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NATURE ENVIRONMENT AND POLLUTION TECHNOLOGY

Article In Press

PEER-REVIEWED PREPUBLISHED MANUSCRIPT

This is a peer-reviewed prepublished version of the paper to be published in **Vol. 26, No. 1, March 2027.**

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RECEIVED
4 June 2026

CITE THIS ARTICLE

Priyambada, I.B., Sumiyati, S., Budihardjo, M.A. and Nurdin, L.F., 2027. Waste-to-Energy Potential of Domestic Waste Through a Biodrying-Based Refuse-Derived Fuel Production Scenario in Jepara Regency, Indonesia. *Nature Environment and Pollution Technology*, 26(1), D1948.

https://doi.org/10.46488/NEPT.2027.v26i01.D1948

EARLY-ACCESS STATEMENT

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PUBLICATION STATUS

PEER REVIEW	ONLINE VERSION	FINAL ISSUE
Completed	**Prepublished**	**March 2027**

Original Research

Waste-to-Energy Potential of Domestic Waste Through a Biodrying-Based Refuse-Derived Fuel Production Scenario in Jepara Regency, Indonesia

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Abstract: Indonesia's growing urban waste volumes and overburdened landfill infrastructure require integrated treatment strategies beyond conventional collection and disposal. This study assesses the waste-to-energy (WtE) potential of domestic waste in Jepara Regency, Indonesia, through a biodrying-based refuse-derived fuel (RDF) production scenario. Waste generation and composition data were collected through field sampling in four districts: Jepara, Tahunan, Kedung, and Mlonggo. Sampling followed SNI 3964:2025 and was supplemented by population and economic projections using arithmetic, geometric, and least-squares methods for the 2025–2043 planning period. The results showed an average per capita waste generation rate of 0.48 kg/person/day, with food waste dominating the composition at 50.81%, followed by plastic at 23.10%. Material balance analysis projected a total waste input of 151.49 tonnes/day by 2043. From this input, the biodrying-based facility is expected to recover 62.80 tonnes/day of RDF at 96% processing efficiency while producing only 2.62 tonnes/day of inert residue. With moisture content reduced to the target level of 25% through a 21-day biodrying cycle, the projected RDF calorific value is expected to exceed 4,500 kcal/kg, approaching sub-bituminous coal equivalence. These findings indicate that biodrying-based RDF production offers a technically promising and scalable pathway for sustainable WtE development in Indonesian regency-level contexts, pending experimental validation of the projected fuel-quality parameters. As a planning-level assessment, the biodrying process parameters and RDF calorific value reported in this study are projected from material balance analysis and comparison with previously reported biodrying performance, rather than measured directly for the Jepara waste stream; experimental validation is therefore recommended as a subsequent research step.

Keywords: Refuse-derived fuel; Biodrying; Waste-to-energy; Solid waste management; Calorific value

1. INTRODUCTION

Indonesia continues to face significant challenges in managing municipal solid waste (MSW) due to increasing waste generation from household and commercial activities. The current waste management system still relies heavily on conventional collection, transportation, and disposal, a method that is increasingly unable to address the growing complexity of environmental problems caused by waste accumulation (Yansen, 2021). Most MSW originates from household waste, which contains different waste types that require appropriate processing methods to optimise resource recovery and reduce environmental impacts (Hemidat et al., 2019). Population growth and urban development have placed increasing pressure on existing waste disposal facilities, many of which have already exceeded their designed capacity, thereby contributing to long-term environmental degradation (Achi et al., 2024). Similar problems are also observed globally, particularly in developing countries, where rapid urbanisation challenges the capacity of existing waste management systems (Ferronato and Torretta, 2019, Kaza et al., 2018). In the Indonesian context, MSW management faces critical challenges as waste volumes continue to increase annually, while a substantial proportion remains improperly managed. This condition underscores the urgency of adopting waste-to-energy (WtE) approaches as part of integrated solid waste management strategies (Syaiful et al., 2024). Current waste disposal practices must therefore shift towards more sustainable approaches that support material recovery and resource recycling. This shift has encouraged the development of the WtE concept as a viable approach for sustainable MSW management (Beyene et al., 2018). The generation of green energy from waste has been widely recognised as a promising strategy to simultaneously mitigate carbon emissions and address waste management challenges, particularly in developing regions where population growth and urbanisation have intensified the burden on existing disposal infrastructure (Niyomukiza et al., 2024).

WtE systems offer a promising solution by converting waste materials into useful energy resources while reducing the amount of waste requiring final disposal (Ram et al., 2021, Kumar and Samadder, 2017). Among WtE options, refuse-derived fuel (RDF) technology is notable because it converts landfill-bound, non-recyclable combustible waste into a usable fuel (Zhao et al., 2016). Energy recovery from waste through thermochemical and biochemical processes is increasingly recognised as a competitive alternative to conventional disposal, offering advantages such as reduced land occupation, substantial volume reduction, and minimised secondary contamination (Niyomukiza et al., 2024). RDF can partially replace conventional fossil fuels in industrial sectors and power generation systems because it offers relatively high energy output and more consistent fuel properties (Azam et al., 2019). Moisture content remains a key factor controlling RDF quality and combustion performance (Rezaei et al., 2020). Biodrying has therefore been widely investigated as a pre-treatment technology that uses heat generated from aerobic microbial activity to reduce moisture while preserving the combustible fraction of waste (Rigamonti et al., 2012, Bilgin and Tulun, 2015). Previous studies have shown that biodrying can increase the energy content of waste by 30–40%, reduce waste volume, complete treatment within 2–3 weeks, and reduce pollution associated with landfill disposal (Hao et al., 2018, Tom et al., 2016, Wang et al., 2023). The advantages of this method include significant waste-mass reduction and lower emissions of gases such as CH_4, CO_2, SO_2, NO_x, and airborne particulates from landfill sites into the atmosphere (Chungam et al., 2025). The growing challenges of waste generation and landfill dependency, together with the potential contribution of WtE technologies in addressing these issues, are conceptually presented in **Fig 1.** In this context, RDF emerges as one of the most promising WtE pathways, converting combustible waste fractions into an alternative fuel with environmental and resource-recovery benefits, as illustrated in **Fig 2.**

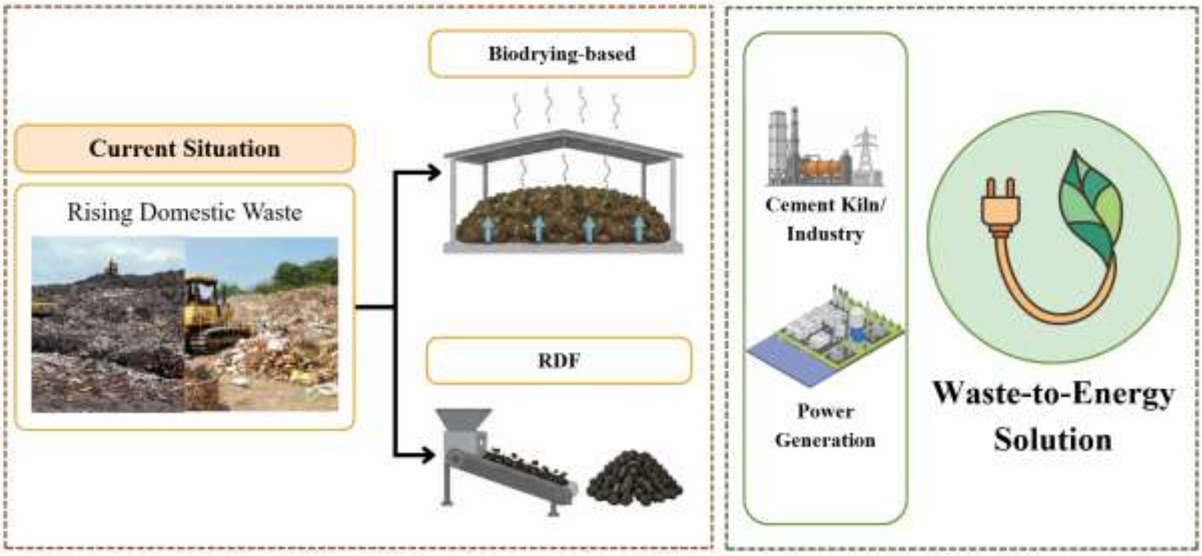

Fig 1: Conceptual framework of domestic waste challenges and WtE solutions. (Authors' own illustration, synthesised from concepts discussed in Yansen, 2021; Ferronato and Torretta, 2019; Kaza et al., 2018)

