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Research Article

# Operationalizing One Health in Surabaya: Successes and Limitations of Community-Led Waste Management Technologies

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**Abstract** | Urban livestock waste poses a challenge to environmental hygiene and a risk of transmitting zoonotic diseases. This study evaluated the performance of three pilot community-based waste management technologies, including poultry manure composting, single-stage biofiltration, and small-scale biogas digesters, implemented in an urban livestock cluster in Surabaya, Indonesia. The assessment was a small-scale field evaluation integrating laboratory testing with routine monitoring of system operation. Laboratory results for the compost showed a high moisture content (44.45%) and a high C/N ratio (46.42), indicating incomplete stabilization compared to the Indonesian National Standard (SNI) requirements. The biofilter demonstrated substantial oil and grease removal (88%), but only a small reduction in BOD and COD (11%), resulting in a final effluent that did not meet quality standards. Biogas production was inconsistent and highly sensitive to seasonal temperature fluctuations, which slowed gas formation during the rainy season. Community participation enabled the installation and routine operation of the technology, highlighting that social adoption is feasible, but technological performance remains susceptible to environmental conditions and design limitations. This study provides key insights into the technical barriers to utilizing wastewater technology for animal waste in urban areas. It also demonstrates the importance of strengthening and scaling up community-based waste management interventions that support One Health, potentially reducing environmental and zoonotic health risks.

**Keywords** | Community participation, One health, Urban livestock, Waste management, Waste technology

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## INTRODUCTION

Currently, the increasing complexity of urban public health challenges requires a multisectoral approach that integrates human, animal, and environmental health (Pratama *et al*., 2024; Ellwanger *et al*., 2022). The One Health framework provides a relevant approach in urban areas like Surabaya. Surabaya, the second largest city in Indonesia, still has urban livestock farming still persists in densely populated residential areas. Poor waste management and close contact between humans and animals increase the risks of zoonotic disease emergence and environmental degradation (Blaiotta *et al*., 2016; Fasya *et al*., 2025; Penakalapati *et al*., 2017). The interconnection between urban planning and public health is increasingly being recognized through system-based tools and frameworks. The One Health approach provides a more ecological perspective in designing healthy and sustainable cities (Bruno *et al*., 2024; Doiron *et al*., 2024).

Surabaya has achieved national and international recognition for its community-based solid waste management programs, which have effectively reduced waste volumes and associated public health risks (Gamaralalage *et al*., 2017; Mulasari *et al*., 2024). Similar participatory approaches in Indonesia demonstrate that community ownership can enhance the long-term sustainability of waste management interventions (Mukhlis *et al*., 2025). These successes reflect a broader policy orientation in Indonesia that emphasizes behavior change and engagement at the household level (Yin, 2018). In this context, Surabaya's "Smart City" vision encourages community involvement in environmental management and offers a strategic opportunity to integrate One Health into urban sustainability agenda (Anthony, 2023; Fauziah *et al*., 2022; Sari *et al*., 2020; Soedirham, 2012).

A critical evaluation of the feasibility studies or scoping assessments that informed the adoption of decentralized waste technologies is needed to ensure their suitability and potential for large-scale implementation across urban environtments (Heryawan and Mukono, 2023; Widyatmika and Bolia, 2024). Previous research in Mojokerto city has demonstrated the viability of biodigesters for converting food waste into energy, suggesting the technology's potential in areas with similar waste composition (Sari *et al*., 2024). This context warrants an examination of whether small-scale, community-based technological interventions are adequate to manage the significant waste volumes and heterogeneous waste streams present in Surabaya, particularly given the city's aspirations for more comprehensive waste management and its limited existing recycling infrastructure (Khiawnoi *et al*., 2025; Setiawan and Indrianingsih, 2020).

