Waste characteristics, FGDs with stakeholders, identify energy losses | Design biodigester v1, pyrolysis v1, IoT sensor architecture, monitoring dashboard | Install pilot systems for batch processing and basic IoT, training for operators and students | Functional tests, data accuracy checks, feedback surveys | Prototype v1, baseline energy report, improvement list |
| Iteration 2 (Months 4-7) | Analyze IoT data, operational audits, safety assessments | Redesign biodigester v2 and pyrolysis v2, enhance IoT dashboard v2 | Implement hardware/software improvements, scale up operations, monitor energy | Validate biogas/fuel stability, product quality tests, IoT sensor accuracy | Stable prototype v2, energy improvement report, energy prediction model |
| **Iteration Stage** | **Analysis** | **Design** | **Implementation** | **Validation** | **Deliverables** |
| Iteration 3 (Months 8-12) | Evaluate Iteration 2 results, economic feasibility, SOP/risk analysis | Finalize large-scale system designs, integrate IoT with energy management, develop training | Implement full-scale systems, retrain operators, integrate full waste-toenergy flow | Comprehensive environmental, economic, social impact evaluation, readiness survey | Final SOP, full IoT integration, final report, replication package |

Source : Team Reseacher, 2025

Implitation BioEnergi Living Lab at TPST 3R Mulyoagung Bersatu demonstrates how a conventional community-based waste management facility can be transformed into an integrated waste-to-energy ecosystem through carefully structured operational flows. The daily event starts from household-level waste preparation, where citizens separate their waste before collection, then proceeds through a series of sorting, treatment, and valorization tasks that generate both material products (compost, maggot feed, soap, fuel oil, biochar) and energy outputs (biogas for cooking and transport fuel). This end-to-end chain is closed by financial reporting and data transfer to local government, ensuring that environmental benefits are linked to economic accountability and policy-level monitoring.

At the TPST 3R node, the first critical stage is waste collection and triage into inorganic, organic, and non-processable fractions. Inorganic waste enters a sub-process where it is sorted, weighed, and recorded in a digital system, allowing the facility to quantify recyclable flows and automatically estimate their market value before packaging and sale to aggregators. This pathway not only generates immediate revenue but also builds a traceable database of material recovery performance that can be used to design incentives, adjust pricing strategies, and evaluate the contribution of recycling to the overall circular economy model at the site (Elroi et al., 2023).

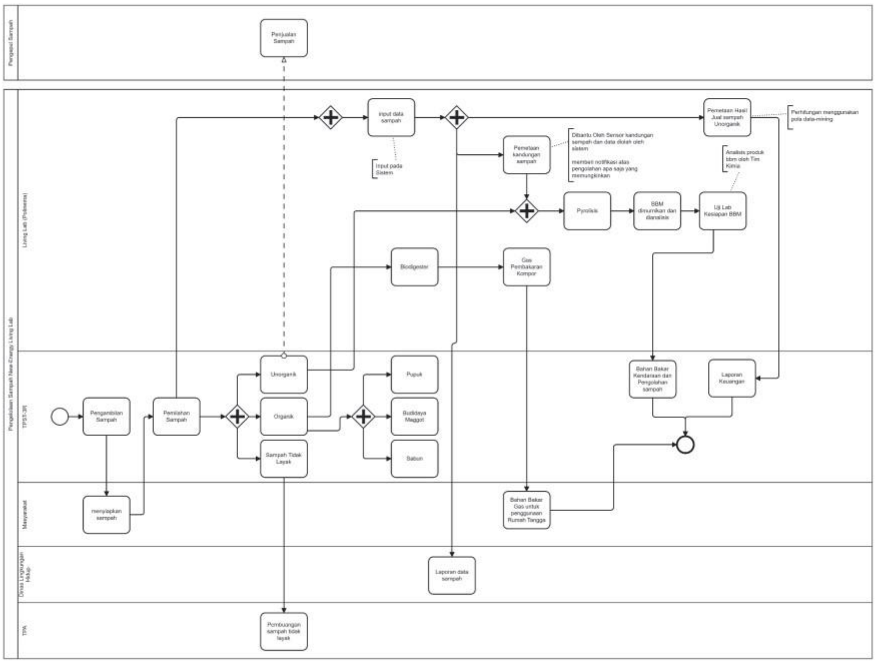
Figure 2. Living Lab Renewable Energy TPST 3R Mulyoagung Sejahtera




Organic waste is routed through multiple valorization branches that exemplify the Living Lab's experimental and multi-output character. Part of the organic stream is converted into compost or liquid fertilizer, another portion is directed to maggot cultivation, and selected fractions are used as feedstock for soap production from used cooking oil and similar residues. In parallel, the Living Lab integrates a biodigester that converts suitable organic substrates into slurry and biogas, which is then utilized directly for household cooking or upgraded to compressed gas for mobility applications; this multipath configuration enables comparative assessment of environmental performance, user acceptance, and economic returns across alternative treatment routes.

