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Governance and Performance of Waste-to-Energy in Indonesia: A Comparative Review of Benowo and Putri Cempo

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Abstract

Indonesia's rapid growth in municipal solid waste generation has increased urgency for low-carbon waste management solutions. In response, the government has accelerated Waste-to-Energy development in 12 designated cities under Presidential Regulation No. 35/2018. This study applies a Systematic Literature Review following PRISMA 2020 guidelines to examine governance frameworks, environmental performance, and economic feasibility of Waste-to-Energy projects in Indonesia, with a comparative focus on the Benowo and Putri Cempo facilities. Literature was systematically retrieved from Scopus, ScienceDirect, SpringerLink, and Google Scholar using policy- and technology-related keywords. The search yielded 21 eligible publications between 2018–2025 that include empirical studies and policy-relevant documents. The results indicate that although both facilities operate under the same national regulatory framework, they differ in financing schemes, risk allocation, and operational efficiency. Benowo's BOT model supported by tipping fees provides financial stability, whereas Putri Cempo's DBFOT scheme requires higher operational efficiency due to the absence of municipal subsidies. Environmental assessments show that Benowo's hybrid gasification and landfill gas system reduces greenhouse gas emissions by up to 57.1% from the pre-2015 level, while gasification at Putri Cempo achieves more than 85% waste reduction with lower emission intensity than conventional incineration. Economic feasibility is sensitive to waste quality, capacity utilization, and policy incentives. The novelty of this study lies in its integrated governance, environmental, and economic perspective linking national policy design with local implementation outcomes. The findings imply that stronger risk-sharing arrangements, improved waste segregation, and transparent environmental audits are essential to ensure sustainability of Waste-to-Energy development in Indonesia.

KEYWORDS

waste-to-energy, governance, environmental performance, economic feasibility.

Introduction

Waste management remains one of the most significant environmental challenges in Indonesia, particularly amid the government's recent acceleration of Waste-to-Energy development in major cities to address landfill overcapacity and climate commitments. The continuously increasing volume of waste has created a persistent and complex problem, resulting in the accumulation of waste in various landfill sites across the country. Numerous studies highlight that population growth is a major driver of rising municipal solid waste generation.

(Lu et al., 2024) identified a linear relationship between urban population size and municipal solid waste generation, indicating that population growth directly increases waste volumes. Similar findings were reported by (Smailbegovic et al., 2025), who showed that demographic factors such as population size, household characteristics, and income levels significantly influence waste generation rates in urban areas. These studies highlight that rising urbanization and demographic pressures are key drivers of increasing municipal solid waste in Indonesian cities.

At present, many Indonesian cities still rely on conventional waste disposal methods. Open dumping and sanitary landfill remain the dominant practices (Damayanti et al., 2021; Romianingsih, 2023). This reliance on landfill-based disposal contributes to higher greenhouse gas emissions and intensifies land scarcity in urban areas, strengthening the rationale for alternative solutions such as Waste-to-Energy (Nurcahyati et al., 2025). Although Law No. 18/2008 requires all final disposal sites (TPA) to be converted into sanitary landfills, only a limited number of cities have complied with this mandate (Romianingsih, 2023). Recent scholarly analyses indicate that global municipal solid waste generation is on a steep upward trajectory, rising from approximately 2.1 billion tonnes in 2023 and projected to reach nearly 3.8 billion tonnes by 2050 based on international waste generation trends (Kun & Ksepko, 2025). In Indonesia, data from the National Waste Management Information System (SIPSN) in 2024 recorded a national waste generation of 36,660,477.19 tons per year, with only 11,385,412.45 tons per year or approximately 32% being properly managed (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2024). These figures indicate that the majority of waste in Indonesia remains insufficiently managed (see figure 1).