Household waste in urban clusters in East Java has been previously assessed by municipal waste agencies and community groups, indicating that 50–70% of the waste is biodegradable, consistent with national evaluations of municipal solid waste composition (Landon *et al*., 2013). In Surabaya, approximately 59% of household waste is organic, with additional nutrient-rich and high-moisture inputs originating from small-scale urban livestock activities (Maulidia and Haryo, 2024). These characteristics are suitable for the operational requirements of composting systems for solid manure, biofilters for animal wastewater, and biodigesters for fresh manure. Previous studies have demonstrated the feasibility of household-scale biodigesters for processing high-moisture substrates (Sari *et al*., 2024). Furthermore, the application of biofilters in similar low-resource environments has also demonstrated substantial reductions in COD, BOD, and TSS (Sugito *et al*., 2024; Darwati *et al*., 2019).

This study assessed whether community-adapted composting, biofiltration, and biogas technologies can achieve functional waste treatment performance and meet Indonesian waste treatment standards under real urban livestock conditions. This study included an evaluation of the technologies' successes, operational challenges, and limitations within a One Health framework.

## MATERIALS AND METHODS

### Study design, time, and location

This study used a mixed-methods evaluation approach to assess the operational performance of three community-adapted waste management technologies: Composting, single-stage biofiltration, and small-scale biogas digestion. The quantitative method used laboratory tests to compare the results with Indonesian National Standards (SNI) and Government Regulations, while the qualitative component involved interviews with livestock farmers to understand user experiences and operational challenges. This pilot study was conducted from August to December 2024 in three urban livestock clusters: a dairy farm, a poultry farm, and a slaughterhouse in Surabaya, East Java.

### Composting technology for poultry manure

The compost production process, as shown in Figure 1, was carried out by the Mekar Sari Farmers Group in Gubeng District using two 50 L compost bags. Fresh chicken manure was mixed with an EM4 solution (30 mL EM4 per 1 L of water) until homogeneous, and the moisture content was adjusted using a hand pressure test. Carbon-rich fillers such as rice husks or sawdust were not added, reflecting common community practice. The mixture was actively fermented for 14 days, followed by maturation for up to 2 months. During this process,


**Figure 1:** (A) The process of preparing poultry manure into compost by community. (B) Storing the mixture in a 50 L compost bag. (C) The final compost packaged for use in 1 kg.

**Table 1:** Observation results during fermentation and maturation of compost.

| Observation time | Color | Odor | Moisture |
|---|---|---|---|
| Day 0 | Light brown; fresh mixture still visible | Strong manure odor | High (wet) |
| Day 14 | Darkening start | Strong odor decreases; slight fermentation smell | Slightly reduced, still moist |
| Day 28 | Darker brown | Odor becomes more stable, less intense | Moist but not wet |
| Day 32 | Uniform dark brown | Mild earthy smell | Moisture stable–slightly dry |
| Day 46 | Nearly black, crumbly texture | Distinct earthy compost smell | Low moisture |
| Day 60 | Black, stable, crumbly | Natural earthy smell, no foul odor | Dry and stable |

physical characteristics, including color, odor, and moisture content, were checked every two weeks and stirred for even distribution (Table 1). After maturation, the compost was air-dried, homogenized, and a 100 g composite sample was collected for laboratory testing. Chemical analysis followed SNI 19-7030-2004, which includes pH, moisture content, carbon, nitrogen, phosphorus, potassium, and the C/N ratio to determine compost stabilization and compliance with organic fertilizer standards.

## Biofilter technology for poultry slaughterhouse wastewater

The installation and operation of the biofilter reactor by the trained community took place at an informal poultry slaughterhouse in Ngagelrejo Village (Figure 2). The system consists of a modified plastic tank (75–80 L) containing a thick plastic divider that separates two internal chambers and is connected via PVC pipes for the waste inlet and outlet. The reactor consists of two internal chambers: a 27–30 L sedimentation chamber where coarse solids settle, and a 42–48 L filtration chamber filled with bioball media to encourage biofilm development. Wastewater enters the system by gravity, flowing first into the sedimentation chamber and then into the filtration chamber before exiting through the outlet. The hydraulic retention time was estimated at 8 hours following the poultry slaughter time. Influent and effluent samples (100 mL each) were collected once, reflecting the pilot nature of the project. Laboratory analyses were conducted according to the APHA Standard Method Baird and Bridgewater (2017), measuring TSS, $BOD_5$, COD, oil and grease, and ammonia. Results were evaluated against the wastewater quality thresholds established by East Java Governor Regulation No. 72/2013.

