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Material Recovery Facilities and RDF Technology for Waste Optimization in Small Cities: a Material Flow Analysis

Nando Ade Amarylly Putra[1*], Arseto Yekti Bagastyo[2]
[1,2]Department of Environmental Engineering, Faculty of Civil Planning and Geo Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia 60111.
*Corresponding author. Email: nandoamarylly@gmail.com

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Abstract

The challenge of managing increasing waste generation is not exclusive to metropolitan areas but is also faced by smaller cities, including Biak Numfor Regency, particularly within the population centers of Biak Kota and Samofa Districts. This study employs Material Flow Analysis (MFA) to map waste flows and evaluate technological interventions based on primary sampling data referring to SNI 3964:2025. predominantly organic (42.86%) and plastics (26.18%). Simulation results suggest that Scenario II, which deploys six units of Material Recovery Facilities (TPS 3R), meets thw goals set by the National Medium-Term Development Plan of the Republic of Indonesia (RPJMN) 2029. Furthermore, Scenario III, which integrates TPS 3R with a Refuse Derived Fuel (RDF)-based Integrated Waste Processing Site (TPST), effectively reduces landfill residue to below 10%, in alignment with the National Long-Term Development Plan of the Republic of Indonesia (RPJPN) 2045. The findings conclude that the proposed integrated infrastructure is technically feasible for achieving national waste reduction mandates. However, practical implementation necessitates operational reforms, particularly rigorous source segregation and modernized collection logistics, to ensure feedstock quality and optimize facility performance.

Keywords: Biak Numfor, Material Flow Analysis (MFA), RDF, TPS 3R, TPST Waste Reduction Scenarios

1. Introduction

Waste management in small cities, specifically in archipelagic regions, faces challenges related to limited landfill space and a lack of intermediate-treatment facilities. In Biak Numfor Regency, Biak Kota and Samofa Districts serve as population centers, contributing 54.2% of the total waste generated. The increase in waste generation in this region poses a serious challenge, as the performance of existing waste management systems remains suboptimal. Based on the National Waste Management Information System (SIPSN) data, the regional waste reduction achievement has only reached 17.31%, a figure significantly below the national reduction target of 30%. This gap indicates systemic inefficiencies from upstream to downstream.

Currently, the management system relies on a conventional "collect-transport-dispose" pattern. However, this approach has some fundamental limitations. As highlighted in broader studies, the “collect-transport-dispose” waste management approach exhibits several significant weaknesses throughout its various stages. First, in the collection phase, inefficiencies arise from an inadequate supply of waste containers and weak transportation systems, as observed in urban areas where door-to-door collection methods suffer from low patronage or accessibility problems. This results in inconsistent waste pickup and contributes to indiscriminate waste disposal by the public, reinforcing the perception that waste management is solely a government responsibility rather than a shared societal duty (Douti et al., 2017). In addition, the absence of formal facilities such as Material Recovery Facilities (TPS 3R) and Integrated Waste Processing Sites (TPST) places an increasingly heavy burden on the Aibyowki Landfill (TPA). The direct impact of this limited system capacity is the occurrence of waste overload at several Temporary Storage Sites (TPS), potentially causing environmental health issues and degrading the urban aesthetics of the area. Formal facilities are crucial components of modern waste management systems because they enable the segregation, recovery, and recycling of materials before disposal in landfills, thus minimizing the volume and toxicity of landfill waste (Sarigiannis et al., 2020). Therefore, a partial approach is no longer adequate for resolving these complex issues.

The disparity between national mandates and local infrastructure readiness is particularly acute in archipelagic regions. While the National Long-Term Development Plan of the Republic of Indonesia (RPJPN) 2025-2045 sets an ambitious target of reducing landfill residue to under 10% by 2045, small island cities like Biak Numfor will face a 'double burden' of waste management. First, limited land availability restricts the potential for landfill expansion, making volume reduction an absolute necessity rather than an option. Second, the logistical cost of transporting recyclable materials to recycling industries, which are predominantly concentrated on Java Island, creates a significant economic barrier and often renders the recycling supply chain financially unviable.

Consequently, reliance on conventional 'collect-transport-dispose' methods is no longer sustainable. This study addresses a critical gap in waste management strategies for archipelagic small cities by proposing an integrated model that combines decentralized TPS 3R with Refuse Derived Fuel (RDF)-based TPST. This specific integration is pivotal for ensuring regional energy independence and overcoming the economic barriers of transporting recyclables, thereby offering a scalable solution for regions with similar 'double burden' constraints.

In waste management planning, technological development can offer solutions for effective and efficient waste management. Previous studies in similar archipelagic contexts have highlighted the importance of system optimization, such as the implementation of mapping information systems to enhance waste bank performance in Batam City (Hidayat & Nugraha, 2023). Complementing such approaches, one method for determining the appropriate technologies is Material Flow Analysis (MFA). MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Budihardjo et al., 2023). In this study, the MFA was utilized to map waste mass flows and design measurable technical intervention scenarios based on national targets, specifically the National Medium-Term Development Plan of the Republic of Indonesia (RPJMN) 2025-2029 and the National Long-Term Development Plan of the Republic of Indonesia (RPJPN) 2025-2045.

