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From Mixed Household Waste to Source-Separated Resource Recovery: Generation, Composition, Density, and Energy Characteristics in Kalibeji Village

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ABSTRACT

Background: Rural communities in Indonesia often rely on mixed-waste disposal or incineration despite limited information on the physical, compositional, and energy characteristics of household waste. Understanding these characteristics is essential for developing technically appropriate and resource-oriented waste management systems.
Aims: This study aimed to characterize household waste in Kalibeji Village, Kebumen Regency, Indonesia, and to evaluate a technically appropriate waste management pathway based on waste generation, composition, density, moisture content, ash content, calorific value, and the relationship between household expenditure and waste generation.
Methods: Household waste characterization was conducted over eight consecutive days based on SNI 3964:2025. Waste generation, bulk density, and physical composition were measured, while laboratory analyses were conducted to determine moisture content, ash content, and calorific value. The relationship between monthly household expenditure and waste generation was evaluated using regression analysis.
Results: Household waste generation averaged 0.41 kg capita^{-1} day^{-1}, equivalent to approximately 2.13 t day^{-1} at the village scale. The average bulk density was 138.59 kg m^{-3}. Organic waste dominated the waste stream, accounting for 71.24%. Laboratory analysis indicated a high moisture content of 53.3%, an ash content of 7.75%, and an LHV range of 1,944.78cal g^{-1}. Regression analysis showed a statistically significant positive relationship between household expenditure and waste generation ($p = 0.0384$). The high proportion of organic waste and moisture content indicates that mixed-waste incineration is not the most technically appropriate primary treatment pathway for Kalibeji Village. A source-separated system should instead prioritize household-scale biological treatment of organic waste through composting or Black Soldier Fly (BSF) bioconversion, recovery of dry recyclables, and controlled handling of residual and household hazardous waste. The study demonstrates that village-scale waste characterization can provide an evidence-based foundation for transitioning from mixed-waste disposal toward an integrated rural resource-recovery system.

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1. Introduction

Poor waste management is a major contributor to environmental pollution, particularly when waste generation exceeds the capacity of existing management systems (Lawa et al., 2021). In Indonesia, waste management remains challenging due to population growth, changing consumption patterns, and increasing constraints on land availability. The prevailing management paradigm continues to rely largely on a collect–transport–dispose approach, while only approximately 60% of waste generated in major Indonesian cities is estimated to be transported to final disposal sites (TPA) (Alfian & Phelia, 2021). These challenges are not limited to urban areas. Rural and peri-urban communities are also experiencing increasing waste generation, growing quantities of packaging waste, and limited access to adequately engineered waste management infrastructure. For example, Survase *et al.* (2025) reported that rapid population growth and infrastructure development in Nahre Village, India, were associated with increased waste generation, demonstrating that waste management challenges can intensify alongside rural development.

Kalibeji Village, located in Sempor District, Kebumen Regency, Central Java, provides a relevant case for examining this transition. The village has established community-based household waste collection and transport to a local temporary storage or transfer point. However, a substantial proportion of the collected mixed waste is subsequently destroyed using a simple community-built incinerator. Although this practice can rapidly reduce waste volume, its technical suitability is uncertain when heterogeneous waste streams are burned together, particularly when they contain substantial quantities of wet organic waste, plastics, sanitary waste, and other residual fractions. Such a practice is also inconsistent with the waste-management hierarchy, which prioritizes waste prevention and reduction, reuse, recycling and material recovery, followed by energy recovery and disposal as the least preferred option (Finnveden *et al.*, 2005). Therefore, determining whether mixed-waste incineration is technically appropriate requires an assessment of the physical and physicochemical characteristics of the waste stream rather than relying solely on its ability to reduce waste volume.

Waste characterization provides the essential basis for such an assessment. Waste characteristics can vary considerably among locations because of differences in geographical conditions, socioeconomic characteristics, regional activities, and consumption patterns (Exposto & Janugara, 2021). The waste generation rate determines collection requirements, labour needs, transport frequency, and overall system capacity. According to Aprilia *et al.* (2024), waste management system design should account for the specific characteristics of waste generation and composition to improve operational efficiency and management effectiveness. Bulk density provides additional information for determining storage and collection capacity, vehicle loading, and transport requirements. Waste composition identifies the proportions of organic, recyclable, and residual fractions, while moisture content, ash content, and heating value provide important indicators for assessing the technical suitability of biological treatment, material recovery, and thermal treatment. Despite the importance of these parameters, comprehensive waste characterization datasets at the village scale remain relatively limited compared with those available for urban areas.

Previous studies have reported waste generation rates and compositions for several Indonesian communities. Riswan *et al.* (2011) reported a waste generation rate of 0.38 kg capita^{-1} day^{-1} in South Daha District, with organic waste accounting for 47% of the waste stream. Similarly, Ratya & Herumurti (2017) reported a generation rate of 0.35 kg capita^{-1} day^{-1} and a waste density of 154.93 kg m^{-3} in Rungkut Village, with organic waste comprising 62.5% of the total waste. These studies applied the sampling procedure specified in SNI 19-3964-1994 and primarily focused on conventional characterization parameters, including waste generation, density, and composition. However, there remains a need for village-scale characterization that integrates these parameters with physicochemical

indicators relevant to treatment selection, particularly in communities where mixed-waste incineration is currently practiced.