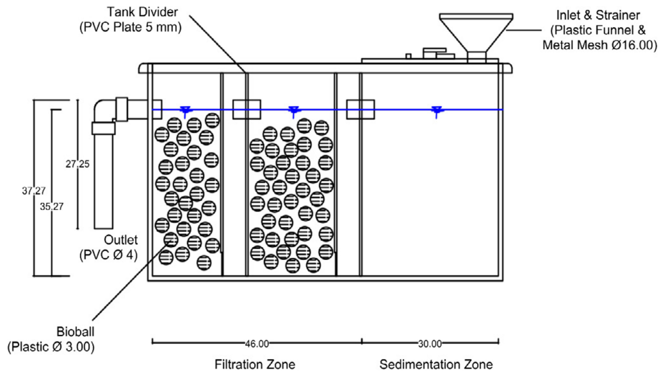


**Figure 2:** Biofilter reactor.

## Biogas digester technology for cattle manure

Two fixed-drum biogas digesters with capacities of 150 L and 550 L were installed and operated by trained dairy farmers in Bendul Merisi Village. The biogas digesters were constructed from a sealed plastic drum (150 L) and a water tank (550 L) with an inlet and gas outlet on top of the drum, and an outlet on the side of the drum. The 150 L digester operated in both the dry and rainy seasons, while the community-replicated 550 L unit operated only in the rainy season (Figure 3A). Fresh cow dung was mixed with water in a 1:1 ratio to form a slurry, and approximately 30 L of slurry was fed into each digester daily. Due to the lack of instruments for monitoring temperature, pH, pressure, or gas volume, performance was evaluated based on the time to initial gas production, defined as the successful ignition of the first flame from a stove connected to the biogas outlet (Figure 3B).

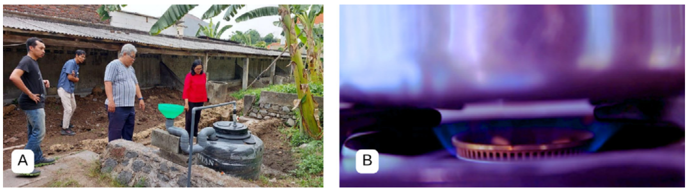


**Figure 3:** (A) Installation of the biogas digester 550 L at the dairy cattle farm in Bendul Merisi Village. (B) The biogas was channeled to the stove and produced a blue flame.

### Qualitative operational assessment (monitoring interviews)

User experiences and practical challenges were recorded through brief monitoring interviews conducted during routine evaluation visits between October and December 2024. A total of 30 participants, consisting of poultry farmers (n=15), poultry slaughterhouse butchers (n=5), and dairy farmers (n=10), were interviewed as they were directly responsible for operating the composting unit, biofilter, or biodigester.

The interviews focused on daily operational practices, difficulties encountered (e.g., compost turning, wastewater filtration, or digester feeding), and user perceptions of the benefits and limitations of each system under urban conditions. All interviews were informal, and responses were recorded as field notes. Responses were then reviewed and grouped into common themes to identify the most frequently encountered operational issues.