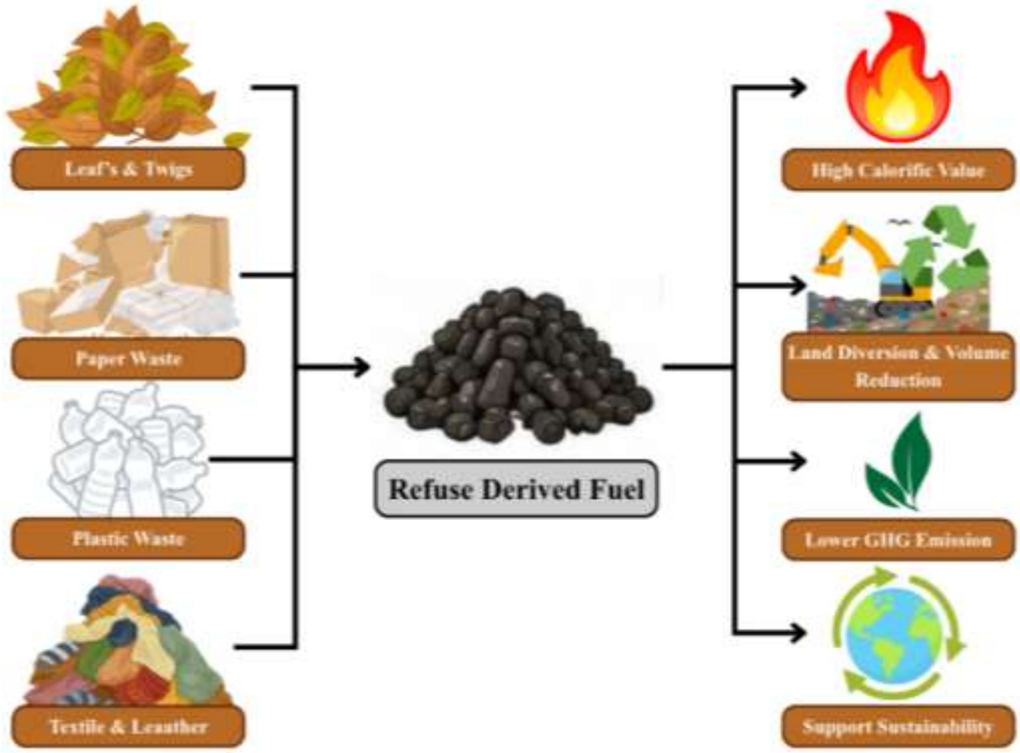

Fig 2: RDF feedstock fractions and resulting benefits. (Authors' own illustration, based on RDF feedstock and benefit categories discussed in Zhao et al., 2016; Azam et al., 2019)

Although biodrying technology has shown promising results, several knowledge gaps remain regarding its performance and wider application. Previous studies have mainly assessed system functionality and short-term operational performance, while extended planning and deployment stages remain less frequently examined (Lwin et al., 2024). Much of the existing literature also originates from countries with more established waste management systems, meaning that the findings may not be directly transferable to countries such as Indonesia, where waste management challenges differ substantially (Ferronato and Torretta, 2019, Kaza et al., 2018). The performance of biodrying and the potential for RDF production depend on local waste composition, climatic conditions, collection systems, and resource availability. Moreover, relatively few studies have linked biodrying evaluation with future waste-generation projections based on population growth forecasts (Lwin et al., 2024, Kaza et al., 2018). Taken together, these gaps indicate that no existing study has integrated field-based domestic waste characterisation with population- and economic-growth-based projections within a single biodrying-based RDF planning framework for an Indonesian regency-level context. This study addresses that gap by combining primary waste sampling data with long-term population and gross regional domestic product (GRDP) projections to develop an integrated, planning-level assessment of biodrying-based RDF production potential. The study also provides a methodological template applicable to comparable secondary cities in Indonesia and other developing regions.

This study develops a simulation model to describe how biodrying technology can be applied to domestic waste treatment under a WtE system using current data on waste generation, waste composition, waste management infrastructure, and field-based sampling results. The research presents an original approach by integrating biodrying-based RDF production assessment with Indonesian population growth projections to establish a comprehensive framework for future waste management and energy recovery planning. The study aims to evaluate the potential role of biodrying technology in sustainable domestic waste management in Indonesia and to estimate its contribution to renewable energy generation for future waste management strategies.

2. MATERIALS AND METHODS

2.1. Study area

This study is a planning-level, scenario-based assessment. Biodrying was not physically conducted; instead, the RDF production scenario was developed from field-based waste characterisation, material balance modelling, and comparison with previously published biodrying performance data. The study focused on domestic waste analysis through waste sampling at selected locations in Jepara Regency. Jepara Regency was selected because its current waste disposal system continues to rely on conventional collection and transportation to landfill sites. Waste is transferred directly to final disposal without treatment at the initial collection point. Jepara Regency is one of 35 regencies in Central Java Province, Indonesia, and covers an area of 102,025 ha. Geographically, the regency extends from 110°9′48.02″ to 110°58′37.40″ E and from 5°43′20.67″ to 6°47′25.83″ S. This study investigates a proposed integrated waste management facility that would convert domestic waste into RDF through biodrying. Four districts were examined: Jepara, Tahunan, Kedung, and Mlonggo. The distribution of the selected sampling areas is presented in **Fig 3**. These districts were selected because they represent diverse geographical and population characteristics, allowing local domestic waste-generation patterns to be examined more comprehensively. Sampling locations in the four districts were determined using proportionate stratified random sampling based on administrative position, total population, and geographical characteristics (Edjabou et al., 2015). Data on population, waste quantity, and waste composition were then used to forecast future RDF production and assess the operational feasibility of a biodrying-based waste management system.