For the composition of national waste in 2024 by waste type, food waste remains the dominant category at 37.84%, followed by plastics at 19.52%, wood/yard waste at 13.38%, and paper/cardboard at 11.17%. Meanwhile, based on waste generation sources, households contribute the largest share at 46.31% of the total national waste. This is followed by traditional markets (15.67%), commercial activities (14.3%), residential and other urban areas (13.84%), offices (4.97%), and public facilities (3.44%), with other sources accounting for 1.47% (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2024).

One of the key strategies adopted by the Indonesian government to address the increasing volume of municipal solid waste is the conversion of waste into renewable energy through the development of Waste-to-Energy (WtE) facilities (see figure 2). Waste-to-Energy refers to a group of technologies that convert municipal solid waste into useful forms of energy, such as electricity, heat, or fuel, through various conversion pathways. These technologies are considered an essential component of sustainable urban waste management systems because they can reduce the volume of waste while simultaneously providing an alternative source of energy (Farooq et al., 2021). This initiative is mandated under Presidential Regulation (Perpres) No. 35 of 2018, which instructs the acceleration of waste processing installations into electrical energy using environmentally sound technologies in 12 designated cities. The regulation initially identified Palembang, Tangerang, South Tangerang, Jakarta, Bandung, Bekasi, Semarang, Surakarta, Surabaya, Makassar, Manado, and Denpasar as the pilot locations for implementation. As highlighted by (Azis et al., 2021), Waste-to-Energy technology represents a promising solution for addressing municipal solid waste issues in Indonesia while contributing to the supply of renewable energy. Broadly, WtE technologies are classified into four main categories, physical, thermal, biochemical, and bio-electrochemical processes (see figure 3). These technological pathways offer different mechanisms for converting waste into usable energy, reflecting the diverse characteristics and treatment needs of municipal solid waste (Jamilatun et al., 2023).

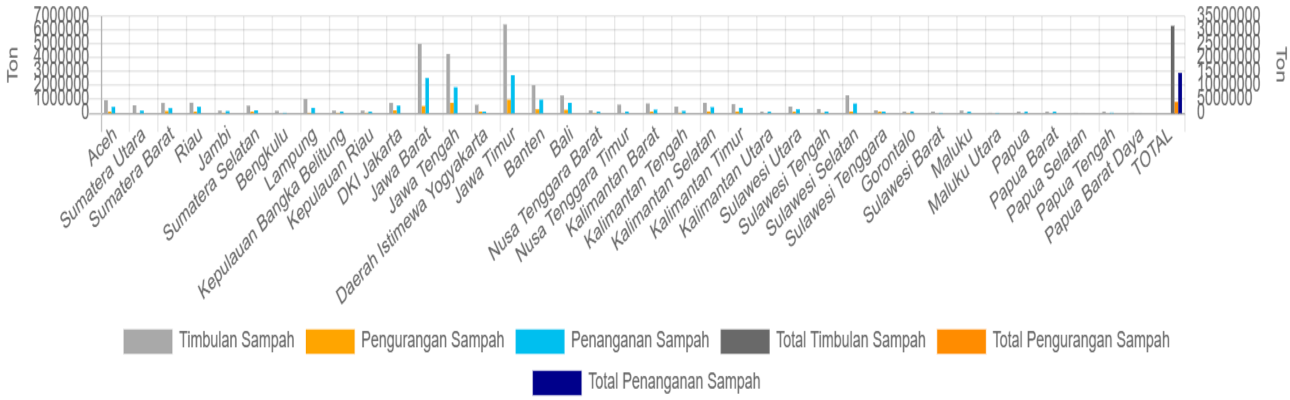
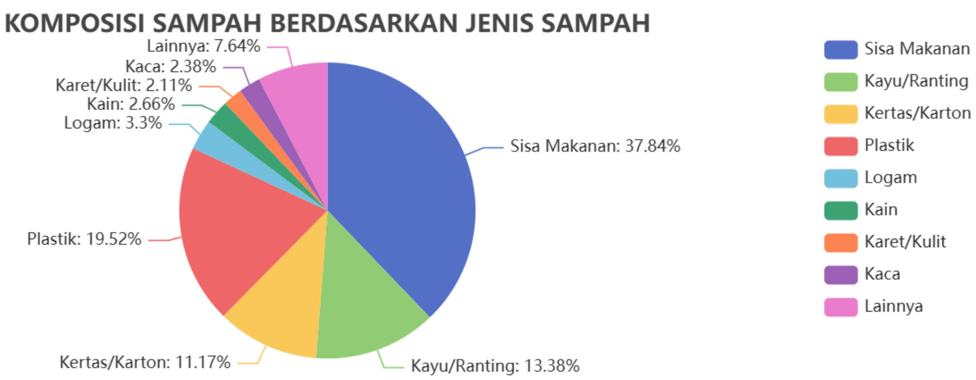