## RESULTS AND DISCUSSIONS

### Evaluation of poultry manure composting

Laboratory test results showed that the poultry manure compost produced by the community contained adequate macro- and micronutrients. However, the moisture content (44.45%) and C/N ratio (46.42%) exceeded the maturity threshold set in SNI 19-7030-2004 (Table 2). A high C/N ratio indicates incomplete microbial degradation. This is consistent with the absence of filler material and irregular manual turning as reported during monitoring interviews (Table 5). High C/N values are known to slow thermophilic activity and delay compost stabilization (Cai *et al.*, 2024; Nada, 2015). Excessive moisture was also a limiting factor, as levels above 40% reduce oxygen diffusion and inhibit heat generation during composting (Guo *et al.*, 2012). Studies on poultry manure composting have shown that rice husks or sawdust increase porosity, enhance aeration, and accelerate microbial activity, especially when the initial C/N ratio is high (Tang *et al.*, 2023). The absence of these materials in this study contributed to suboptimal degradation. Similar observations have been reported in rapid composting systems, where an inadequate C/N balance leads to longer maturation times, higher $NH_3$ emissions, and unstable final compost product (Li *et al.*, 2022).

**Table 2:** Compost laboratory analysis results.

| Parameter | SNI Standard (%) | Result (%) |
|---|---|---|
| pH | 6.8–7.49 | 7.55 |
| Moisture | <16 | 44.45 |
| Carbon (C) | 9.80–32 | 33.89 |
| Nitrogen (N) | >0.4 | 0.73 |
| Phosphorus (P) | <0.10 | 0.31 |
| Potassium (K) | 0.20 | 0.65 |
| C/N Ratio | 10–20 | 46.42 |

In addition to these indicators, the compost pH was 7.55, slightly above the SNI standard range of 6.8–7.49. The slightly alkaline pH may have resulted from the release of uric acid and ammonia during poultry litter decomposition, a phenomenon also documented in studies of chicken manure composting in Indonesia (Dewi *et al.*, 2017). Similar pH elevations during poultry manure composting have also been reported in other studies, where nitrogen mineralization and ammonia volatilization contributed to an alkaline shift in the compost matrix (Hwang *et al.*, 2020).

The phosphorus (P) content reached 0.31%, which exceeded the SNI standard of <0.10%. This elevated P level is consistent with the naturally high phosphorus load of poultry manure, as poultry litter typically contains substantial amounts of mineralized P due to the poultry diet and limited nutrient dilution (Bernal *et al.*, 2009). The absence of carbon-rich bulking agents likely contributed to this concentration, as these materials are known to dilute nutrient levels and improve stabilization during composting (Mushtaq *et al.*, 2019). This deviation indicates that the compost had not yet reached full maturity and may require improved aeration, a longer curing period, or the addition of lignocellulosic materials to achieve nutrient balance.

This study indicates that although community-adapted composting is feasible, the product may not meet Indonesian National Standards (SNI) without improvements. Improvements such as regular turning, optimized aeration, and the addition of carbon-rich fillers are needed to meet existing standards (Gani *et al.*, 2021).

### Evaluation of biofilter for poultry slaughterhouse wastewater

A simple biofilter system using bioballs was implemented to reduce the environmental impact of wastewater from a

**Table 3:** Wastewater laboratory analysis results.

| No | Sampling Point | TSS (mg/L) | BOD (mg/L) | COD (mg/L) | Oil & Grease (mg/L) | Ammonia (mg/L) |
|---|---|---|---|---|---|---|
| 1 | Inlet (raw wastewater) | 938 | 4054 | 7702 | 1840 | 1666.8 |
| 2 | Biofilter 1 | 832 | 3896 | 7429 | 360 | 3333.6 |
| 3 | Biofilter 2 | 828 | 4290 | 8179 | 780 | 1738.8 |
| 4 | Outlet (control tank) | 592 | 3610 | 6884 | 220 | 1436.4 |
| Standard | Regulatory Limit (East Java Governor Regulation No. 72/2013) | <100 | <200 | <100 | <15 | <25 |
| Pollutant removal efficiency | % Reduction (Inlet–Outlet) | 14% | 11% | 11% | 88% | 14% |