Accordingly, this study aims to quantify the waste generation rate, volume, bulk density, composition, and selected physicochemical characteristics of household waste in Kalibeji Village and to use these measurements to evaluate the technical implications for waste management planning. The contribution of this study is not merely the application of SNI 3964:2025 to a rural community, but the integration of standardized waste characterization with a data-driven diagnosis of an existing mixed-waste management practice. In particular, the study evaluates whether the measured waste characteristics support continued mixed-waste incineration or indicate the need for source separation and alternative recovery-oriented treatment pathways. Particular attention is given to the large organic fraction, recyclable materials, residual waste, and hazardous household waste (HHW), as these fractions have different treatment requirements and environmental implications.

This approach addresses a broader, policy-relevant question: what waste management pathway is technically consistent with the measured characteristics of a rural Indonesian household waste stream? Source separation is particularly relevant because Indonesian waste-management policy, including Law No. 18 of 2008 on Waste Management, recognizes waste sorting as an important component of waste management. Thus, the characterization results are used not only to describe the existing waste stream but also to establish an empirical basis for evaluating source separation, material recovery, biological treatment, residual management, and the limitations of mixed-waste thermal treatment in a village-scale context.

2. Methods

2.1. Study area

The study was conducted in Kalibeji Village, Sempor District, Kebumen Regency, Central Java, Indonesia. The village has a population of 5,164 residents comprising 1,661 households distributed across six community units (RW). Existing waste management relies on community collection, transfer to a local temporary storage point and final destruction of much of the mixed waste using a simple incinerator. This condition makes the village a suitable case for evaluating whether current practice is consistent with measured waste characteristics.

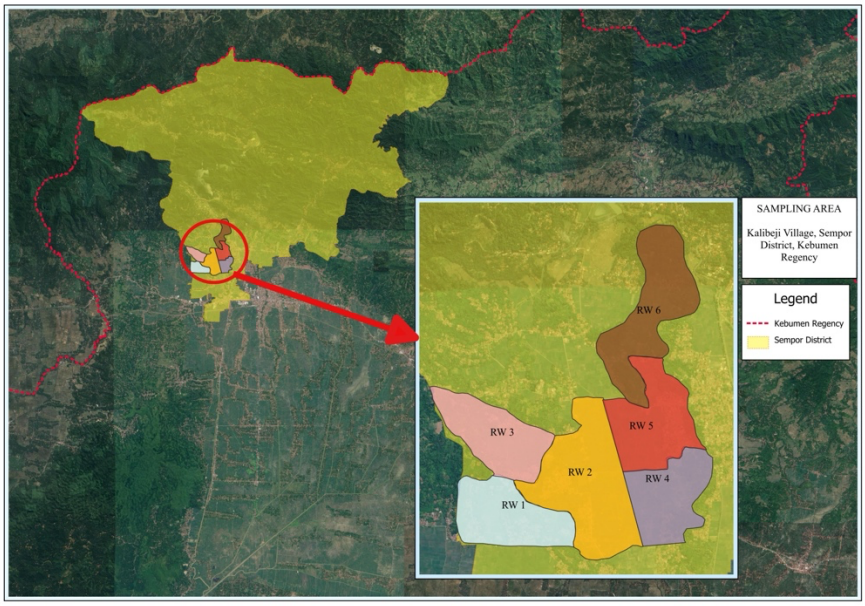


Figure 1. Waste sampling location

2.2. Sampling design and field measurement

The sampling approach followed the principles of SNI 3964:2025 on the sampling and measurement of household waste and waste similar to household waste. Waste sampling was conducted for eight consecutive days, from 29 July to 5 August 2025, to cover weekdays, weekend conditions, and the day after a holiday.

2.2.1. Determination of sampling points

The number of households for this waste sampling is determined based on the following formula (SNI 3964:2025), for a population of ≤ 1,000,000 people.

$$Ps = Cd\sqrt{PT} \quad (1)$$

*note:
Ps = sample size
Cd = coefficient of small city (0,5)
Pt = total population

Based on the village population and the SNI sampling equation, the minimum sample requirement was calculated as 36 residents, then the total population was divided by three (representing family members) to arrive at a sample size of 12 households. The field campaign was expanded to 24 household sampling points to improve spatial representation across the village, furthermore this serves as a data safe factor in cases where a household is unwilling to have its waste sampled.

The sampling points were determined using a purposive sampling approach. This method was employed to select the sampling areas, specifically RW 02, RW 03, RW 04, and RW 05. These areas were selected based on the existing availability of waste management services, which facilitated the sample collection process. Households were selected as sampling points using a random sampling method. Within each predetermined area, sampling points were randomly distributed among households to ensure an unbiased selection of sampling locations.