A distinct innovation dimension lies in the combination of pyrolysis and digital monitoring for specific residual streams that are not adequately addressed by conventional composting or digestion (Lindkvist et al, 2019). Selected organic residues and plastic-rich fractions are processed through pyrolysis to produce fuel oil, syngas, and solid carbon, all of which are subjected to laboratory testing to verify fuel quality, safety, and regulatory compliance. The integration of IoT sensors and machine learning algorithms allows real-time monitoring of feedstock characteristics, process parameters, and product quality, and the system can recommend optimal processing routes, issue alerts when compositions deviate from safe thresholds, and predict energy output under varying input conditions, turning the facility into a data-rich experimental platform rather than a static treatment plant.

Figure 3.  Business Process Model and Notation BioEnergi Living Lab TPST 3R Mulyoagung




- BPMN model starts with a start event representing the initiation of daily waste management activities at the household level. Households perform the first task, namely preparing and pre-sorting waste before collection by TPST 3R operators.
- After collection, TPST 3R conducts a sorting task that classifies waste into organic, inorganic, and non-processable fractions. An exclusive gateway is used to branch the process into three paths according to waste type: inorganic waste is routed to recycling and sale activities, organic waste is routed to multiple valorization options (composting, maggot cultivation, biodigester), and non-processable waste is sent to the landfill.
- At the end of each branch, energy and product outputs, together with the associated financial data, are consolidated in a final recording task, which leads to the end event "Energy, products, and financial report consolidated". This simple BPMN representation clarifies the main actors, decision points, and value-creation routes in the BioEnergi Living Lab process.

BPMN (Business Process Model and Notation) suitable to integrated for model TPST 3R Mulyoagung Bersatu for standard graphical notation designed to effectively model and visualize business processes, developed by the Object Management Group (OMG) to improve communication and provide a comprehensive framework for workflow analysis and optimization (Gudek, 2019; Martinek, 2018). Its core components include flow objects (activities, events, gateways), connecting objects (sequence flow, message flow), and artifacts/data, which together enable a clear representation of process logic and interactions between participants (Martinek, 2018). In practice, BPMN supports process improvement by helping identify workflow weaknesses and facilitating clearer communication among stakeholders, and it is widely implemented in tools such as Bizagi Modeler and Camunda Modeler (Mursyada, 2024) However, BPMN still has limitations, particularly for document-centric processes and security challenges in cloud environments, which motivates further research and possible extensions to the notation (Maroua et al., 2020).

Finally, the Living Lab perspective is reinforced by the way information and responsibility are distributed across stakeholders and governance levels. Sensors continuously track variables such as pH, gas composition, temperature, moisture, and organic–inorganic ratios, and these data feed into dashboards that guide operators in choosing between biodigestion, pyrolysis, composting, or maggot production for each waste batch. Nonprocessable waste is transparently dispatched to the regional landfill, while aggregated tonnage and performance indicators are reported to the Environmental Agency, closing the loop between community practice, technological experimentation, and public policy. This configuration positions TPST 3R Mulyoagung Bersatu not only as a service provider but as a living laboratory where co-created, evidence-based innovations in circular waste-to-energy systems can be piloted, refined, and eventually replicated in other localities.

## Conclusion

BioEnergi Living Lab at TPST 3R Mulyoagung Bersatu shows that community waste management can be transformed from a linear "collect–transport–dispose" pattern into an integrated circular system that generates both products and energy. Starting from householdlevel sorting, the process systematically directs inorganic, organic, and residual fractions into differentiated value chains: recycling and sales, composting, maggot cultivation, soap production, biodigestion, and pyrolysis. Model clarifies roles, decision points, and data flows, demonstrating that waste can be managed as a controlled resource stream rather than a passive burden. Integration of IoT-based monitoring and data analytics further strengthens the Living Lab character of the system by enabling real-time sensing of waste characteristics, predictive recommendations for optimal processing routes, and traceable financial and environmental performance.

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