**Table 4:** Biogas production volume and seasonal variations in small-scale digesters.

| ID | Volume (L) | Season | Ambient temperature* | Time to first ignition | Observation |
|---|---|---|---|---|---|
| D1 | 150 | Dry (Sep-Oct) | 34-37° C | 2 weeks | Faster gas onset; warm ambient temperature supports anaerobic activity |
| D1 | 150 | Rainy (Nov-Dec) | 24-30° C | 4 weeks | Slower gas formation due to cooler temperature and higher moisture |
| D2 | 550 | Rainy (Nov-Dec) | 24-30° C | 4 weeks | Large volume + rainy season reduce heat retention → slow onset |

Note: *Data were obtained from BMKG (2024)

poultry slaughterhouse (Dewi *et al*., 2022; Hasanah and Sugito, 2017). Laboratory tests of the treated wastewater showed that the biofilter was ineffective as a standalone treatment unit because pollutant reductions were minimal and the effluent exceeded government regulatory standards. Although oil and grease reduction was quite high (88%), it showed minimal reductions in $BOD_5$ (11%), COD (11%), TSS (14%), and ammonia (14%), resulting in effluent concentrations above the discharge limits stipulated in East Java Governor Regulation No. 72/2013 (Table 3). This pattern is consistent with evidence that single-chamber biofilters lack sufficient retention time and biological surface area for significant organic removal in slaughterhouse wastewater (Fan *et al*., 2025). Previous studies have shown that multistage or hybrid systems combining sedimentation, anaerobic-aerobic biofiltration, and constructed wetlands can achieve BOD and COD reductions exceeding 70% (Saha *et al*., 2025). This highlights the limitations of the single-stage design used in this study.

This study showed anomalous results in the concentrations of BOD, COD, and oil and grease in Biofilter 1 and Biofilter 2 that increased compared to the inlet, indicating that the mid-stage biofilter units were not operating effectively. Temporary rises in soluble organic matter have been reported in fixed-film systems when particulate organic matter becomes trapped in the media and undergoes hydrolysis, releasing dissolved COD and BOD back into the effluent (Alvarado *et al*., 2021; Morgenroth *et al*., 2002). Interview results (Table 5) indicated user difficulties with clogging, media cleaning, and inconsistent flow regulation. These operational issues are known to reduce biofilm stability and hydraulic efficiency, which can lead to an increase rather than a decrease in organic pollutant concentrations (Achmadi *et al*., 2020; Hayder *et al*., 2017; Rehman *et al*., 2021). A similar anomaly occurred in the ammonia concentration, which doubled in Biofilter 1. This pattern is consistent with ammonification, in which organic nitrogen retained in the media is mineralized into ammonia. Under conditions of limited oxygen transfer or suppressed nitrifying activity, nitrification cannot proceed effectively, leading to ammonia accumulation (Simsek *et al*., 2012; Tiquia, 2002).

The limited performance observed raises public health concerns. Poultry slaughterhouse wastewater is known to be a reservoir of antimicrobial-resistant bacteria (Savin *et al*., 2021; Ugbo *et al*., 2023). AMR *E. coli* has been reported in wastewater pathways and can contaminate food or community water sources (Permana and Bambang, 2019; Sudarmadi *et al*., 2020; Verburg *et al*., 2019). Furthermore, food contaminated with *E. coli* carries a risk of foodborne illness, which can be caused by ingesting the bacteria through contaminated food products (Maghfiroh *et al*., 2024; Pradana *et al*., 2023; Wibawati *et al*., 2024). Similar findings have been reported in Surabaya, where *E. coli* AMR was detected in chicken meat sold in traditional markets. This finding suggests that upstream contamination from farms and slaughterhouses may contribute to environmental disease spread (Sudarmadi *et al*., 2020). Therefore, the integration of additional filtration stages, aeration units, or constructed wetlands is recommended to enhance pollutant removal and mitigate AMR risk.