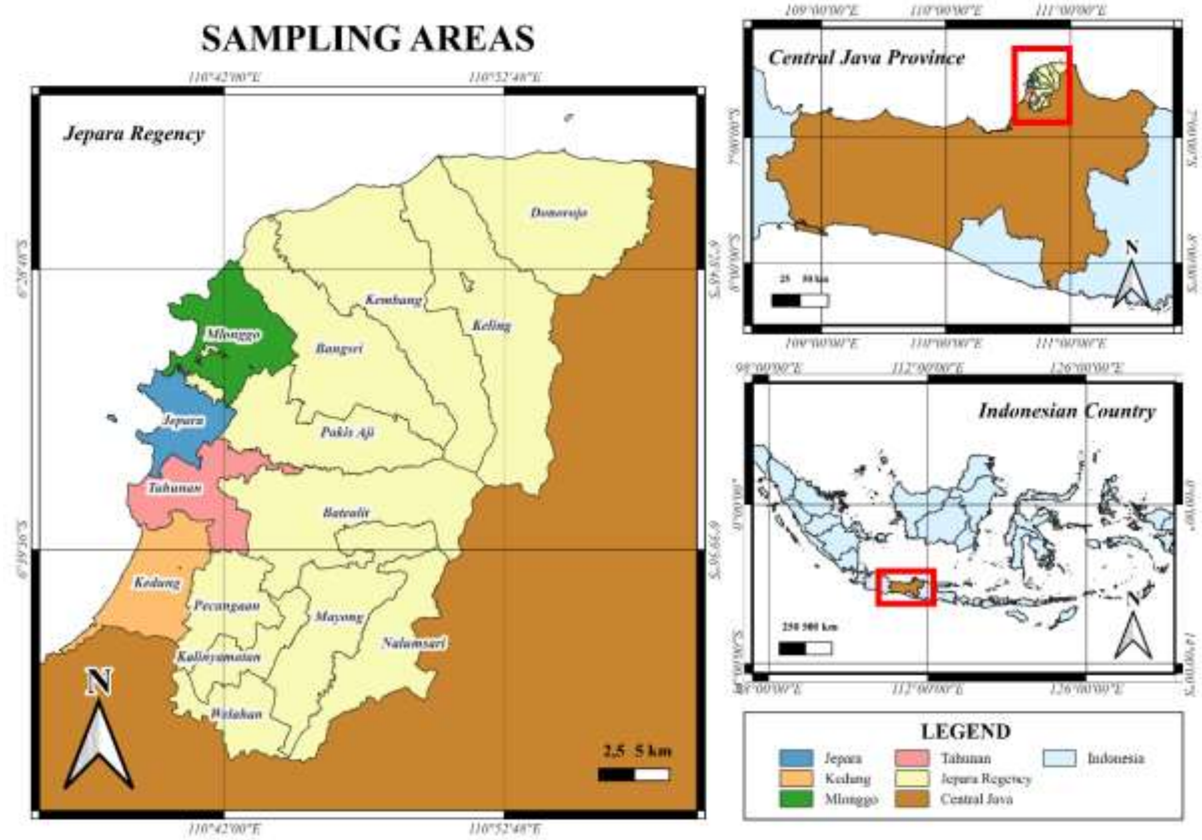

Fig 3: Sampling areas

2.2. Experimental setup

The experimental framework consisted of two integrated components: (1) field sampling and characterisation of domestic solid waste collected from residential sources in four selected districts of Jepara Regency, namely Jepara, Tahunan, Kedung, and Mlonggo; and (2) a scenario-based evaluation of biodrying-based RDF production using the characterised waste stream. Primary data on waste generation rates, waste composition, and physicochemical properties were obtained through field sampling conducted in accordance with SNI 3964:2025. The study workflow consisted of four sequential stages. First, domestic waste sampling was conducted to determine generation rates and composition characteristics in the selected districts. Second, waste generation and composition data were analysed to identify combustible fractions suitable for RDF production. Third, population and economic growth projections were developed to estimate future waste generation during the planning period. Finally, a biodrying-based RDF production scenario was evaluated to assess the potential recovery of domestic waste into alternative fuel and its applicability for sustainable waste management planning in Jepara Regency. **Fig 4** presents the overall experimental workflow, highlighting the integration of waste characterisation, projection analysis, and biodrying-based RDF scenario evaluation employed in this study.

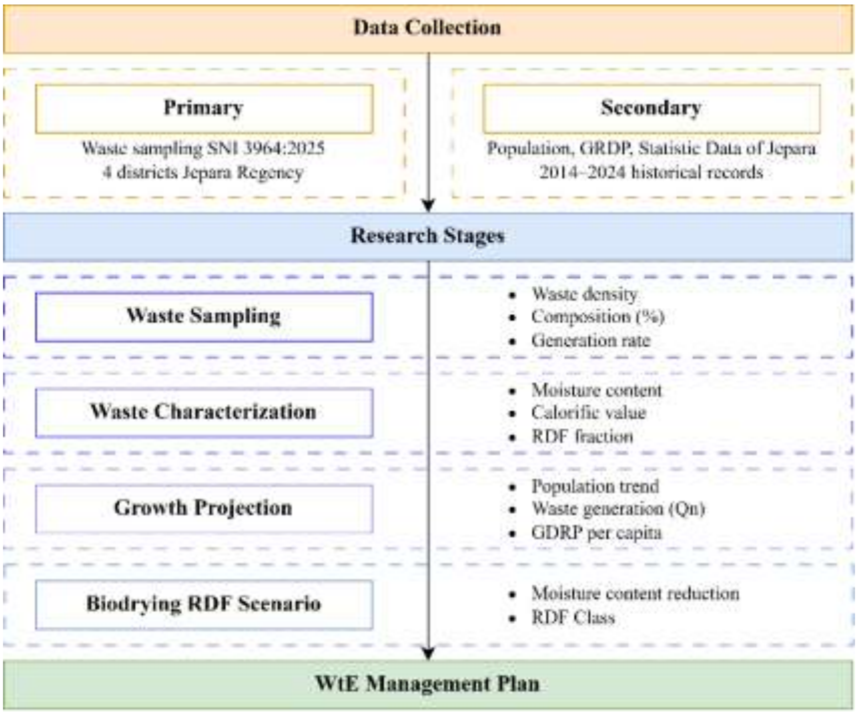

Fig 4: Experimental stages

2.3. Domestic waste sampling procedure

Domestic waste sampling was conducted to obtain primary data on waste generation rates and composition in the study area. The sampling procedure followed Indonesian National Standard SNI 3964:2025 concerning methods for collecting and measuring samples of waste generation and composition from household waste and household-like waste. Sampling locations were determined based on residential sectors stratified into three socioeconomic categories: high-, medium-, and low-income households. These categories were defined using criteria derived from population welfare data, household income or expenditure levels, electricity connection classifications, and house type, including permanent, semi-permanent, and non-permanent housing. **Fig 5** presents the workflow of the domestic waste sampling procedure, including sample collection, weighing, volume measurement, homogenisation, quartering, and waste composition sorting.

The number of sample units was calculated based on the population size of the study area. Although the total population of Jepara Regency exceeds one million, the actual sampling frame for this study was limited to four districts: Jepara, Tahunan, Kedung, and Mlonggo. The combined 2024 population of these four districts was 378,067 (BPS, 2025), which falls below the one-million threshold. Therefore, instead of the standard formula for large populations (see Equation (1)), the simplified formula for populations of one million or fewer was applied:

$$P_s = C_d \times \sqrt{P_t} \quad (1)$$

where P_s is the number of sample individuals, Cd is the city type coefficient (Cd = 0.5, as specified in SNI 3964:2025 for this population range), and Pt is the total population of the targeted study area (378,067). Using this formula, the required sample size was calculated as approximately 307 individuals.

The number of sampled household heads (K) was derived by dividing P_s by the average household size (N, assumed to be five people per household), yielding a minimum requirement of 62 households. To ensure robustness, 68 households were sampled, thereby meeting and modestly exceeding the statistical minimum. The number of sampled houses per economic stratum and district was calculated proportionately based on population share, as shown in Equation (2):

$$N_r = S_n \times K \quad (2)$$

where S_k represents the number of samples in a specific stratum or district, and S_n represents the proportional share of that sector relative to the total sampling frame. Accordingly, the 68 sampled households were distributed across the four districts based on their population shares: 16 households in Jepara (23.5%), 15 in Kedung (22.1%), 21 in Tahunan (30.9%), and 16 in Mlonggo (23.5%), as detailed in **Table 1**.

Field collection was carried out using standardised equipment, including 54-L sampling boxes, weighing scales, measuring tape, trash bags, gloves, and masks. The sampling procedure at each measurement point consisted of the following steps: (1) plastic bags were distributed to households one day before collection; (2) source information was recorded on field forms; (3) the empty sampling box was weighed; (4) waste samples were placed into the sampling box; (5) the box was shaken three times from a height of 20 cm to compact the contents; and (6) the weight and height of compacted waste in the box were recorded to determine volume and bulk density.

After individual weighing, all waste samples were combined on a tarp and mixed until homogeneous. When the total sample mass was less than 100 kg, all waste was sorted directly by component type on the tarp. When the total sample exceeded 100 kg, the quartering method was applied: the homogenised pile was divided into four equal sections, two opposing sections were retained, the remaining two were discarded, and the retained portions were reweighed to confirm that they totalled at least 100 kg before sorting proceeded. Waste was then sorted and weighed by component categories, including food waste, garden waste, wood/twigs, paper, plastic sheets, hard plastic, metal, textiles, rubber, glass, hazardous waste, disposable diapers, and residue. The sampling framework is shown in **Table 1**.