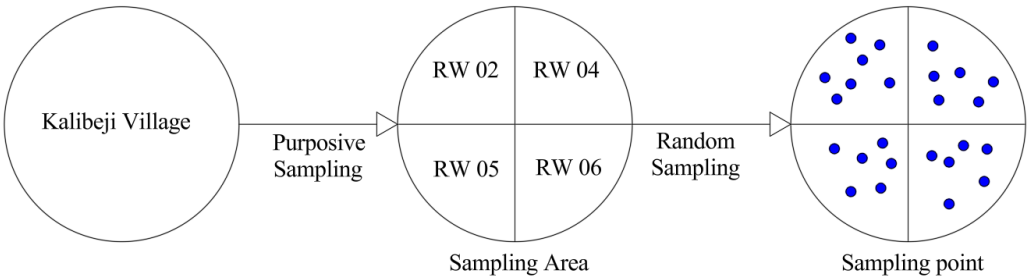


Figure 2. Simulation of the Method for Determining Sampling Points

One day before sampling, plastic bags were distributed to participating households, and basic household information was collected. Pre-survey data collection was conducted to obtain general information about the participating households and their socioeconomic conditions, including monthly household expenditure. Total wet mass was recorded using a digital hanging scale. Bulk volume was measured with a wooden volume box with a 0.30 m x 0.30 m base after settling the waste by dropping the box three times, following the field compaction procedure used in the draft study. Waste was then sorted into 13 categories: kitchen waste, garden waste, wood, paper/cardboard, plastic films, rigid plastics, metals, textiles, rubber/leather, glass, household hazardous waste, nappies/sanitary waste, and other residues. Each fraction was weighed, and its bulk volume was measured to estimate fraction-

specific density. The waste sampling process will ultimately provide data on waste weight, volume, density, and composition.

2.2.2. Waste Sampling Preparation and Procedure

The following describes the procedure for conducting household waste sampling.

1. Waste sampling was conducted in the residential area of Kalibeji Village, Sempor, over an eight-day sampling period
2. One day prior to sampling, a preliminary site survey was conducted to identify the sampling locations and distribute plastic waste bags (trash bags) to the selected households
3. Household interviews and questionnaire surveys were conducted during the preliminary survey to collect relevant household information
4. A sampling logbook was prepared to systematically record information for each sampling point, including the sampling point, sample code, collection date, waste volume, waste weight, and waste composition. The detailed sampling logbook is provided in the Appendix
5. Waste collection was conducted from the selected households each morning, beginning at approximately 07:00. An additional waste container was provided to each household, and each collected waste container was labeled with the corresponding sample identification and collection information
6. The collected waste was transported to a designated central location, where it was weighed and measured for volume before being sorted into predefined waste categories to determine waste generation and composition.

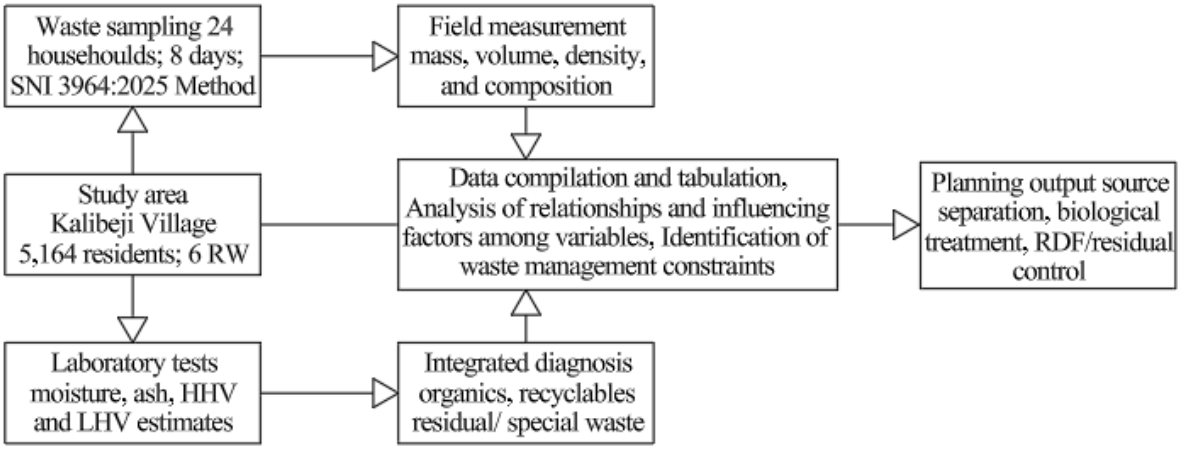


Figure 2. Study design and decision logic used to convert household waste characterization into management recommendations.

2.3. Laboratory characterization and energy-value calculation

Laboratory analysis was conducted using mixed household waste. After the household waste was completely sorted by type and its weight and other relevant characteristics were measured, all sorted waste fractions were recombined and thoroughly mixed to obtain a homogeneous sample representative of the mixed household waste stream. The homogenized sample was subsequently used for laboratory analysis. Samples were grouped into three temporal categories: working day, holiday, and one day after a holiday. Approximately 2 kg of homogenized waste was placed in labeled, sealed plastic bags, stored in a dark container, and transported to an accredited laboratory. Moisture content, ash content, and high heating value (HHV) were measured. Low heating value (LHV) was estimated from the HHV and moisture-related corrections using equations reported in the Indonesian waste-

management literature (equation 2), enabling interpretation of energy potential under more realistic moisture conditions.