## Evaluation of biogas production and seasonal variation

Adequate manure management practices are often lacking among smallholder dairy farmers in Indonesia. Limited land, high adoption costs, and perceived difficulties in implementing waste management technologies mean


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that more than half of farmers still discharge manure into the surrounding environment (Ariningsih *et al.*, 2022; Navyanti and Adriyani, 2016). This can create a favorable environment for the development and spread of disease vectors. Furthermore, dairy farm wastewater contains suspended solids that are difficult to settle naturally, complicating waste treatment and increasing environmental pollution risks (Pangestika and Putra, 2020). Biogas technology has been introduced in dairy farm clusters to manage manure while generating renewable energy for household or agricultural use (Agustin *et al.*, 2024).

In this study, daily gas yield and methane content were not measured due to the lack of compatible monitoring instruments. Biogas production varied significantly with the season. The 150 L digester produced gas effectively for two weeks during the dry season (at room temperature 28–33°C), but slowed to about four weeks during the rainy season (24–27°C). The 550 L digester, which operated only during the rainy season, also exhibited slower gas formation (Table 4). This observation aligns with previous studies showing that temperature influences anaerobic digestion, with methanogenic activity decreasing sharply below 25°C (Hupfauf *et al.*, 2018; Kandhro *et al.*, 2024; Sabbir *et al.*, 2021).

In addition to temperature, inadequate insulation was identified as a major inhibitor of methane production (Castano *et al.*, 2014). Performance could be improved through insulation, solar-heated influent tanks, or co-digestion to stabilize the C/N ratio. Previous studies have highlighted the importance of incorporating real-time monitoring systems into the design of small-scale biogas digesters for successful operation and maintenance (Issahaku *et al.*, 2024). Although gas production was slow, the resulting biogas produced a blue flame upon combustion (Figure 3B). A blue flame indicates a higher methane content, reflecting good biogas quality (Ulva *et al.*, 2022).

## Qualitative findings from monitoring interviews

Short monitoring interviews conducted between October and December 2024 provided complementary insights into the operational performance of the three systems (Table 5). Interview results (n=30) indicated a general understanding of the basic operating procedures for the composting bags (12/15), biofilter units (4/5), and biodigesters (7/10). However, several recurring challenges were reported, including difficulty maintaining optimal compost moisture (3/15), occasional clogging or displacement of bioballs in the filtration chamber (2/5), and inconsistent slurry feeding of the digesters (4/10). These issues reflect common constraints in community-based waste management, where limited technical skills and variable environmental conditions impact system stability (Fauziah *et al.*, 2022; Mulasari *et al.*, 2024).

**Table 5:** Summary of key operational findings from monitoring interviews.

| Theme | Key points | Community Quotes |
|---|---|---|
| Operational capacity | Users understood the basic operation of composting bags, biofilters, and biodigesters. Basic skills improved over time (e.g., compost turning, reassembling bioballs, adjusting digester inlet). | **Quote 1:** *"It is sometimes difficult to keep the moisture at the right level. When it becomes too wet, the smell gets stronger and it is harder to turn."* **Quote 2:** *"We never use rice husks or other fillers. During the rainy season the compost takes a very long time to dry."* |
| Main challenges | Difficulties maintaining compost moisture; bioball clogging/displacement; inconsistent digester slurry loading. | **Quote 3:** *"When the flow becomes too strong, the bioballs shift out of place and we have to fix them again."* **Quote 4:** *"The filter once became clogged, so we took it apart and washed the media. After that the flow improved."* **Quote 5:** *"Sometimes we forget to load the same amount of slurry every day, so the gas production is not always stable."* |
| Perceived benefits | Reduced odor, cleaner livestock areas, and less visible waste accumulation. | **Quote 6:** *"Since using the composting and biogas units, the smell around the sheds has decreased and the area feels cleaner."* **Quote 7:** *"The waste no longer piles up like before, so the surroundings look tidier."* |
| Environmental/contextual constraints | System stability affected by rainfall and limited urban space. | **Quote 8:** *"During heavy rain the system becomes unstable, and we cannot control the moisture or the flow as well as usual."* **Quote 10:** *"Our space is very limited, so installing and adjusting the unit is sometimes difficult."* |
| Community collaboration | City government (site access), university (troubleshooting), farmer groups (corrective actions). | **Quote 9:** *"The government helped us get permission to use the site, so the installation could run smoothly."* **Quote 10:** *"When we had problems, the university team explained what to fix and showed us how to do it."* |