2. Methods

2.1 Study Area

This research presents a case study in Biak Kota and Samofa Districts, Biak Numfor Regency, which is included in the small city category. These districts were selected because they represent the primary centers of population and economic activity within the regency.

Fig. 1. Map of Study Area

2.2 Data Collection and Sampling Strategy

Primary data on waste generation and composition were collected through sampling for eight consecutive days for Household Waste (SRT) and three days for Waste Similar to Household Waste (SSSRT), in accordance with SNI 3964:2025. Primary data on Household Waste (SRT) generation rates were obtained through direct measurement using stratified random sampling based on economic level (low, medium, and high). The sample size was calculated using the Cochran Method with a 95% confidence level (Z = 1.96) and a 5% margin of error (Cochran, 1977). Because the population size is finite, the calculated sample size was adjusted using a finite population correction factor. For sampling quantification and data conversion, the average household size was assumed to be five persons per household.

The samples were distributed proportionally based on economic level to ensure representative characteristics. The percentage distribution of economic levels within the population sample was determined by interpreting the World Bank classification outlined in SNI 3964:2025 (Appendix C) and utilizing data on monthly per capita expenditure published by BPS-Statistics of Biak Numfor Regency (2025).

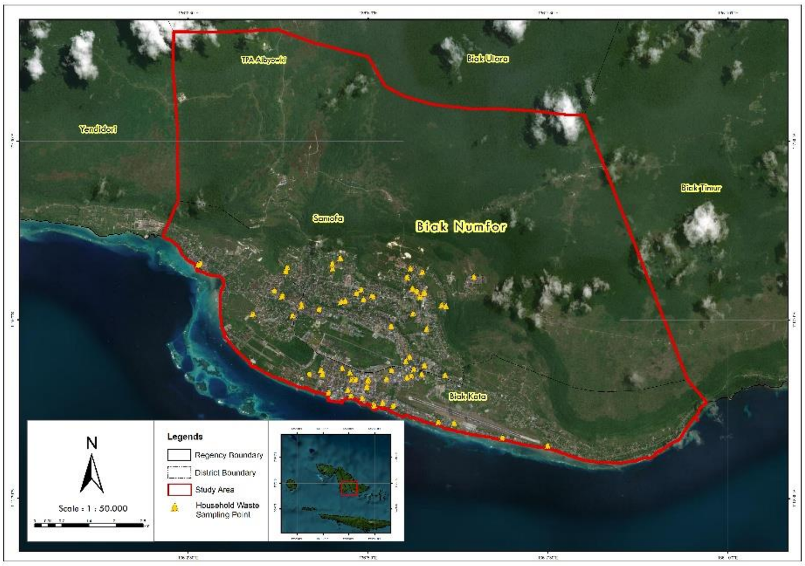

Fig. 2. Map of Household Waste Sampling Locations

For Waste Similar to Household Waste (SSSRT), the generation rate was obtained by measuring waste samples from Commercial Areas, Industrial Areas, Special Areas, Social Facilities, Public Facilities, and/or Other Facilities. The SSSRT sampling locations refer to the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 6 of 2022 concerning the National Waste Management Information System.

2.3 Population and Waste Generation Projection

The accuracy of Material Flow Analysis (MFA) simulations depends on the validity of the mass input data entering the system boundary. In the context of long-term waste infrastructure planning, the total mass input is a function of population size and per capita generation rates, which correlate directly with demographic growth and economic prosperity (Tchobanoglous et al., 1993). Consequently, to ensure that the designed scenarios remain relevant to the waste volumes of the target periods, this study projected future waste generation based on population projections. Population projections were calculated using Arithmetic, Geometric, and Least Square methods, with the final method selected based on the correlation coefficient (r) being closest to 1 or -1 and the smallest standard deviation among the three. Waste generation for each target year was calculated by multiplying the population proportion of each economic level (derived from the total projected population) by the specific per-capita waste generation rate for that level, as obtained from primary field sampling.

2.4 MFA and Sceario Development

Material Flow Analysis (MFA) is a systematic method based on mass balance principles, where the total input into a system equals the total output, enabling a holistic mapping of waste mass flow profiles and evaluation of waste management system performance. MFA has been extensively employed in waste management to quantify and visualize material flows from generation to final disposal or recovery, thereby identifying bottlenecks and opportunities for improvement in waste systems (Allesch and Brunner, 2016; Muchangos et al., 2016). The system boundary covers Biak Kota and Samofa Districts, where total waste generation is treated as input, whereas recycled, composted, animal feed, or landfilled materials/waste residue are categorized as output. The flow was modeled using STAN (subSTance flow ANalysis) 2.7.101 software. STAN is a freely available tool that supports MFA, which is based on the mass balance principle used to quantify the flows and stocks of materials or substances in defined systems. STAN enables the modeling of these flows by considering data uncertainties and performing nonlinear data reconciliation using weighted least-squares minimization and error propagation, ensuring more reliable and consistent flow estimates (Cencic, 2016). The modeling process was conducted through three staged scenarios:

- Scenario I (Baseline): Represents the existing condition without intervention, utilizing 2025 primary generation data as the main input and 2024 secondary data (SIPSN) for existing facility performance (informal and community-based sectors).
- Scenario II (Medium-Term Target): Designed to meet the RPJMN 2025-2029 targets (38% treated, 47% residue) through the intensification of existing facilities and the construction of new Material Recovery Facilities (TPS 3R). The required number of facility units was determined by performing a Capacity Gap Analysis between the target treated waste and the existing capacity. To estimate the operational performance of TPS 3R, the reduction efficiency was calculated using theoretical Recovery Factors (RF).
- Scenario III (Long-Term Target): Projected to achieve RPJPN 2025-2045 targets (90% treated and 10% residue) through upstream-downstream integration. This scenario involves distributed TPS 3R units (utilizing the same Recovery Factors as Scenario II) and an RDF-based TPST. The technical parameters for the TPST, specifically for Refuse Derived Fuel (RDF) production, were adopted from literature studies related to the performance of RDF plants in Indonesia.

2.5 Study Limitation and Assumption

It is important to acknowledge the limitations of this modeling approach. The MFA scenarios assume an ideal condition of community participation in waste segregation at the source, particularly for Scenarios II and III. Temporal variations in waste generation due to seasonal factors (e.g., fruit seasons or religious holidays) were averaged into annual projections. Additionally, the primary data collection was limited to physical characterization (generation and composition), and proximate analysis, such as moisture content and calorific value measurements, was not conducted. Therefore, parameters regarding biodrying efficiency and RDF energy potential were adopted from the relevant literature. While mass balance provides a robust theoretical framework, actual operational performance is contingent on feedstock quality and technical maintenance.

3. Results and Discussion

3.1 Population Projection and Waste Generation Rate Characteristics

Estimating future waste generation loads is highly dependent on population growth dynamics because population size and growth influence the total waste produced. Studies have highlighted that as populations increase, especially in urban areas, the generation of municipal solid waste (MSW) correspondingly rises owing to higher consumption patterns, economic growth, and urbanization (Lu et al., 2021; Garg et al., 2025; Pardini et al., 2019). Based on a statistical analysis of historical population data for Biak Kota and Samofa Districts (2020-2024), the Least Square method was established as the selected projection method. This selection was based on a very strong correlation coefficient (r) of 0.89 across all test methods; however, the Least Square method demonstrated the lowest error rate with a standard deviation (S) of 283.04 compared to the Arithmetic and Geometric methods.

Primary data on Household Waste (SRT) generation rates were obtained through direct measurement using stratified random sampling of 77 households (KK). Samples were distributed proportionally based on economic level consisting of Low (40 KK), Medium (29 KK), and High (8 KK) income groups. The measurement results identified variations in waste generation rates across economic levels. As presented in **Table 1**, the high-income level had the highest waste generation rate at 0.60 kg/capita/day, while the low-income level had the lowest rate at 0.34 kg/capita/day.

Table 1. Profile of household waste (SRT) generation rate based on economic level

Economic Level	Population Proportion (%)	Waste Generation Rate (kg/capita/day)
Low	51.7	0.34
Medium	38.3	0.55
Hogh	10	0.60

The integration of population projections with specific waste generation rates forms the basis for calculating SRT load. Additionally, the calculation of the total regional waste load accounts for the contribution of Waste Similar to Household Waste (SSSRT). Based on the baseline data from 2025, the SSSRT generation ratio was identified as 0.128 times the total SRT generation. This ratio was used to project non-domestic waste growth, assuming that it grows proportionally to domestic activity. This methodological assumption is substantiated by Karak et al. (2012), who established that municipal solid waste generation is inextricably linked to socio-economic factors, where increased domestic consumption and urbanization trigger a corresponding rise in commercial waste and waste similar to household waste.

Table 2. Population projection and total waste generation

Year	Population Projection (inhabitants)	SRT Generation (t/y)	SSSRT Generation (t/y)	Total Waste Generation (t/y)
2025	79,906	12,965.72	1,666.85	14,632.57
2029	81,306	13,192.89	1,696.08	14,888.97
2045	86,906	14,101.56	1,812.90	15,914.46

Total waste generation serves as the quantitative basis (input) in the mass balance calculation to determine the design capacity of processing facilities (TPS 3R and RDF-based TPST) in the subsequent scenario analysis

3.2 Baseline Waste Generation and Composition (2025)

Based on the sampling results, the total combined waste generation (SRT and SSSRT) in the study area in 2025 is 14,632.57 t/y. The combined waste density was 310.72 kg/m³. The waste composition profile is dominated by organic materials and plastics, as detailed in **Table 3**.