Table 1. Laboratory Methods for Characterizing Waste

No	Waste parameters	Test Method
1	Moisture content	ASTM D2216-98
2	Ash content	ASTM E830-87
3	Calorific value	Parr Bomb Kalorimeter 6400

The calorific value testing conducted in the laboratory produced higher heating value (HHV) data, which were subsequently converted to lower heating value (LHV). Equation for Determining the Lower Heating Value (LHV) (Dorfmann, 1985)

$$PCI = PCS\left(1 - \frac{Hu}{100}\right) - 5.83\,(Hu + 9H) \quad (2)$$

*Note
PCS : Pouvoir Calorifique Superieur/High Heating Value (kcal/kg)
PCI : Pouvoir Calorifique Inferiuer/Low Heating Value (kcal/kg)
Hu : Moisture Content (%)
H : Hydrogen content (H=7,1%); Charkhestani & Kebria (2022)

2.4. Data analysis

Daily waste generation was calculated as wet mass per household per day and converted into per-capita generation using an average household size of three residents. Village-scale waste generation was estimated by multiplying the per-capita value by the village population. Bulk density was calculated as wet mass divided by measured volume. Composition was expressed as mass percentage of the total sorted waste. For management interpretation, kitchen and garden waste were grouped as the organic fraction, paper/cardboard, plastics, metals, and glass were grouped as dry recyclables, and the remaining fractions were grouped as residual or special waste. This study also investigated the relationship between household expenditure and waste generation using linear regression analysis. The statistical regression analysis was conducted using Microsoft Excel, with a significance level (α) of 5% as the criterion for statistical testing.

3. Results and Discussions

3.1. Waste generation, volume, and density

The average household waste generation rate was 1.28 kg household^{-1} day^{-1}, corresponding to 0.41 kg capita^{-1} day^{-1}. At the village scale, this equals approximately 2.13 t day^{-1}. The estimated daily volume was 16.0 m^3 day^{-1}, derived from the mean bulk density of 138.59 kg m^{-3}. These values indicate that Kalibeji Village requires a collection and processing system sized for a relatively small but continuous waste stream, rather than a sporadic clean-up-oriented system.

Fasya *et al.* (2025) reported that household waste generation rates in Indonesia range from approximately 0.14 to 0.88 kg capita^{-1} day^{-1}. The waste generation rate in Kalibeji is consistent with the findings of the aforementioned study, but remains lower than the rates reported in major cities in Indonesia. Qonitan *et al.* (2021) reported an average waste generation rate of 0.69 kg capita^{-1} day^{-1} across several major Indonesian cities, including Jakarta, Bekasi, Bandung, Semarang, Surabaya, etc. Table 2 shows that the average waste density measured in this study was 138.59 kg m^{-3}. This value is relatively comparable to those reported in previous studies. Hapsari & Herumurti (2017) reported a household waste density of 146.02 kg m^{-3} in Sukolilo District, Surabaya City. The lower waste generation rate in Kalibeji compared with those reported for major cities in Indonesia may be partly

attributed to differences in household consumption patterns, which are closely associated with monthly household expenditure. A more detailed analysis of this relationship is presented in the following subsection. These findings indicate that the waste generation rate observed in Kalibeji Village is within the range reported by previous studies in Indonesia.

Daily variation was visible during the eight-day sampling period. The highest measured waste mass occurred on the first sampling day, while bulk density reached its maximum on the sixth day. Such variation is expected in household waste characterization because food preparation, garden cleaning, rainfall exposure, and household storage practices influence the wet mass and volume of waste. The variation also underlines the importance of multi-day sampling rather than relying on a one-day observation.

Table 2. Daily household waste generation, volume and density in Kalibeji Village.

Date	Total sampled waste (kg)	kg HH^{-1} d^{-1}	kg cap^{-1} d^{-1}	L HH^{-1} d^{-1}	kg m^{-3}
Tue, 29 Jul 2025	40.05	1.67	0.54	13.84	120.60
Wed, 30 Jul 2025	28.20	1.18	0.38	9.68	121.45
Thu, 31 Jul 2025	32.55	1.36	0.44	10.05	134.95
Fri, 1 Aug 2025	27.45	1.14	0.37	8.74	130.90
Sat, 2 Aug 2025	30.15	1.26	0.41	8.81	142.55
Sun, 3 Aug 2025	28.30	1.18	0.38	6.90	170.89
Mon, 4 Aug 2025	27.75	1.16	0.37	8.29	139.52
Tue, 5 Aug 2025	31.40	1.31	0.42	8.85	147.83
Mean	**30.73**	**1.28**	**0.41**	**9.39**	**138.59**

3.2. Physical composition and recovery potential

The waste stream was highly organic. Kitchen waste accounted for 59.45% of the total mass and garden waste accounted for 11.79%, giving an organic fraction of 71.24%. Plastic films formed the largest non-organic fraction at 10.04%, followed by paper/cardboard at 4.19%. Household hazardous waste represented only 0.18% by mass, but it requires separate handling because its risk is not proportional to mass share. The composition of waste varies from day to day, as certain types of waste are not generated on a daily basis, such as glass, rubber, and wood waste. In contrast, some waste fractions tend to dominate and are generated consistently on a daily basis, particularly kitchen waste. This finding is consistent with the study conducted by Shofi *et al.* (2023), which reported that organic waste was the dominant waste fraction in Janti Village, Sidoarjo, accounting for approximately 64% of the total waste generated daily.

The high proportion of organic waste generated in Kalibeji Village necessitates effective and appropriate management strategies. One potential approach is the use of biological agents for organic waste bioconversion, particularly Black Soldier Fly (BSF) larvae. BSF larvae have been reported to reduce approximately 50–70% of various types of organic waste, including food waste. This bioconversion process can generate BSF larval biomass with potential applications as an alternative feed resource for livestock, while the residual material remaining after bioconversion can be utilized as an organic fertilizer for agricultural and plantation activities (Lorenta In *et al.*, 2023).