Despite the challenges, most participants reported tangible benefits, including reduced odor (25/30), cleaner livestock environments (27/30), and less visible waste accumulation (22/30). These observations are consistent with previous studies showing that small-scale composting and biogas systems can improve environmental hygiene in dense urban livestock environments (Elsabbagh *et al*., 2025; Syaputri *et al*., 2024; Wisniewska *et al*., 2021). Field notes also documented gradual improvements in user competency, including improved compost turning practices (13/15), reinstalling the bioball chamber after clogging (5/5), and adjusting the digester inlet pipe (7/10). Although no formal skills assessment was conducted, these observations suggest that the technologies can be operated within existing community capacity. This study reflects the principles of social innovation, highlighting the importance of building community-based resilience through decentralized, locally contextualized strategies (Imperiale and Vanclay, 2023; Tahir, 2023; Van *et al*., 2023).

A practical example of this collaboration occurred when the city government facilitated site access, the university team provided troubleshooting guidance, and the farmers implemented corrective actions to address blockages in the biofilter unit. By applying the penta-helix model and promoting shared ownership, this initiative exemplifies the WHO's call to operationalize One Health at the local level (WHO, 2023). This model offers a replicable example for other urban environments seeking to transition to Smart Healthy Cities. Furthermore, a comprehensive review of urban health transformation underscores the importance of cross-sector collaboration and grassroots innovation as fundamental elements for achieving sustainable and inclusive Smart Healthy Cities (Haryono *et al*., 2024; Danielli *et al*., 2023).

## CONCLUSIONS

This study found that community-based composting, biofiltration, and small-scale biogas systems can be implemented in urban livestock settings, but their performance is still limited by design constraints, environmental conditions, and operational inconsistencies. The compost did not meet national standards due to high moisture and C/N ratio, the biofilter achieved only minor reductions in key pollutants, and biogas production slowed during the rainy season. Despite these challenges, community participation enabled routine operation and provided visible environmental benefits. Overall, the findings show that decentralized waste technologies have the potential to support urban One Health efforts, but technical improvements and more robust operational guidance are needed to ensure reliable and sustainable performance.


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## NOVELTY STATEMENT

This study is the first to assess community-led urban livestock waste management in Surabaya under a One Health framework, combining lab evaluation, field monitoring, and social adoption insights to reveal both the potential and limitations of decentralized composting, biofiltration, and biogas systems.

## AUTHOR'S CONTRIBUTION

LM: Conceptualized the study, designed the methodology, conducted the investigation, prepared the original draft, administered the project, and supervised the overall workflow. SSNS: Contributed to the conceptual design and methodology, validated the results, participated in reviewing and editing the manuscript, and supported funding acquisition. FKM: Contributed to the conceptualization, performed data curation and visualization, conducted formal analysis, and assisted in project administration. CIP: Contributed to the conceptual design and methodology, participated in investigation, provided resources, reviewed and edited the manuscript, and supervised the research process. FAR: Contributed to conceptualization and methodology, provided essential resources, validated the findings, and supervised the study. BU: Conducted data curation and investigation, and contributed to reviewing and editing the manuscript. LNY: Validated the results, performed formal analysis, and supervised the research.

### Generative AI and AI-assisted technology statement

No generative AI was used for the scientific content, data analysis, and conclusions. AI tools were only used to improve language clarity, with all edits verified by the authors.

### Conflict of interest

The authors have declared no conflict of interest.

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