Table 3. Results of waste composition analysis

No	Waste Composition	Percentage (%)
1	Food Waste	36.02
2	Garden Waste/leaves	5.23
3	Wood (twigs, branches)	1.61
4	Paper/carton/cardboard	10.08
5	Plastic sheets	15.33
6	Rigid Plastic	10.85
7	Metal	3.26
8	Textile	1.85
9	Rubber and leather	1.02
10	Glass	3.28
11	Hazardous Waste	1.80
12	Nappies (diapers, sanitary pads)	6.69
13	Others	2.98
	Total	100.00

Composition analysis revealed that the total organic fraction (accumulating food, garden, and wood waste) in the study area was 42.86%. This figure is notably lower than the regional reference data from the National Waste Management Information System (SIPSN) (2024), which recorded an organic composition of 51.56%. This divergence is likely attributed to the specific characteristics of the study area (Biak Kota and Samofa Districts), which serve as the regency's urban and commercial hubs. Accelerated urbanization in these districts correlates with a shift in consumption patterns towards packaged goods, resulting in a higher proportion of inorganic waste, particularly plastic (26.18%). Urban living often entails a greater reliance on convenience products and packaged foods, driving up plastic consumption and waste generation. This shift is closely linked to increased population density, changes in lifestyle, and economic development within urban areas, where accessibility to packaged goods is easier and the demand for convenience is higher (Shin et al., 2020).

From a technological perspective, this specific composition profile presents a strategic advantage in Scenario III. The relatively lower moisture-laden organic content combined with a higher share of high-calorific plastics in refuse-derived fuel (RDF) significantly enhances its heating value, which in turn optimizes the fuel combustion efficiency (Payomthip et al., 2022).

3.3 Scenario I: Existing Condition (Baseline)

The MFA analysis for the existing condition identified that 11,128.35 t/y (76.05%) of the total generation of 14,632.57 t/y was transported directly to the landfill (TPA) without any processing. Formal TPS 3R facilities that have been built are not yet operational; therefore, waste reduction relies solely on the informal sector (Waste Banks, Collectors) and small-scale composting, which manages 3,729.10 t/y (**Table 4**).

Table 4. Existing waste processing facility data

No	Existing Facilities	Input (t/y)	Output (t/y)				Total Output (t/y)	Residue to TPA (t/y)
			Compost	Animal Feed	Creative Product	Recycled Materials		
1	Compost House	200.75	129.60	36.50	-	-	166.10	34,65
2	Small Scale Composting	1,961.88	355.88	730.00	-	-	1,085.88	876,00
3	Main Waste Bank	716.60	54.75	-	-	564.52	619.27	97,33
4	Unit Waste Bank	17.28	0.24	-	-	17.04	17.28	-
5	Metal Collector	701.90	-	-	-	701.90	01.90	-
6	Cardboard Collector	127.75	-	-	-	127.75	127.75	-
7	MSMEs	2.94	-	-	2.94	-	2.94	-
	Total	3,729,10	540.47	766.50	2.94	1,411.21	2,721.12	1,007.98

Source : Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2023

Material flow analysis in the existing scenario illustrated in **Figure 3.** From the total waste managed by the informal sector (existing facilities), a recovery rate of 17.06% of the total waste generation was achieved, including:

- Inorganic recyclables totaling 1,186.33 t/y (8.11% of total generation) are recovered by Main Waste Banks, Unit Waste Banks, and Collectors to be sent to Large Collectors and/or the Recycling Industry. A small portion of inorganic waste is utilized by Micro, Small, and Medium Enterprises (MSMEs) for creative products.
- Organic waste utilization of 766.5 t/y as animal feed by Compost Houses and Small-Scale Composting facilities.
- Organic waste utilization into compost by Compost Houses, Small-Scale Composting, Main Waste Banks, and Unit Waste Banks totaled 540.47 t/y.

There are 1,007.98 t/y of residue sent to the TPA, representing waste that cannot be processed.