Table 1: Sampling Framework and Distribution of Sampled Households Across Socioeconomic Strata

District	Total Population (2024)*	Proportional Share (Sn)	Minimum Required Households (K≥62)^	Actual Sampled Households (K=68)	Socioeconomic Stratum Breakdown (Households)		
					High	Medium	Low

District	Total Population (2024)*	Proportional Share (Sn)	Minimum Required Households (K≥62)^	Actual Sampled Households (K=68)	Socioeconomic Stratum Breakdown (Households)		
					Income	Income	Income
Jepara	85,821	22.7%	14	16	5	6	5
Kedung	83,931	22.2%	14	15	5	5	5
Tahunan	117,579	31.1%	19	21	7	7	7
Mlonggo	90,736	24.0%	15	16	5	6	5
Total	378,067	100.0%	62	68	22	24	22

Fig 5: Domestic waste sampling procedure

2.4. Waste generation and composition analysis

Domestic waste analysis followed the sampling design specified in SNI 3964:2025, the current Indonesian National Standard for household waste sampling. The generation and composition calculation procedure used in this standard (see Equation (4)) is consistent with the original SNI 19-3964-1994 and is retained in the updated 2025 standard. GRDP per capita at fixed prices was used as an indicator of regional economic conditions and household consumption capacity. Economic expansion is associated with higher regional income, which may influence consumption patterns and, consequently, waste generation. Domestic waste generation and composition were calculated using the procedures specified in SNI 19-3964-1994 and SNI 3964:2025 (SNI, 1994).

$$Waste\ Generation = Pi\ x\ BTi \quad (3)$$

$$Weight\ Composition = \%\ Composition\ x\ Weight\ Generated\ Waste \quad (4)$$

The variable Pi represents the total population in year *i*, and BTi represents the amount of waste generated per capita in year *i*. The unit of analysis refers to residents living in the study area. Domestic waste generation and composition were calculated using Equation (5), while waste generation projections were calculated using Equation (6) and Equation (7). Qn refers to waste generation in the following *n* years (kg); Qt is waste generation in the first year of calculation; Cs is city improvement or growth; Ci is the growth rate of the industrial sector; Cp is the growth rate of the agricultural sector; Cqn represents the rate of increase in per capita income; and P is the population growth rate.

$$Qn = Qt\ (1 + Cs)n \quad (5)$$

$$Cs = \frac{(1 + \frac{Ci + Cp + Cqn}{3})}{1 + P} x100\% \quad (6)$$

2.5. Population and economic projection analysis

Data analysis was conducted using Microsoft Excel for planning calculations. Secondary data were obtained from reports published by the Central Statistics Agency of Indonesia and included population growth, regional economic output, and the distribution of existing waste management facilities in Jepara Regency. Population projections were used to estimate changes in domestic waste generation over time. Sample size determination was performed through mathematical evaluation to identify an appropriate number of samples. The study began by developing a domestic waste management planning framework for Jepara Regency, including an assessment of the need for integrated waste treatment operations.

Population projections for the next 20 years were calculated using three methods: arithmetic, geometric, and least-squares. The projection method was selected through correlation and standard deviation testing to identify the method producing the lowest standard deviation. Standard deviation measures the dispersion of data points from their mean. A small standard deviation indicates relatively stable data patterns with low variability between individual data points, whereas a high standard deviation indicates greater variability and less predictable year-to-year patterns (Houben et al., 2015). The projection results indicate the annual population growth factor. **Table 2** presents the projection methods used in this study.

Table 2: Projection methods

Arithmetic	Geometric	Least-squares
$Pn = Po + rn$	$Pn = Po\ (1 + r)^n$	$Y = \alpha - bX$
Pn = total population in year *n*	*Pn* = total population in year *n*	*Y* = value of the variable based on the regression line
Po = total population at the beginning	*Po* = total population at the beginning	*X* = independent variable α = constant

Arithmetic	Geometric	Least-squares
n = number of years counted r = population growth rate	n = number of years counted r = population growth rate	b = linear regression coefficient

2.6. RDF production scenario using biodrying

RDF production in this study was evaluated through a biodrying-based processing scenario applied to the characterised mixed domestic waste stream. Biodrying is a bio-oxidative treatment process in which heat generated by microbial decomposition of the organic fraction is used to evaporate moisture from mixed waste, thereby reducing water content and increasing the calorific value of the resulting solid fuel. Biodrying is designed to minimise mass loss through decomposition and maximise the dry mass available for energy recovery. The biodrying process was modelled in three sequential stages: (1) pre-processing, (2) biodrying treatment, and (3) post-processing and RDF classification. In the pre-processing stage, incoming waste was mechanically screened to remove oversized inert materials and coarse fractions unsuitable for biodrying. During the biodrying stage, the pre-processed waste was retained in compartments for a target period of 21 days. This retention time is longer than the 7–14-day range commonly reported in the biodrying literature (Bilgin and Tulun, 2015; Tom et al., 2016), reflecting the higher initial moisture content and lower bulk density of the mixed domestic waste stream characterised in this study (see Table 5), as well as the conservative design approach adopted to ensure that the target moisture content of 25% is consistently achieved across all eight compartments. Following biodrying, the dried mass was subjected to mechanical screening. The final RDF product was classified according to relevant quality parameters. **Fig 6** illustrates the biodrying-based RDF production scenario adopted in this study, including waste pre-processing, moisture reduction through biodrying, and post-processing for RDF recovery and classification.

The biodrying compartments were designed with a forced-aeration configuration using perforated ventilation pipes spaced 1 m apart, with vent holes 0.5 inches in diameter at 30-cm intervals, following the aeration design principles reported by Lwin et al. (2024) for market-waste biodrying. Airflow is supplied through a forced-aeration system using a centrifugal blower fan sized to provide positive-pressure distribution throughout the pile, sufficient to overcome resistance within the waste matrix and accelerate convective moisture evaporation without requiring an active, energy-intensive thermal drying unit. Detailed blower sizing, including capacity and static pressure, forms part of the subsequent detailed engineering design phase and is outside the scope of this planning-level study. Process control in the design is based on a fixed pile-turning interval of seven days across eight compartments to promote uniform aerobic conditions and moisture evaporation. The design endpoint is defined by the target moisture content of 25%, rather than by a fixed temperature trajectory, consistent with the approach described by Budihardjo et al. (2022).

Fig 6: RDF production scenario using biodrying

2.7. Material balance analysis

Mass balance calculations were carried out for the projected planning period from 2025 to 2043, with annual waste input quantities derived from population projections and per capita waste generation rates following established projection methodologies. Output streams were recalculated annually to reflect changes in waste generation volume while maintaining constant compositional and recovery parameters. This approach enabled assessment of the long-term RDF production potential and residue-reduction performance of the proposed biodrying-based waste management system.

3. RESULTS AND DISCUSSION

The current waste management system in Jepara Regency includes waste collection points, waste bank facilities, 3R (Reduce, Reuse, and Recycle) waste processing sites, and landfills. However, the system continues to follow a conventional approach, in which residents dispose of waste at the source before workers collect it at designated points and transfer it directly into waste containers. No sorting activities are conducted at the collection points because the waste is transported directly to Bandengan Landfill. The establishment of a suitable waste processing facility, supported by an appropriate treatment approach, is therefore necessary to reduce the volume of waste entering Bandengan Landfill. At present, Jepara Regency does not have an integrated waste processing site (IWPS) that functions specifically as a landfill waste-reduction facility.

3.1. Existing condition of domestic waste management in Jepara Regency

Based on data from the Jepara Regency Environmental Agency, total waste generation reached 157,571.51 tonnes in 2024 and increased to 168,085 tonnes in 2025, reflecting annual growth of 6.44%.

Despite this increase, only 54.76% of the generated waste was managed through formal collection and treatment systems, leaving more than 76,000 tonnes per year unmanaged and potentially contributing to environmental pollution. Waste management in Jepara Regency currently relies on collection points, waste banks, 3R waste processing sites (TPS3R), and Bandengan Landfill, the only landfill serving the regency. However, Bandengan Landfill receives only around 150–152 tonnes of waste per day, substantially lower than the estimated daily generation of more than 500 tonnes. This indicates that a considerable proportion of waste remains untreated, is openly burned, or is disposed of into water bodies. To improve waste management performance, 14 new TPS3R facilities were established between 2023 and 2024, increasing processing capacity to more than 28,000 tonnes per year. Nevertheless, the existing infrastructure remains insufficient to accommodate the growing waste volume, and residual waste from TPS3R operations continues to be transported to Bandengan Landfill. This highlights the need for alternative waste treatment solutions, such as an RDF-based IWPS. A summary of the existing waste management infrastructure available in Jepara Regency is presented in **Table 3**.