The management of residual waste and other specific waste streams, particularly household hazardous waste (HHW), also requires careful consideration. Although HHW does not constitute a dominant proportion of the total waste stream, it can have significant environmental impacts due to its hazardous characteristics. One important source of HHW is discarded electronic equipment, which may release hazardous contaminants, including heavy metals, if improperly managed. A study

conducted by Udousoro *et al.* (2026) revealed that rapid technological development has generated additional environmental challenges, particularly the increasing accumulation of electronic waste (e-waste). The study, conducted at the Uyo Village Road Dumpsite, Nigeria, found that waste printed circuit boards (WPrCBs) contained the highest concentrations of metals, particularly copper (Cu), reaching 168,664.33 mg/kg, and lead (Pb), reaching 80,004 mg/kg. Collectively, these two metals accounted for nearly 70% of the total metal content. The study also reported that soil samples exhibited moderate levels of contamination, while borehole water samples contained lower concentrations of arsenic (As), cadmium (Cd), and selenium (Se).

The management of HHW should comply with the applicable regulatory framework. In Indonesia, household B3 waste management is regulated under Peraturan Menteri lingkungan Hidup No. 9 of 2024, which establishes provisions for the management of HHW. At the village scale, one practical measure is the implementation of an appropriate temporary storage system. HHW segregated at the household level can be collected and transported to the village waste management facility for containerization and temporary storage before being transferred to an authorized waste management entity. The storage containers should meet the requirements stipulated by the applicable regulations, including color coding according to waste type, appropriate labeling, water-tight construction, secure covers, ease of handling and relocation, ease of emptying and cleaning, and sufficient capacity according to the quantity of waste generated. Implementing these requirements at the village level can support the safe handling of HHW and minimize potential risks to human health and the environment.

The composition profile indicates that a source-separated system would be more technically robust than mixed-waste burning. A study conducted by Chen (2023) revealed that the application of household waste incineration is ineffective for several reasons, including the mixed condition of the waste and the predominance of fresh food waste. This condition is further exacerbated by the common practice of washing fresh food before consumption, which increases the moisture content of the resulting food waste. At the measured per-capita generation rate, the organic fraction alone corresponds to approximately 1.53 t day^{-1}. This is sufficiently large to justify decentralized composting, black soldier fly larvae treatment, anaerobic digestion or a combination of biological options, depending on land availability, operator capacity and product-use pathways. Dry recyclables (plastic, paper/ cardboard, metals) represent approximately 0.21 t day^{-1} and should be recovered before any residual treatment decision is made.

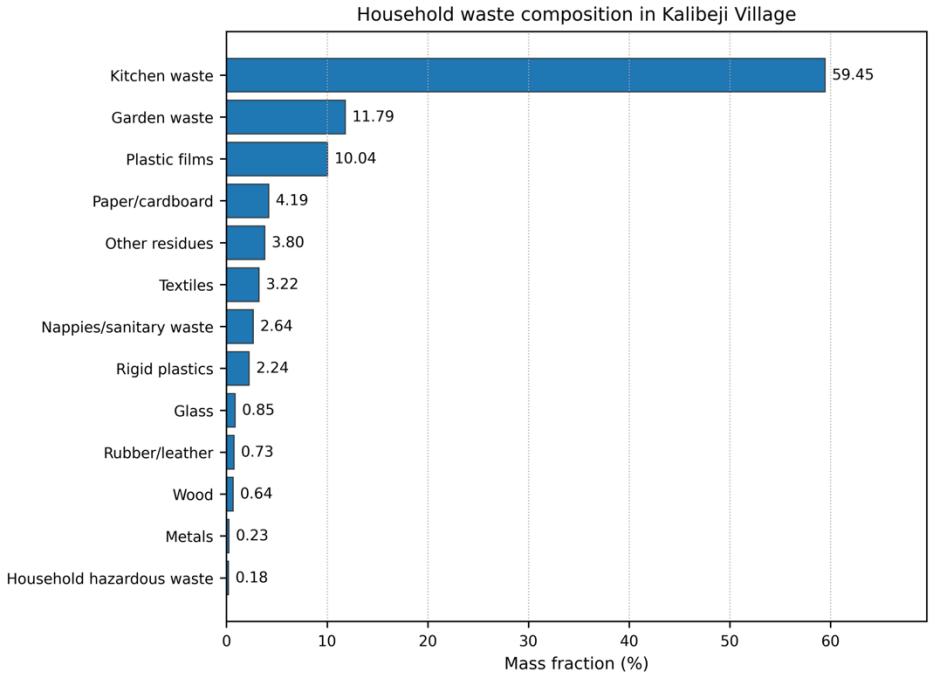


Figure 3. Mass-based household waste composition in Kalibeji Village. Bars are sorted by increasing mass fraction.

3.3. Fraction-specific density and operational implications

Fraction-specific density provides operational information beyond waste composition alone. Kitchen waste had the highest average density among the dominant fractions (192.97 kg m^{-3}), followed by garden waste (152.79 kg m^{-3}). In contrast, plastic films and rigid plastics had considerably lower densities of 80.04 and 65.46 kg m^{-3}, respectively. These differences are operationally important because low-density plastics occupy a relatively large storage and vehicle volume compared with their mass contribution, whereas wet organic waste contributes substantially to load weight and increases the potential for leachate generation. Consistent with these findings, Hoang *et al.* (2024) reported that low waste density can affect waste management systems, particularly waste collection system (WCS) capacity and operational efficiency.