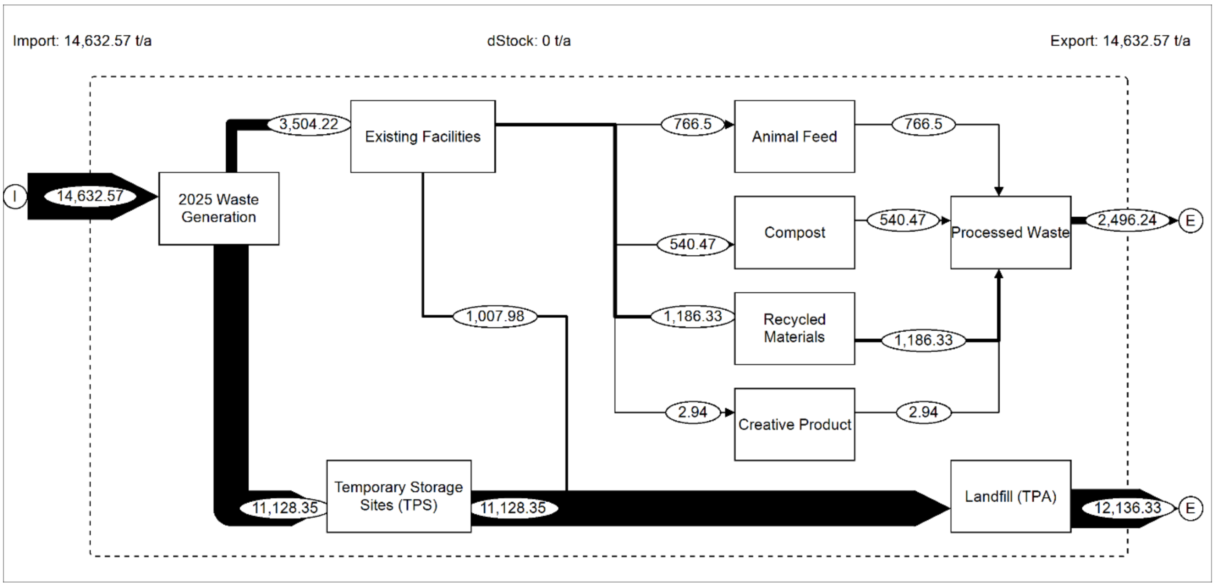

Fig. 3. Material flow analysis of scenario I

3.4 Scenario II: Medium-Term Target (2029)

Scenario II is formulated as a medium-term strategy to accelerate the achievement of the RPJMN 2025-2029 targets, where the proportion of processed waste targets 38% with a maximum residue limit to TPA of 47%. This simulation restricted the system to a service coverage of 85% (12,655.62 t/y) of the total projected generation of 14,888.97 t/y, while the remaining 15% was assumed to be unmanaged waste. A capacity gap analysis was conducted on existing facilities, which have a corrected input capacity of 3,439.77 t/y; this value is a correction of secondary data (3,729.10 t/y) by limiting the metal flow to be consistent with waste composition proportions. Based on this capacity, a target input load for the new facilities was identified as 9,215.85 t/y.

To determine the required number of new TPS 3R units, a target input load was converted into a daily volume of 81.26 m³/day (density 310.72 kg/m³) and compared with the 2023 TPS 3R Technical Guidelines design standard by the Ministry of Public Works and Housing (PUPR), which sets a capacity of 15 m³/day/unit for a regional scale (1,000 households) in Small Cities. Based on this ratio, a theoretical requirement of 5.42 ≈ 6 units of TPS 3R was determined. The processing efficiency at TPS 3R was calculated based on the theoretical Recovery Factor (RF), referring to the study by Wasaraka et al. (2021) in Klawuyuk Village, East Sorong District, Sorong City, considering regional similarities. Sorong City and Biak Numfor Regency are in the same regional area with similar demographic profiles, consumption patterns, and waste composition characteristics. The similarity of these factors is crucial because directly affect the type of composition, quantity of waste produced, as well as the efficiency of waste recovery systems (Fan et al., 2021; Giannis et al., 2016).

Table 5. Theoritical recovery factor (RF) for TPS 3R facilities

Waste Composition	RF (%)
Organic Waste(Food Waste, Leaves, and Twigs)	58.71
Plastic	65.95
Metal	8.25
Glass	9.52
Paper and Carton/Cardboard	60.28
Rubber and Leather	29.06
Textile	48.96