Table 3: Summary of existing waste management infrastructure in Jepara Regency

No.	Facility Type	Location / District	Quantity	Notes
1	Landfill (Final Disposal Site)	Bandengan, Jepara District	1 unit	Only operational landfill; overloaded as of 2024 (~152 tonnes/day of input)
2	3R Waste Processing Sites (TPS3R)	Various districts	14 units	Built in 2023–2024; used for compost and recyclables production
3	Waste banks	Sub-district level	Multiple units	Community-based recyclables collection
4	Arm-roll / collection trucks	Regency-wide collection routes	9 trips/day	Planned for operations as the study basis
5	RDF-based IWPS (planned)	Bandengan Landfill area	100 tonnes/day proposed	Submitted to the Ministry of Public Works (PUPR); grant-based funding

3.2. Population and GRDP characteristics of Jepara Regency

The Jepara Regency Central Statistics Agency reported that the total population reached 1,264,598 people in 2023, while the region generated IDR 31.14 billion in GRDP per capita. The manufacturing sector produced the highest GRDP value, reaching IDR 12,990.36 billion in 2023. The agricultural sector produced the lowest GRDP value, amounting to IDR 4,705.88 billion. The GRDP of Jepara Regency increased continuously from 2019 to 2023, indicating rising economic development, increasing regional income and individual earnings, evolving economic patterns, rising inflation, and improving living standards among Jepara residents. Higher income tends to increase purchasing power, which may lead to higher consumption. This observation is consistent with Zainuddin and Ria (2022), who demonstrated that increasing social wealth is associated with higher expenditure. Rising public consumption may also encourage businesses to increase production, thereby generating positive effects on economic growth (Abbas et al., 2011). The population and GRDP trends of Jepara Regency from 2019 to 2023 are summarised in **Table 4**.

Table 4: Population and GRDP of Jepara Regency from 2019 to 2023

Year	Total Population (people)	GRDP per Capita (billion rupiah)	Industrial GRDP (billion rupiah)	Agricultural GRDP (billion rupiah)
2019	1,257,912	24.11	10,471.30	3,949.10
2020	1,184,947	25.49	10,517.53	4,170.12
2021	1,188,510	20.90	11,252.61	4,182.05
2022	1,192,811	29.34	12,013.01	4,470.77
2023	1,264,598	31.14	12,990.36	4,705.88

3.3. Population and GRDP projections for waste management planning

The amount of waste generated in an area is strongly influenced by population size (Liu and Wu, 2011). Among the three projection methods evaluated, namely arithmetic, geometric, and least-squares, the least-squares method yielded the lowest standard deviation (SD ≈ 45,880 people) when fitted against the 2019–2023 historical population data in Table 4. By comparison, the arithmetic and geometric methods each produced SD values of approximately 72,520 people. The least-squares method was therefore selected for the 2025–2043 population and GRDP projections used in this study. Population projections are needed to estimate population growth at the end of the planning period, namely 2043. The selected projection method produced the lowest variation after analysis of the available statistical data. **Fig 7** illustrates the projected growth trends of these economic indicators. Waste generation is also associated with community consumption patterns and the level of regional economic development. The calculations show that agricultural and industrial GRDP growth follows the projected increase in annual waste generation. This indicates that increasing agricultural and industrial activity may contribute to greater waste generation (Tong et al., 2022). Goodness of fit was additionally evaluated using the coefficient of determination (R^2). Given the limited length and non-monotonic pattern of the 2019–2023 historical population series (see Table 4), R^2 values were low for all three methods: approximately 0.01 for the least-squares method and negative for the arithmetic and geometric methods, which were anchored only to the two end-year values. Standard deviation was therefore retained as the primary model-selection criterion.

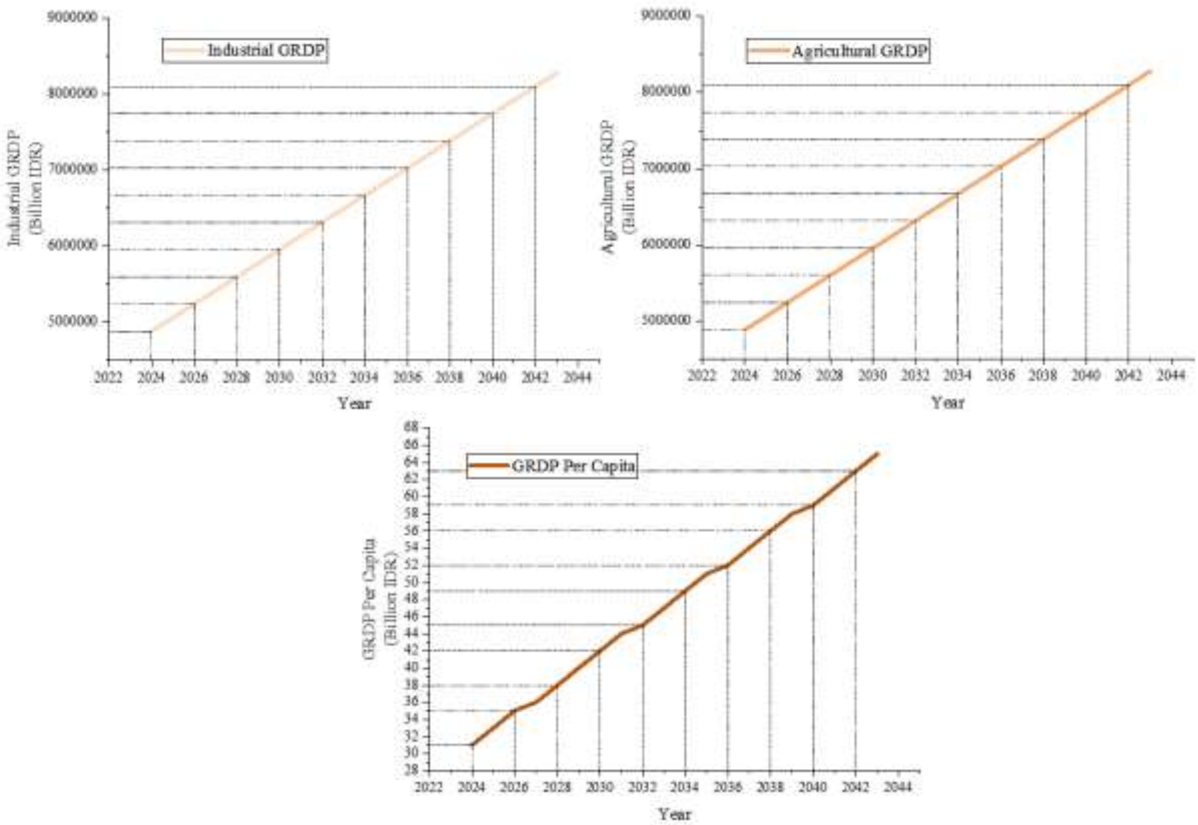

Fig 7: GRDP projection

3.4. Domestic waste generation in the selected districts

The overall average domestic waste generation rate in the four study districts was 0.48 kg/person/day, equivalent to 1.8 L/person/day. This value is below the average reported for major Indonesian cities, namely 0.69 kg/person/day, and the national estimate of 0.68 kg/person/day (Kaza et al., 2018). This difference is expected because the study area consists of semi-urban and peri-urban residential districts rather than densely urbanised city centres. Among the four districts, Mlonggo recorded the highest per capita generation rate, at 2.1 L/person/day or 0.58 kg/person/day, while Jepara District recorded the lowest, at 1.4 L/person/day or 0.39 kg/person/day. Tahunan District generated 1.7 L/person/day or 0.50 kg/person/day, and Kedung District generated 1.9 L/person/day or 0.44 kg/person/day. The relatively higher volumetric generation in Kedung compared with its gravimetric rate reflects the lower bulk density of waste in that district, at 232.4 kg/m³, potentially attributable to a greater proportion of low-density materials such as leaves, twigs, and packaging in the waste stream of semi-rural households.

The raw household-level daily weighing records collected during the 8-day sampling period were not retained in a form that permits calculation of standard deviations or confidence intervals for per capita generation rates. Only aggregated per-district means are therefore reported in Table 5. This limitation is acknowledged in the present study, and future waste characterisation surveys in this region are recommended to archive full household-level raw data to enable formal uncertainty and variability analysis.