For Kalibeji Village, this means that the collection system should not be designed only on the basis of total mass. Containers for dry recyclables require adequate volume, while organic waste containers require leak control, odor management, and frequent collection. The density data therefore support at least a three-stream system: organics, dry recyclables (plastic, paper/cardboard, metals), and residual/special waste.

Table 3. Waste composition and fraction-specific density.

Waste fraction	Average density (kg m^{-3})
Kitchen waste	192.97
Garden waste	152.79
Plastic films	80.04
Paper/cardboard	69.83
Other residues	94.11
Textiles	111.45
Nappies/sanitary waste	115.79
Rigid plastics	65.46
Glass	117.71

Rubber/leather	57.24
Wood	52.55
Metals	45.14
Household hazardous waste	34.72

3.4. Moisture, ash, and energy characteristics

The characterization results of the mixed household waste samples indicated a moisture content of 53.3% and a mean ash content of 7.75%. The mean HHV was 5,617.21 cal g^{-1}. However, HHV alone may overestimate the practical energy potential of moist household waste because a portion of the energy released during combustion is consumed in evaporating the water contained in the waste. The estimated LHV values were 1,944.78 cal g^{-1} (Equation 2), depending on the correction equation applied.

Gustannanda *et al.* (2023) reported a moisture content of 88.16% in food waste. According to the study, this high moisture content was attributed to the conditions of the waste storage area and the composition of the food waste, which was predominantly composed of vegetables and fruits. This condition is similar to the kitchen waste generated in Kalibeji Village, which is predominantly composed of food residues from household cooking activities and uneaten food. The study conducted by Qonitan *et al.* (2021) reported a relatively similar value, with a household waste ash content of 6.12%. Another finding reported in this study was the lower heating value (LHV) of household waste, which was 2,268.6 cal g^{-1}.

These results are important for evaluating the current practice of mixed-waste incineration. Although the HHV appears high, the high moisture and organic fractions reduce practical combustibility. In addition, mixed burning can include plastics, sanitary waste, and household hazardous materials, which increases the need for air-pollution control and safe ash handling. Without such controls, simple incineration should not be treated as a high-quality final treatment option.

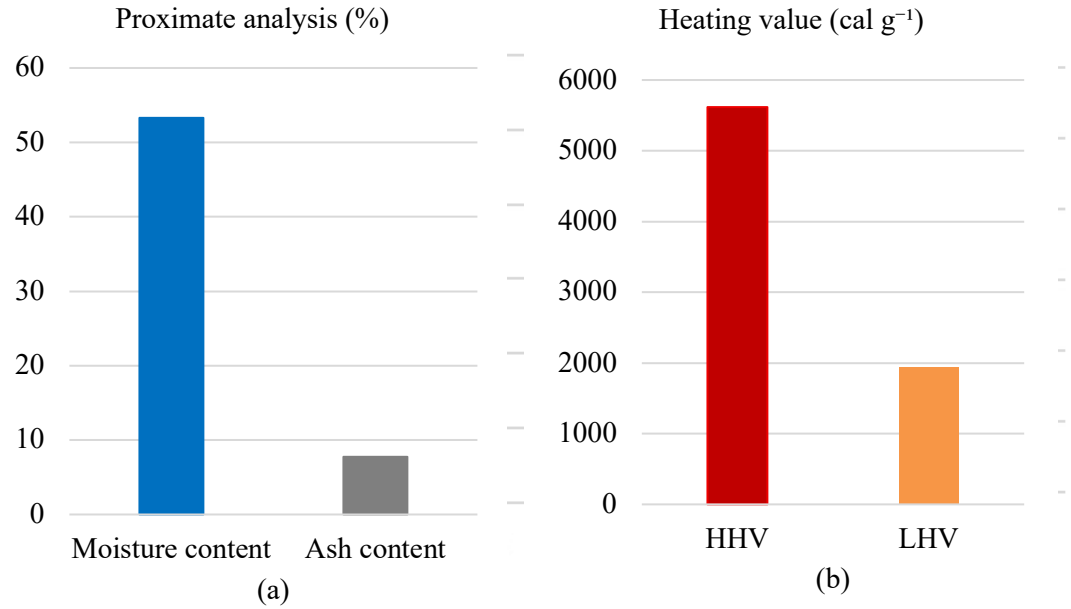


Figure 4. Physicochemical characteristics of the sampled household waste. Bars show means and error bars show standard deviation; points show individual composite samples. (a)Proximate indicators; (b)Heating value estimates.

3.5. The Effect of Household Expenditure on Waste Generation

One day prior to waste sampling, general household data were collected from the households selected as waste sampling sites. One of the variables collected was monthly household expenditure. Economic Classification Based on Statistics Indonesia (BPS) Guidelines, with a slight adjustment using the 2025 poverty line for Kebumen Regency of IDR 502,841.00 per capita per month as the reference threshold.

Table 4. Household Classification Based on Consumption Expenditure

No	Expenditure categories	Monthly Household Expenditure (IDR capita^{-1})	Number of Households
1	Poor (P)	< IDR 502,841	6
2	Vulnerable (V)	IDR 502,841 – IDR 754,261	11
3	Aspiring Middle Class (AMC)	IDR 754,261 – IDR 1,759,943	5
4	Middle Class (MC)	IDR 1,759,943 – IDR 8,548,297	2
5	Upper Class (UC)	> IDR 8,548,297	0

The data presented in the table above were subsequently compared with the amount of waste generated by each household to examine the influence of household expenditure on waste generation. The waste generation data used in this analysis consisted of food waste and its associated packaging, specifically plastic and paper waste. The selected waste fractions were considered relevant because food expenditure accounts for the largest proportion of household expenditure in Kebumen Regency, representing 53% of total household expenditure (BPS, 2025). The results of the regression analysis are presented below.