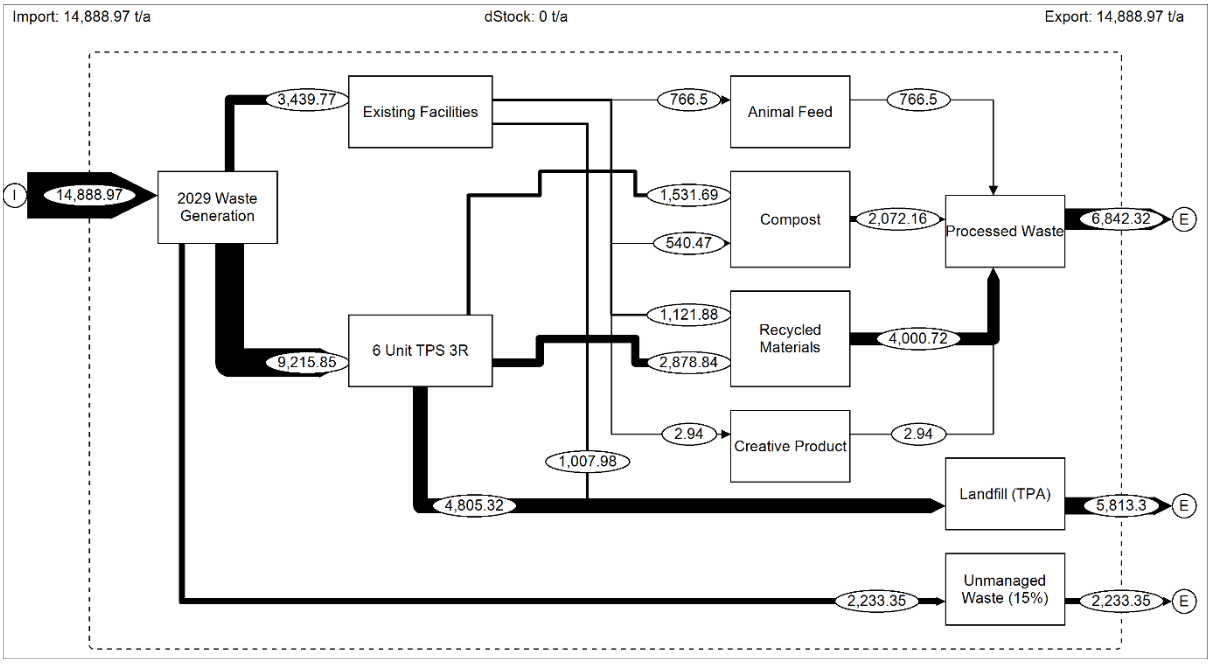

Fig. 4. Material flow analysis of scenario II

As illustrated in **Figure 2**, the mass flow to the TPA was significantly reduced through the processing scheme at TPS 3R. The effectiveness of this reduction is highly influenced by the characteristics of the input material that enters the facility. The technical details regarding the separation of organic and inorganic fractions and the calculation of the final residue are outlined in **Table 6**.

Table 6. Mass balance and reduction performance for planned 6 units of TPS 3R

No	Waste Component	Input (t/y)	Output[1] (t/y)	Residue to TPA (t/y)
1	Organic (Food & Garden)	2,608.92	1,531.69	1,077.23
2	Inorganic Recyclables (Non-Metal)	4,951.58[2]	2,878.84	2,072.74
3	Residue & others	1,655.35	-	1,655.35
	Total	9,215.85	4,410.53	4,805.32

[1] Calculated based on specific RF for each material according to **Tabel 5**

[2] It consists of the accumulation of recyclable materials (plastic, paper/cardboard, glass, textile, rubber, and leather). The entire potential generation of metal waste (3.26% of total generation) is fully allocated to the existing facility (metal collector). This allocation is based on the absorption capacity of the existing metal collector (701.9 t/y), which exceeds the available metal waste generation in this scenario

The application of these RF parameters to six units of TPS 3R resulted in an increase in processed waste to 45.96% of the total managed waste generation, or 6,842.32 t/y, with the following breakdown:

- Inorganic Recycling: 4,000.72 t/y of the total managed waste is successfully recovered by TPS 3R and Existing Facilities. Additionally, 0.02% of inorganic waste is used as a raw material for creative products.
- Organic Utilization (Animal Feed): 6.06% of the total managed waste is utilized as animal feed
- Organic Utilization (Compost): 2,072.16 t/y (16.37%) was utilized as compost.

The residue entering the TPA was successfully suppressed to 39.04% (5,813.30 t/y), which meets the RPJMN 2029 target.

While the MFA simulation demonstrated that six units of TPS 3R are mathematically sufficient to meet the reduction targets, the realization of the RF is highly sensitive to the quality of the input waste. The model implicitly assumes that the waste entering these facilities has undergone preliminary sorting at the household level. In practice, if the community participation rate in source segregation is low, the facilities will be inundated with mixed wastes. This mixed waste often leads to inefficiencies and increased operational costs at treatment and disposal sites, as additional sorting is required and contamination reduces the quality of the recyclable materials (Bashir et al., 2020). Therefore, the technical deployment of TPS 3R infrastructure must be preceded by and synchronized with a rigorous social engineering program to ensure the feedstock purity.

3.5 Scenario III: Long-Term Target (2045)

Scenario III is designed to address long-term waste management challenges in accordance with the RPJPN 2025-2045 vision, targeting a residue to TPA ratio of below 10% and 90% processed waste. Based on population projections and waste generation rates, the total waste generation load in Biak Kota and Samofa Districts in 2045 is estimated to reach 15,914.46 t/y.

The technical strategy applied is upstream-downstream integration using six units of TPS 3R as upstream processing facilities and the addition of one unit of Refuse Derived Fuel (RDF)-based Integrated Waste Processing Site (TPST) as an advanced/final processing facility. The RDF-based TPST is designed to process residues from existing facilities and TPS 3R, as well as waste not handled by TPS 3R.

Before determining the intervention facility processing load, the input capacity of existing facilities was adjusted to 3,546.01 t/y; this increase was due to the rising availability of metal materials (proportional to 2045 waste generation), which is fully absorbed by the collector sector. Thus, the waste load to be handled by the intervention infrastructure (TPS 3R and TPST) is 12,368.45 t/y. However, the technical specification evaluation of six TPS 3R units with a design volume of 15 m^3/day/unit and a density of 310.72 kg/m^3 identified a maximum input capacity limit for TPS 3R of 10,207.15 t/y. This resulted in 2,161.30 t/y of waste not handled upstream, which was diverted directly to the RDF-based TPST. The reduction efficiency is calculated using the Recovery Factor (RF) for TPS 3R, while RDF-based TPST performance adopts parameters from the Cilacap RDF Plant (Maulidayanti et al., 2024), including RDF product conversion of 40% and mass shrinkage (moisture loss) of 41.65% from the biodrying process, which reduces moisture content from 55.44% to 23.63% and increases the calorific value to approximately 15 MJ/kg (3,585 kcal/kg).