Figure 1. National Waste Management Performance

(Source: SIPSN KLH, 2024)



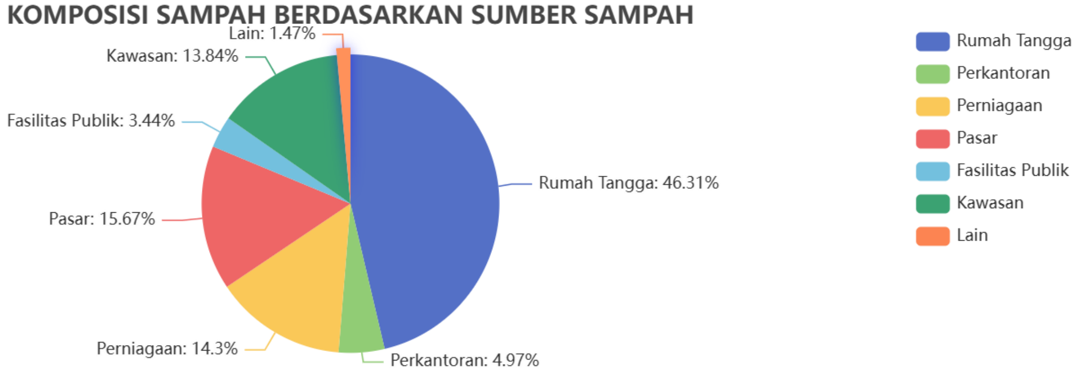


Figure 2. Waste Composition in Indonesia Based on: a.Waste Types b.Waste Sources

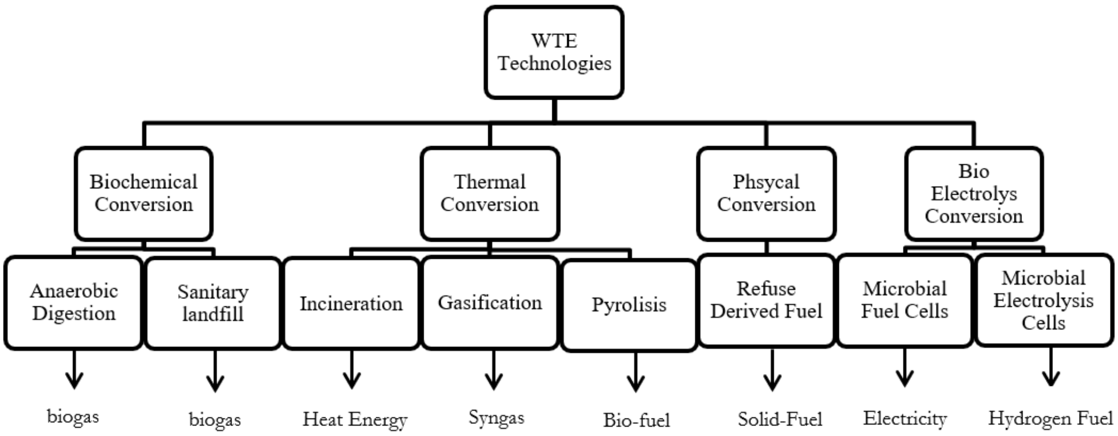


Figure 3. Classification of Waste-to-Energy (WtE) technologies and their respective energy outputs.