Table 5. Regression Analysis Results

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.3319	0.3001	1.1060	0.2807	-0.2904	0,9542	-0.2904	0.9542
Expend (X)	0.2964	0.1304	2.2724	0.0332	0.0259	0,5669	0.0259	0.5669

The results above show that the coefficient has a positive value, indicating that higher monthly household expenditure is associated with an increase in the amount of waste generated, particularly kitchen waste and its associated packaging, such as plastic and paper waste. The next column, P-value, indicates the statistical significance of the relationship between household expenditure as the independent variable (X) and waste generation as the dependent variable (Y). The significance level was determined based on an alpha (α) value of 5% or 0.05. Therefore, a regression result with a P-value below 0.05 indicates a statistically significant relationship. The P-value obtained from the regression analysis was 0.0384, indicating that household expenditure has a statistically significant effect on waste generation.

Higher household consumption expenditure is associated with greater waste generation. As discussed in the previous subsection, waste generation rates in major Indonesian cities are generally higher than those measured in Kalibeji Village. Surabaya provides one such example, where monthly household expenditure on food reaches IDR 1,145,921 capita^{-1} month^{-1} (BPS of East Java Province, 2025), whereas field data collected in Kalibeji Village indicate a substantially lower expenditure of approximately IDR 585,757 capita^{-1} month^{-1}. This expenditure level is relatively comparable to data reported by the BPS of Kebumen Regency (2025), which indicates an average monthly food expenditure of approximately IDR 565,260 capita^{-1}. These differences in household food expenditure

may partly explain the lower waste generation rate observed in Kalibeji compared with major urban areas such as Surabaya.

Improving societal welfare is one of the key objectives of government policy, while household consumption or expenditure is one of the indicators of improvements in societal welfare. An increase in household welfare may consequently affect the amount of waste generated, as demonstrated by the analysis presented above. According to a 2025 publication by Statistics Indonesia (BPS), food expenditure remains the largest component of monthly household expenditure in Indonesia, accounting for 49.42%, followed by expenditure on housing and household facilities (25.41%), goods and services (12.79%), and other expenditures (12.38%). These findings provide a strong basis for considering food waste and its associated packaging as important components in waste management planning.

A study conducted by Citrasari *et al.* (2025) showed that municipal solid waste landfills in Indonesia contribute significantly to methane emissions, which is a potent greenhouse gas that plays an important role in climate change. The study also revealed that 63% of the waste disposed of at landfills consists of biodegradable organic materials, which contributes to increased methane generation during the decomposition of organic waste under anaerobic conditions. The direct impacts of excessive methane production can also be observed in the form of landfill fires. Data from the same study indicate that 41.27% of landfill fire incidents, corresponding to 26 cases reported between 2005 and 2025, were attributed to methane emissions.

3.6. Management implications for Kalibeji Village

The results of the waste characterization and data analysis shift the planning focus from simply determining how to burn mixed waste more efficiently to preventing valuable and potentially problematic waste fractions from entering the same disposal stream. Therefore, a realistic improvement of the waste management system should begin at the household level rather than at the incineration facility. The proposed management pathway consists of three integrated actions: (i) separating kitchen and garden waste for biological treatment and direct management at the household level; (ii) recovering dry recyclables (inorganic waste) through sorting, storage, and distribution through appropriate sales channels; and (iii) separating nappies, household hazardous waste (HHW), and other residual waste for controlled disposal or engineered residual waste treatment.

This pathway is consistent with the measured data. Organics dominate the waste stream and x, leachate and moisture problems if stored in mixed form. Dry recyclables are large enough to justify organized recovery but low enough in density to require appropriate storage space. Residual and special waste are relatively small by mass but technically important because they determine the environmental safety of final handling. Figure 5 summarises the mass allocation implied by the measured composition and generation rate.

The waste generated is targeted to be segregated at source into three categories: organic waste, inorganic waste, and hazardous household waste (HHW). The target is for 80% of households in Kalibeji Village to implement waste segregation, while the remaining 20% are expected to continue generating mixed waste before it is transported to the temporary waste collection facility in the village. Segregated organic waste will be treated directly by households through composting or bioconversion using Black Soldier Fly (BSF) larvae. Inorganic waste and HHW will be transported to the temporary waste collection facility. The inorganic waste will then be sorted by waste management personnel into several categories, namely plastics, paper/cardboard, metals, and residual waste. Residual waste and HHW will subsequently be transported to the next waste management facility or to the final disposal site (landfill).