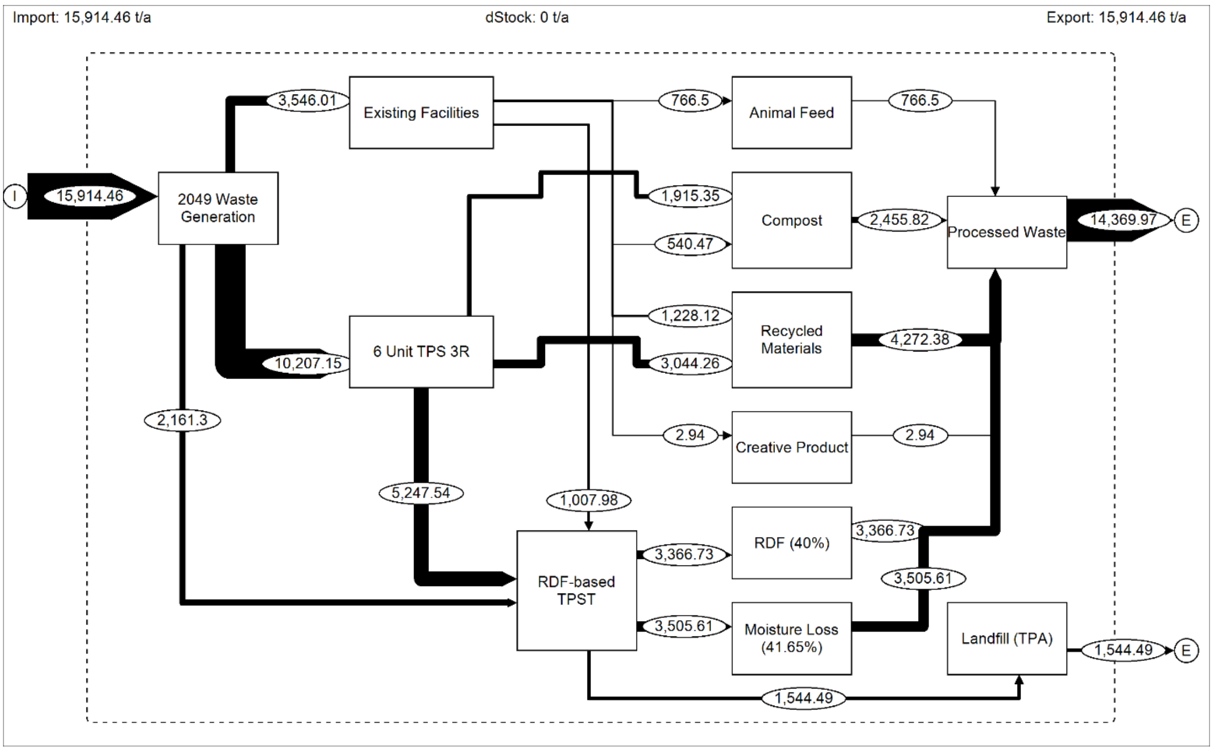

Fig. 5. Material flow analysis of scenario III

At the upstream level, 7,497.64 t/y of waste is successfully processed by six units of TPS 3R and existing facilities with the following breakdown:

- Inorganic Recycling: 4,272.38 t/y recovered as recyclable material sent to Large Collectors and/or Recycling Industries. In addition, 2.94 t/y of inorganic waste is utilized as raw material for creative products.
- Organic Utilization (Animal Feed): 6 766.5 t/y of organic waste utilized as animal feed.
- Organic Utilization (Compost): Organic waste from food and garden waste utilized as compost reached 2,455.82 t/y.

Waste not handled by upstream facilities, along with generated residues, totaling an accumulation of 8,416.82 t/y, is processed at the TPST into RDF. With a conversion efficiency of 40%, this facility can produce 3,366.73 t/y of RDF. In addition to product conversion, significant mass reduction occurred via the biodrying mechanism, where shrinkage due to water evaporation (moisture loss) reached 41.65%.

From an energy perspective, the feasibility of the proposed RDF production was robustly supported by the specific waste characteristics of the study area. As established in the baseline analysis, the waste stream in the study area is characterized by a high fraction of inorganic waste, particularly plastic (26.18%). This composition profile presents a strategic advantage for thermal treatment, as the substantial plastic content inherently acts as a high-calorific booster. Furthermore, the simulation results that combine this high-calorific feedstock with the biodrying performance detailed previously are projected to meet industrial combustion standards. Based on the study by Maulidayanti et al. (2024), a moisture content of 23.63% directly correlates to an RDF with a calorific value of 3,585 kcal/kg. This energy content is significant when evaluated against the Indonesian National Standard (SNI 8966:2021) for Solid Recovered Fuel (Bahan Bakar Jumputan Padat). The projected value successfully surpassed the Grade 2 specification (>3,000 kcal/kg) required for cement kiln co-processing and approached the Grade 1 standard. Consequently, the resultant Lower Heating Value (LHV) of the RDF in the study area is theoretically expected to remain stable above this industrial benchmark, validating the technical viability of RDF-based TPST integration.