Table 5 summarises the primary sampling results for daily domestic waste generation across the four study districts, including volumetric and gravimetric generation rates per capita and estimated bulk density values. Bulk density values were derived from measurements using the standard 54-L sampling box, consistent with the SNI 3964:2025 protocol.

Table 5: Domestic waste generation in Jepara, Tahunan, Kedung, and Mlonggo Districts

District	Average Waste Generation (volume/day)		Average Waste Generation (volume/person/day)		Bulk Density (kg/m^3)
	Volume/day	Weight/day	L/person/day	kg/person/day	
Jepara	119.5	32.84	1.4	0.39	274.7
Tahunan	135	38.41	1.7	0.50	284.5
Kedung	143.3	33.30	1.9	0.44	232.4
Mlonggo	127	34.99	2.1	0.58	275.5
Average	131.2	34.89	1.8	0.48	266.8

3.5. Composition of domestic waste and its suitability for RDF production

The calculation of domestic waste generation requires waste generation percentages, which reflect the direct relationship between population size and waste quantity (Han et al., 2018). Domestic waste production generally increases as population increases. Table 6 shows that domestic waste generation also tends to be positively associated with income. For example, domestic waste production in high-income settlements is greater than that in low-income settlements. Otoniel et al. (2008) reported that different generations and income groups consume different types of containers, as higher-income households tend to use more domestic packaging than lower-income households. The sampling results show that food waste is the most dominant component of domestic waste, accounting for 50.81% of the total. This high proportion of food waste is likely associated with inadequate food handling, distribution, and post-harvest processing practices. The composition of domestic waste generated in the study area is presented in **Fig 8**, which shows the dominance of food waste and plastic fractions compared with other waste components. A study in the United Kingdom found that households generated approximately 40% of their food waste by preparing more food than household members could consume (Quested and Johnson, 2009). Cox and

Downing also identified several behavioural factors contributing to household food waste (Lyndhurst et al., 2007). The second-largest waste category in the present study is plastic, accounting for 23.10% of the total waste composition. Other notable waste types include leaves and twigs, paper and cardboard, and miscellaneous materials. Among thermochemical WtE technologies, incineration has been shown to generate the highest energy output from mixed MSW streams, while pyrolysis offers superior energy recovery for organic and wood-based fractions. This suggests that a combined approach may optimise overall energy potential (Syaiful et al., 2024).

3.6. Domestic waste generation projection during the planning period

The graph in **Fig. 9** shows projected domestic waste generation in Jepara Regency across the four study districts, namely Jepara, Tahunan, Kedung, and Mlonggo, for the 2025–2043 planning period. The vertical axis shows average daily waste generation per person in kilograms (kg/person/day), while the horizontal axis shows the projected years from 2024 to 2043. The graph indicates that domestic waste generation is projected to increase steadily across all four districts. Mlonggo District produces more waste than the other districts, beginning at 0.59 kg/person/day in 2024 and increasing to 0.70 kg/person/day by 2043. Tahunan District records intermediate waste generation values, while Kedung and Jepara Districts show lower but steadily increasing waste generation trends. These results indicate that the study areas are expected to experience rising domestic waste generation due to population growth, urban expansion, and changing consumption patterns over the next two decades. The findings demonstrate the need for improved waste management systems, including new facilities capable of handling increasing waste volumes.

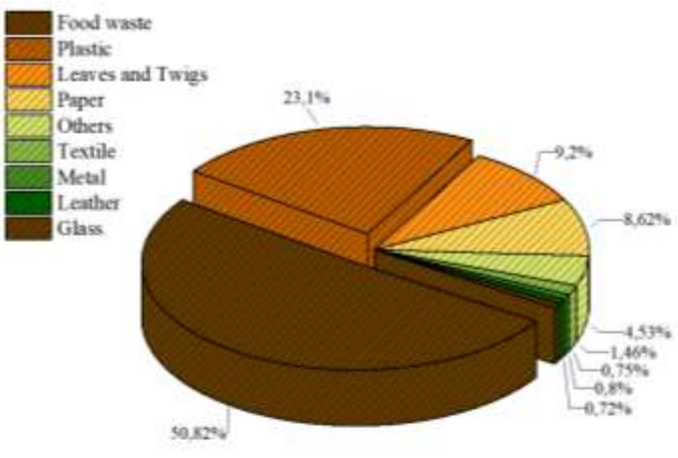

Fig 8: Composition of domestic waste

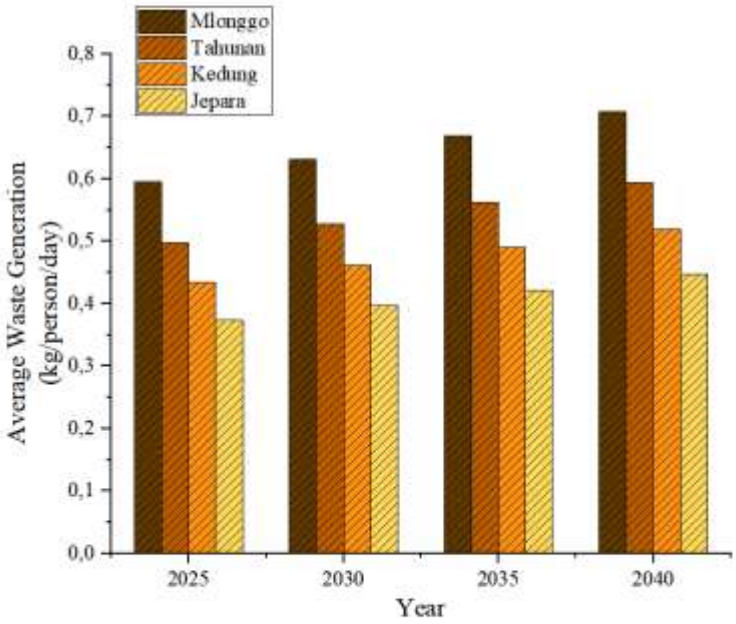

Fig 9: Projections of domestic waste generation

3.7. Material balance of domestic waste conversion into RDF

RDF is an alternative fuel produced from combustible waste materials such as plastics, rubber and leather, textiles, wood, paper, synthetic resins, wastewater treatment sludge, and processed sludge (Chiemchaisri et al., 2010). RDF is generated by mechanically separating combustible fractions from non-combustible materials through processes such as shredding, screening, air classification, and drying (Liu et al., 1996). RDF represents a waste management technique that transforms waste into energy, specifically fuel. It is produced by mechanically separating the combustible fraction from the non-combustible fraction of waste (McDougall et al., 2008). The technology has been widely implemented in Europe, the United States, and Japan as a WtE strategy (Fu et al., 2005). Depending on the characteristics of incoming waste and the desired fuel quality, RDF production commonly involves source separation, size reduction, classification, removal of metals and inert materials, drying, and densification (Caputo and Pelagagge, 2002).

In Jepara Regency, a considerable amount of residual waste from TPS3R facilities and temporary disposal sites is still transported to the landfill, resulting in a high volume of waste entering the Bandengan Landfill. To address this issue, an RDF-based IWPS was evaluated using a biodrying process, with facility design based on projected waste generation in 2043. The RDF feedstock consists of combustible waste fractions, including plastics, leaves and twigs, paper and cardboard, rubber and leather, and textiles, with an estimated processing efficiency of 96% and 4% residual waste. Material balance analysis was used to evaluate changes in waste mass and volume throughout the processing stages, which include sorting, shredding, biodrying, and screening. Biodrying was selected as the primary drying method because it can reduce moisture content by up to 66.7% while remaining cost-effective for large-scale applications (Budihardjo et al., 2022). Furthermore, moisture reduction can significantly improve the calorific value of the resulting RDF, thereby enhancing its suitability as an alternative fuel source (Frei et al., 2004). The composition of waste fractions suitable for RDF production and their corresponding recovery through the biodrying-based processing system are presented in **Table 6** and **Fig 10**.