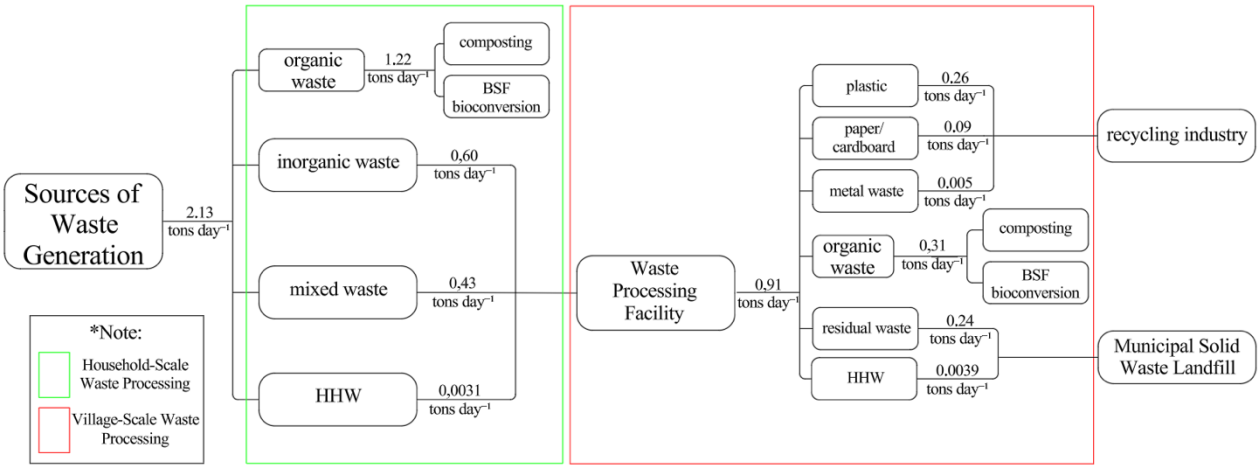


Figure 5. Proposed source-separated resource-recovery pathway based on measured mass composition and village-scale extrapolation.

Table 6. Management implications derived from the Kalibeji Village waste characterization.

Stream	Mass share (%)	Estimated mass (t d^{-1})	Planning issue	Recommended pathway
Organic waste	71.63	1.52	High moisture and high density; main source of odour and leachate	Source-separated composting, Black Soldier Flies (BSF) treatment or aerobic digestion
Inorganic waste	16.76	0.36	Low density; requires storage volume and market access	Household separation, dry storage and material recovery
Residual/HHW	11.62	0.25	Small mass share but high environmental relevance for nappies, Hazardous Waste and residues	Separate collection, controlled disposal and avoid uncontrolled mixed burning

The discussion presented throughout this study has addressed several key aspects of sustainable waste management. From a technical perspective, the analysis has considered the treatment processes and management systems that could be applied based on the observed waste characteristics. From a regulatory perspective, applicable government regulations can provide an important framework for guiding waste management practices. In addition, community participation is essential, particularly because effective waste management should begin at the household level through source segregation and responsible waste handling.

Another important aspect is financing, which plays a critical role in sustaining waste management systems over the long term. However, inadequate financial support from local governments remains a

significant challenge. Fitri & Ferza (2020) identified financing as one of the major challenges to achieving sustainable waste management. Funding can be obtained from several sources, including village funds (*Dana Desa*). However, access to village funding generally requires the waste management group to have formal legal recognition from the village government. The establishment of a legally recognized waste management group therefore represents an important institutional aspect that supports the implementation and sustainability of village-scale waste management.

Another potential financing mechanism is the implementation of household waste collection fees, whereby households receiving waste collection services contribute a predetermined fee to support operational costs. Thus, village funding and household-based waste collection fees can serve as complementary financing mechanisms to support the continuity and sustainability of waste management services at the village level. The integration of technical, regulatory, community, institutional, and financial aspects is therefore essential for developing a waste management system that is not only technically feasible but also institutionally and financially sustainable.

3.7. Limitations and future work

This study provides a useful village-scale baseline, but several limitations should be addressed before broader generalization. First, sampling was conducted over eight days in one season; seasonal sampling is needed because rainfall, fruit seasons, agricultural activity and holiday periods can change waste generation and moisture. Second, household socioeconomic stratification was not explicitly analysed. Third, volatile matter, fixed carbon, elemental composition, chlorine content, plastics polymer type and emission measurements were not included, although these variables are important for rigorous thermal-treatment evaluation. Fourth, the study does not yet include cost analysis, greenhouse-gas accounting or community acceptance testing. Future research should combine seasonal waste characterization with pilot-scale source separation and life-cycle assessment of biological treatment, material recovery and residual management scenarios.

4. Conclusions

Household waste in Kalibeji Village averaged 0.41 kg capita^{-1} day^{-1}, equivalent to about 2.13 t day^{-1} for the village population. The average bulk density was 138.59 kg m^{-3}, producing an estimated daily volume of 16.0 m^3 day^{-1}. The waste stream was dominated by kitchen and garden waste (71.24%), followed by dry recyclable fractions, especially plastic films. Laboratory results showed high moisture (53.3%), moderate ash content (7.75%) and a realistic LHV of 1,944.78 cal g^{-1}. These characteristics indicate that mixed-waste incineration is not the most technically appropriate default pathway for the village. A stronger management strategy should prioritize source-separated biological treatment of organics, recovery of dry recyclables and controlled handling of residual and special waste. The study demonstrates how household waste characterization can transform a community-led disposal practice into a more evidence-based rural resource-recovery system.

5. Conflict of Interest Declaration

The authors declare that there is no conflict of interest regarding the publication of this article. The authors also confirm that this manuscript is original and free from plagiarism.

6. Author Contribution Statement

All authors contributed equally to the conduct community service project, data analysis, and writing and preparation of this article.

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