The entire process of Scenario III produced a final residue of 1,544.49 t/y (18.35% of input) that must be disposed of in the TPA. The residue represents reject material that does not meet fuel technical specifications, including non-combustible fractions (inert) such as glass and metal that escaped sorting, as well as high-density combustible fractions such as wet organic material and diapers (nappies) that are difficult to dry optimally. The detailed mass balance explaining the transformation of the input into RDF products and water vapor is presented in **Table 7**.

Table 7. Mass balance and reduction performance in TPS 3R and RDF-based TPST integration

No	Flow Component	Mass (t/y)	Description
A	**Stage 1: TPS 3R (Maximum Capacity)**		
1	Maximum Input Capacity	10,207.15	Design limit of 6 Units TPS 3R (15 m³/day)
2	Recovery (Compost & Recycling)	4,959.61	Reduction from processed waste only
3	TPS 3R Output Residue	5,247.54	To RDF- based TPST
B	**Input Flow to TPST**		
4	Waste Flow Load beyond TPS 3R capacity	2,161.30	Waste flow to RDF-based TPST
5	Existing Facility Residue	1,007.98	To RDF-based TPST
C	**Stage 2: Processing at RDF- based TPST**		
6	Total Input RDF-based TPST (Sum of 3+4+5)	8,416.82	Accumulation of residue and bypass flow
7	Refuse Derived Fuel (RDF) Product	3,366.73	40% Conversion of Total TPST Input
8	Moisture Loss (Evaporation)	3,505.60	41.65% Shrinkage during Biodrying
9	Final Residue to TPA	1,544.49	Remaining 18.35% Inert

With this technological integration, the total processed waste (including mass reduction in TPST) reached 90.3% (14,562.68 t/y). The final residue to be landfilled is only 9.7% (1,351.78 t/y); thus, the waste management target referring to RPJPN 2045 has been met.

The selection of biodrying-based RDF technology in Scenario III is strategically justified by the tropical climatic conditions of Biak Numfor. Given the high rainfall intensity and humidity, waste often arrives at facilities with moisture content around or above 55%, rendering direct incineration energy inefficient, including high operational costs and mechanical maintenance difficulties. Waste drying or other moisture reduction processes prior to incineration are crucial for improving the thermal efficiency and feasibility of incineration as a waste-to-energy solution (Chua et al., 2019; Febijanto et al., 2024). The biodrying process leverages the exothermic heat from microbial decomposition to naturally evaporate water, validating a modeled moisture loss of 41.65%. However, the sustainability of this scenario extends beyond production and relies heavily on the off-taker ecosystem. Unlike major islands such as Java Island, which have established industries, the market for RDF in archipelagic regions is limited. The success of RDF-based TPST creates a supply push dynamic that must be matched by demand-pull from local energy consumers, such as co-firing at local power plants (PLTU) or industrial boilers. Without a secured off-taker agreement, the produced RDF risks accumulating as dry waste, merely shifting the burden from wet landfilling to dry storage.

3.6 Managerial Implications and Policy Recommendations

The transition from a linear 'collect-dump' system (Scenario I) to an integrated circular approach (Scenario III) necessitates a fundamental restructuring of municipal waste management governance. Based on the technical requirements of the modeled scenarios, two critical managerial implications emerge:

(1) Logistical operations must undergo a paradigm shift. The diversion of waste streams to distributed TPS 3R units and centralized RDF-based TPST implies that the current waste collection and transportation system, which still transports mixed waste, is no longer adequate. The local government must invest in a segregated collection fleet to prevent the cross-contamination of organic and inorganic fractions during transportation. Failure to modernize the fleet would compromise feedstock quality before it even reaches the processing facilities.

(2) Institutional capacity requires significant strengthening. Managing an RDF plant involves complex industrial processes, such as controlling the biodrying temperature and maintaining shredding machinery, which demand higher technical competency than landfill operations. Consequently, it is recommended that the local government establish a dedicated technical unit, such as a Regional Public Service Agency (BLUD), equipped with a specific budget allocation for Operational Expenditure (OPEX). Institutional agility is crucial to ensure the long-term reliability of the high-tech facilities proposed in Scenario III.

4. Conclusion

Material Flow Analysis (MFA) demonstrates that waste reduction targets are technically attainable. The analysis confirms that Scenario II, utilizing six units of Material Recovery Facilities (TPS 3R), is sufficient to meet the national medium-term targets (2029). However, achieving the national long-term targets (2045) necessitates an integrated approach, combining TPS 3R facilities with an RDF-based Integrated Waste Processing Site (TPST). The success of these technical interventions, however, heavily depends on consistent source segregation to ensure high feedstock quality. Therefore, substantial investment in physical infrastructure must be paired with systemic reforms in segregated waste collection. Mixed and wet waste contribute to contamination, which not only lowers the market value of recyclable materials but also reduces the Recovery Factor. This contamination can further compromise the performance of RDF-based TPST facilities and the quality of the RDF products produced. Additionally, implementing this integrated waste management system will require overcoming challenges related to public participation, infrastructure coordination, and logistical reform.

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