In Indonesia, the development of waste-based power generation Waste-to-Energy (WtE) generally follows three main technological pathways.

Biochemical Conversion

The anaerobic digestion process involves the use of anaerobic microorganisms to break down organic materials under oxygen-free conditions to produce methane gas. Operational conditions, municipal solid waste (MSW) composition, reactor type, and residence time significantly influence the amount of methane generated (Jamilatun et al., 2023; Shah et al., 2021). Another important biochemical pathway is landfill gas harvesting. A landfill is the most common and straightforward biological method for obtaining energy from municipal solid waste (MSW). The biogas produced through landfill decomposition can be utilized for heating or electricity generation. Waste characteristics such as moisture content, organic material composition, waste age or degree of decomposition as well as operational conditions including temperature and pH, strongly affect the quantity and quality of biogas produced (Kouzi et al., 2020).

Thermal Conversion (Incineration, Gasification, and Pyrolysis)

Incineration refers to the combustion of municipal solid waste (MSW) at high temperatures (typically between 800 and 1000 °C) in the presence of sufficient oxygen. Developing countries commonly employ incineration as a waste treatment method (Yong et al., 2019). Gasification is a thermochemical process that converts organic and carbon-based waste materials into synthesis gas (syngas) (Kaur et al., 2023). Pyrolysis, on the other hand, is an endothermic process in which MSW is thermally decomposed in the absence of oxygen, producing three main outputs: pyro-oil, a mixture of oil and water generated through vapor condensation; solid residue, consisting of char and ash with high carbon content; and gas products, primarily composed of carbon dioxide and methane (Jamilatun et al., 2023).

Physical Conversion

Physical conversion in the context of WtE refers to the preliminary stages of waste processing that involve altering the physical characteristics of waste without inducing chemical reactions. These processes include drying, separation, shredding, and the production of Refuse-Derived Fuel (RDF). Such stages play an essential role in improving the energy conversion efficiency of subsequent thermal processes, such as combustion and gasification, and form an integral component of circular economy initiatives by enabling the utilization of waste as an alternative energy source (Rezania et al., 2023).

The implementation of WtE technologies in Indonesia has progressed through the combination of gasification and landfill-gas recovery at the Benowo WtE facility in Surabaya (Affandi et al., 2024), as well as thermal gasification at the Putri Cempo WtE plant in Surakarta (Nurcahyati et al., 2025), both of which have been operating commercially. The successful implementation of WtE or PLTSa projects is not solely determined by technological aspects but also by project governance and management practices grounded in regulatory frameworks. This includes the need for a strong legal and contractual basis, appropriate partnership and financing schemes, as well as continuous monitoring and evaluation to ensure that energy targets are achieved without compromising environmental objectives. This is reflected in the regulatory reviews of WtE development in Indonesia, which emphasize the importance of a solid legal foundation during the project preparation stage, the role of government industry collaboration, and the recognition that technology is not the only limiting factor effective governance and policy harmonization are equally critical (Hamzah & Paliling, 2024).

(Ferdoush et al., 2024) argue that one of the main barriers hindering the transition toward WtE technologies in developing countries is the mismatch between the idea of accelerating WtE system development and its actual implementation in the field, particularly in terms of environmental management and policy governance. Findings from (Sekaringtias et al., 2023) indicate that research on energy transition governance in Indonesia remains limited, especially studies examining the relationship between national policy frameworks and local-level implementation. This gap highlights persistent issues related to institutional coordination, policy integration, and transparency in the execution of renewable energy projects, including WtE initiatives.

Although Presidential Regulation No. 35/2018 provides a national framework for accelerating WtE, evidence on implementation in Indonesia remains scattered and is often discussed separately across governance arrangements, environmental management, and economic feasibility. This fragmentation limits an integrated understanding of how national policy design translates into consistent local practices and performance in operating pilot cities. Therefore, this study consolidates and synthesizes existing evidence from two operating pilots Benowo and Putri Cempo to clarify key barriers and enabling factors for WtE development. The study contributes a clearer basis for strengthening policy coordination, risk allocation, monitoring transparency, and environmental accountability to support WtE scaling across Indonesian cities.