Table 6: Waste composition and processing recovery in 2043

RDF Integrated Waste Processing Site	Percentage	Tonnes/day	m³/day
A. Waste Input Composition (Basis: Total Input)			
Organic			
— Food waste	50.81%	76.98	307.91
— Leaves and twigs	9.20%	13.94	55.77
Inorganic			
— Paper/cardboard	8.62%	13.06	52.23
— Plastic	23.10%	35.00	139.98
— Glass	0.72%	1.09	4.38
— Leather and rubber	0.80%	1.22	4.87
— Textile	1.46%	2.21	8.83
— Metal	0.75%	1.14	4.55
— Others	4.53%	6.86	27.45
TOTAL WASTE INPUT	**100.00%**	**151.49**	**605.97**
B. RDF Processing Recovery (Basis: RDF Feedstock)*			
— RDF product	96.00%	62.80	251.21

RDF Integrated Waste Processing Site	Percentage	Tonnes/day	m³/day
— Inert residue	4.00%	2.62	10.47
TOTAL RDF PROCESS OUTFLOW	**100.00%**	**65.42**	**261.68**

*Note: Food waste (76.98 tonnes/day) and non-combustible recyclables, namely glass and metal (2.23 tonnes/day), are separated at the picking bay before biodrying. The RDF processing recovery percentages in Section B are therefore calculated based on the 65.42 tonnes/day combustible RDF feedstock, not the total waste input.

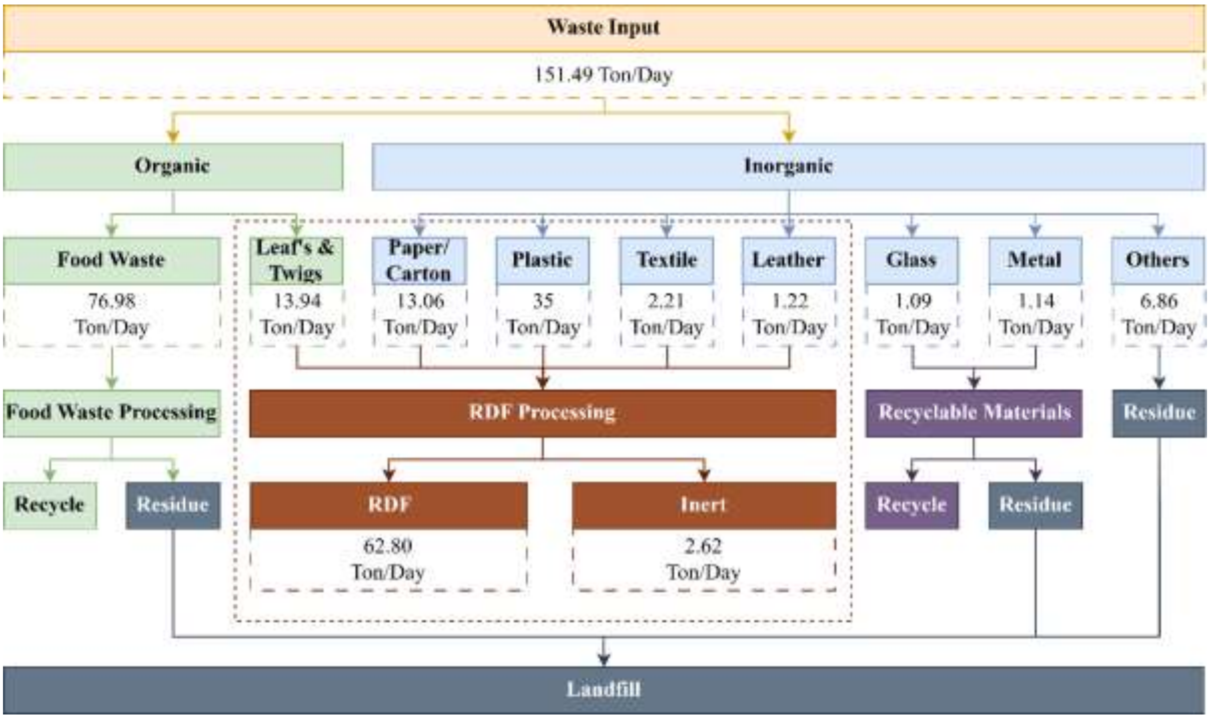

Fig 10: Waste flow diagram

The 96% processing efficiency and 25% target moisture content used in the material balance were adopted from comparable biodrying-based RDF studies, in which moisture reduction of up to 66.7% and processing losses below 5% have been reported under similar mixed-MSW feedstock conditions (Budihardjo et al., 2022; Frei et al., 2004). To assess the sensitivity of projected output to these assumptions, the material balance was recalculated for the 65.42 tonnes/day combustible RDF feedstock at processing efficiencies of 90%, 96%, and 99%. These scenarios correspond to RDF outputs of 58.88, 62.80, and 64.77 tonnes/day, with inert residues of 6.54, 2.62, and 0.65 tonnes/day, respectively. Based on the moisture–calorific value relationship reported for comparable biodried MSW/RDF, namely 3,420–4,708 kcal/kg across a moisture range of 20–30% (Zaman et al., 2021; Budihardjo et al., 2022), the calorific value is expected to reach approximately 4,708 kcal/kg at 20% moisture and decrease to approximately 3,420 kcal/kg at 30% moisture. This underscores the importance of consistently achieving the 25% moisture target to maintain RDF quality above the 4,500 kcal/kg threshold. These results indicate that projected RDF recovery is comparatively robust to moderate variation in processing efficiency, ranging from 58.9 to 64.8 tonnes/day across the 90–99% efficiency range, whereas the resulting calorific value is more sensitive to the achieved moisture content.

3.8. Biodrying process design for RDF production

The design of the IWPS units and areas was based on projected waste generation for 2043. The planning process began by determining the waste transportation system to be used within the service area. In this study, arm-roll trucks were selected as the primary collection vehicles, with nine trips per day planned to accommodate waste transportation requirements. Upon arrival at the facility, waste transport vehicles first enter the recording and weighing station located near the main entrance of the IWPS. This area is intended to record and measure the quantity of waste entering the facility and is designed based on the dimensions and operational requirements of the selected waste transport vehicles.

After weighing, the waste is directed to the picking bay, where materials suitable for RDF production are separated from recyclable materials, such as glass and metals, as well as waste fractions unsuitable for RDF production, particularly food waste. Sorting activities in the picking bay are carried out by scavengers to recover economically valuable materials and remove components that may interfere with downstream processing. Based on the material balance analysis, output from the picking bay amounts to 261.68 m^3/day of RDF feedstock, with a total weight of 65.42 tonnes/day. This material is subsequently transferred to the pre-treatment unit for shredding to reduce particle size to approximately 5 cm. The separated food waste, amounting to 76.98 tonnes/day, is directed to existing district-level TPS3R facilities, where it is processed into compost and cultivated as feedstock for black soldier fly (BSF) maggot farming, consistent with Fig. 10. The shredding process is expected to reduce waste volume by 30%. The pre-treatment unit consists of a shredding machine, belt conveyor, and storage bay. The design capacity of both the shredder and belt conveyor is determined based on the accumulated daily weight of incoming waste and the reject fraction returned from subsequent processing stages.

Following pre-treatment, the waste is processed in the biodrying unit for 21 days until the target moisture content of 25% is achieved. The biodrying facility is designed with eight compartments, with waste turning conducted every seven days and compartment capacities adjusted to accommodate waste generated over a three-day period. Each biodrying bay is equipped with leachate drainage channels and air ventilation pipes spaced 1 m apart, with vent holes measuring 0.5 inches in diameter at 30-cm intervals. After biodrying, the material enters the post-treatment unit, which consists of a screener, belt conveyor, and storage bay. The screener separates the processed material into RDF product and inert residue fractions, consistent with the material balance presented in Table 6, namely 96% RDF product and 4% inert residue. Based on the area requirements of each processing unit, the total land requirement for the RDF-based IWPS was calculated, as summarised in **Table 7**.

Table 7: Land requirements for RDF planning for domestic waste

No	Building Area	Unit	Total Area (m^2)
1.	Weighbridge	1	23
2.	Recording post	1	9
3.	Picking bay	1	256

No	Building Area	Unit	Total Area (m²)
4.	Picking bay for food waste	1	144
5.	Storage bay before biodrying	1	225
6.	Biodrying unit	8	288
7.	Storage bay after biodrying	1	144
8.	Storage bay after screening	1	125
9.	Leachate treatment plant	5	469
10.	Wheel loader and excavator parking lot	1	252
11.	Staff parking lot	1	72
12.	Waste vehicle parking lot	1	775
13.	Laboratory		40
14.	Prayer room	1	9
15.	Toilet	2	9
	TOTAL		2,840

The design of the proposed IWPS incorporates leachate collection and a dedicated leachate treatment plant (see **Table 7**) to manage leachate generated during biodrying, as well as ventilation to support aerobic conditions and limit anaerobic odour generation. Nevertheless, several environmental and operational risks require attention during detailed design and operation. These include odour management during the picking-bay and pre-biodrying storage stages, potential pathogen survival due to the mixed-waste feedstock, air emissions and microplastic release during shredding and screening, chlorine loading in the RDF product originating from plastic fractions, disposal or beneficial use of inert and ash residues, and occupational health and safety measures for scavengers and workers involved in manual sorting. A detailed environmental risk assessment and a formal occupational health and safety plan are recommended before facility construction.

3.9. RDF production potential and alternative fuel implications

The biodrying-based RDF production scenario indicates that domestic waste in Jepara Regency has considerable potential for alternative fuel production. RDF feedstock is primarily derived from combustible waste fractions, including plastic, paper, leaves and twigs, textiles, and rubber, while the dominant food waste fraction is separated before biodrying to improve fuel quality. Through moisture reduction during biodrying, the calorific value of the waste can be significantly increased, enhancing its suitability as a substitute for conventional fossil fuels and supporting sustainable WtE development in the region.

Previous research has demonstrated that biodrying can increase the calorific value of MSW by 55.3% under optimised aeration conditions, achieving a peak calorific value of 17.63 MJ/kg (Zaman et al., 2021). A study on MSW from Semarang's Jatibarang Landfill confirmed that biodrying can increase calorific value from approximately 3,930 kcal/kg to levels meeting or approaching fuel-grade standards (Zaman et al., 2021, Budihardjo et al., 2022). Frei et al. (2004) further documented a 58% increase in calorific value following biodrying, primarily attributable to moisture reduction. For the Jepara scenario, the biodrying unit is designed to reduce waste moisture content to approximately 25% over a 21-day treatment period. Based on comparable studies, this is expected to increase the calorific value of the RDF product to above the operational threshold of 4,500 kcal/kg. A comparative overview of calorific values for various fuel types and MSW processing stages is provided in **Table 8**. It should be noted that the calorific value and moisture-reduction figures presented in this section are projections based on comparison with previously published biodrying studies (see Table 8), rather than direct experimental measurement of Jepara RDF. Experimental characterisation of the produced RDF is therefore recommended as future work.

Table 8: Comparative calorific values of MSW-derived fuels and reference fossil fuels

Fuel Type	Calorific Value (kcal/kg)	Moisture Content (%)	Reference
Raw MSW, before biodrying	1,500–2,400	50–70	Wahyanti et al. (2025)
Biodried MSW/RDF, after biodrying	3,420–4,708	20–30	Zaman et al. (2021) Budihardjo et al. (2022)
RDF, high-quality and plastic-dominant	5,990–25,100	<10	Sari et al. (2024) Hemidat et al. (2019)
Sub-bituminous coal, reference	4,935–6,163	<15	Sari et al. (2024)
MSW Jepara, projected RDF-biodrying scenario	>4,500 target	<25	Primary data; Budihardjo et al. (2022) Frei et al. (2004)

Studies on MSW in Indonesian landfills have demonstrated that thermochemical conversion can yield substantial energy outputs. For instance, the Tamangapa Landfill in Makassar was estimated to generate up to 168.80 MW/day through incineration, confirming the significant energy potential embedded in Indonesian urban waste streams (Syaiful et al., 2024). Beyond energy recovery, the biodrying-based RDF scenario provides additional benefits through waste reduction, landfill diversion, and emission mitigation. In the context of decarbonisation, the substitution of fossil fuels with solid fuel derived from waste has been shown to substantially reduce carbon emissions associated with energy generation, thereby supporting a transition from a linear to a circular economy in waste management (Niyomukiza et al., 2024). The proposed RDF-based IWPS in Jepara is projected to recover 62.80 tonnes/day of RDF by 2043, reducing waste disposal to landfill while supporting alternative fuel production. Effective separation of the high food waste fraction (50.81%) and biodrying treatment are essential to achieve the target moisture content of 25% and maintain RDF quality. Overall, the results indicate that biodrying-based RDF production has strong potential to support sustainable waste management and WtE development in Jepara Regency.

Given its projected calorific value of more than 4,500 kcal/kg and moisture content below 25%, the RDF produced in this scenario is most compatible with co-processing as an alternative fuel in cement kilns. Cement kilns typically accept RDF with calorific values above 3,000–3,500 kcal/kg and moisture content below 20–25% (Sari et al., 2024; Hemidat et al., 2019), which is consistent with existing RDF utilisation practices at several cement plants in Indonesia (Sari et al., 2024). Boiler and power plant applications generally impose additional chlorine and ash-content specifications. As these parameters were not measured in this study, confirmation of RDF suitability for these alternative end uses would require the laboratory characterisation identified in the conclusion section as future work.

4. CONCLUSIONS

This study evaluated the WtE potential of domestic waste in Jepara Regency through a biodrying-based RDF production scenario by integrating field sampling, waste characterisation, population and economic projections, and material balance analysis. The results indicate that the current waste management system remains inadequate. Total waste generation increased from 157,571.51 tonnes in 2024 to 168,085 tonnes in 2025, while only 54.76% of waste was formally managed. Bandengan Landfill, the regency's only landfill, receives only a portion of the generated waste, leaving a substantial amount unmanaged, openly burned, or disposed of into water bodies. Waste sampling revealed an average generation rate of 0.48 kg/person/day, equivalent to 1.8 L/person/day, with waste composition dominated by food waste (50.81%) and plastic (23.10%). These results indicate strong potential for RDF production following appropriate source separation.

Population and GRDP projections suggest continued growth in waste generation through 2043, reinforcing the need for scalable treatment infrastructure. Material balance analysis estimated that the proposed RDF-based IWPS would receive 151.49 tonnes/day of waste and produce approximately 62.80 tonnes/day of RDF after sorting, shredding, and biodrying. The system is expected to achieve a processing efficiency of 96%, with only 4% remaining as inert residue. The biodrying process, designed with an eight-compartment system and a 21-day treatment cycle, is projected to reduce moisture content to 25% and increase the calorific value of RDF to more than 4,500 kcal/kg, making it suitable as an alternative fuel for industrial applications. The findings demonstrate that biodrying-based RDF production represents a technically feasible and scalable WtE solution for Jepara Regency. The proposed facility has the potential to reduce landfill dependency, recover energy from domestic waste, and support sustainable waste management through a circular economy approach. Future studies should focus on experimental validation of RDF quality under local conditions, together with comprehensive techno-economic assessment, including CAPEX/OPEX, RDF selling price, and comparison with landfill disposal costs, as well as environmental assessment, such as life-cycle assessment, to evaluate the long-term implementation feasibility of the proposed facility. In particular, laboratory characterisation of moisture content, calorific value through bomb calorimetry, ash content, volatile matter, fixed carbon, chlorine and sulfur content, and, where relevant, heavy metal concentrations of the biodried RDF product should be prioritised in future experimental work to confirm the fuel-quality projections presented in this study. Future experimental work should also prioritise pilot-scale biodrying trials with continuous temperature and oxygen profiling and periodic moisture-content monitoring to validate the process-design parameters proposed in this study, namely the 21-day duration and 25% target moisture content.

Author Contributions: Conceptualization, I.B.P.; methodology, I.B.P., S.S., and M.A.B.; investigation, I.B.P., S.S., and M.A.B.; data curation, M.A.B.; validation, S.S. and L.F.N.; writing—original draft, L.F.N.; writing—review and editing, L.F.N.

Funding: This research was funded by Universitas Diponegoro through the International Publication Research (RPI) Scheme, using Non-State Budget Revenue and Expenditure Funds (Non-APBN), under Assignment Letter No. 222-553/UN7.D2/PP/IV/2025.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to thank Annisa Sila Puspita for reviewing this article and providing valuable feedback during manuscript preparation.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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