Ferdoush et al. (2024) state that developing countries continue to face institutional barriers, regulatory overlap, and limited coordination between national and local governments in the implementation of WtE projects. As a result, a gap persists between policy and practice, where national policies intended to accelerate renewable energy development have not been fully translated into effective and efficient operational systems. Conversely, environmental performance analyses (Arifianti et al., 2025; Liem et al., 2024) demonstrate that WtE facilities have significant potential to improve energy efficiency and reduce greenhouse gas emissions. However, due to suboptimal implementation of environmental audits and insufficient data transparency, these benefits are not yet maximized. Based on this context, a comprehensive review is needed to examine the governance framework, as well as the environmental and economic performance of WtE/PLTSa facilities in Indonesia.

Methods

This study employs a Systematic Literature Review (SLR) to examine empirical evidence and policy frameworks related to the governance, environmental performance, and economic aspects of Waste-to-Energy (WtE) or PLTSa projects in Indonesia. The review follows the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which emphasize transparency, replicability, and methodological rigor in the literature search and screening process (Page et al., 2021).

The literature search was conducted using the Publish or Perish software, which retrieves data from multiple academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The publication period covered in this review spans from 2018 to 2025, corresponding to the implementation period of Indonesia's WtE acceleration policy. Keywords used in the search included PLTSa, WtE, and Municipal solid waste. These terms were combined using Boolean operators in the following search string: (PLTSa OR Waste-to-Energy OR WtE OR MSW OR municipal solid waste).

All retrieved documents were imported into a reference manager Mendeley for screening and duplicate removal. Documents that were not publicly accessible were excluded from the analysis. In addition to peer-reviewed articles, grey literature such as policy statements, government reports, and publications from relevant organizations was also explored and synthesized. The selection process was carried out following the PRISMA flowchart (Page et al., 2021), which consists of four stages:

1. Identification: Records were identified through database searching, yielding 1,219 records. Duplicate records were removed before screening (n = 284), resulting in 935 records for screening.
2. Screening: Titles and abstracts were screened, and 862 records were excluded based on the exclusion criteria. The remaining 73 records were retained for full-text assessment.
3. Eligibility: Full text articles were assessed to determine their relevance to PLTSa/WtE and policy-related topics. The articles are then selected based on the following criteria (table 1):

   Full-text articles (n = 73) were assessed for eligibility. At this stage, 52 records were excluded based on the eligibility criteria for the following reasons:
   - Global studies without clear relevance or comparative linkage to the Indonesian WtE/PLTSa context (n = 18).
   - Lacked empirical data or analytical content (e.g., commentary/opinion) (n = 12)
   - Not aligned with the review scope (governance, environmental performance, and/or economic aspects) (n = 14)
   - Full text not publicly accessible (n = 6)
   - Duplicate/overlapping versions of the same study (n = 2)
4. Included: Displays the final number of articles used in the thematic analysis and narrative synthesis. total of 21 studies met the criteria and were included in the thematic analysis and narrative synthesis.

In addition to peer-reviewed articles, grey literature such as policy statements, government reports, and publications from relevant organizations was explored and synthesized to capture policy and implementation context. To assess reliability relative to peer-reviewed sources, grey literature was screened for source authority organization, document transparency (clearly stated purpose and traceable data), relevance to WtE governance performance in Indonesia, and currency (recent and aligned with the 2018–2025 policy implementation period). After applying the search strategy, duplicate removal, and eligibility screening criteria, the overall selection process and the number of records retained at each stage are presented in the PRISMA flow diagram (Figure 4).

Table 1. Inclusion and Exclusion Criteria for Literature Selection

Criteria	Inclusion	Exclusion
Publication Year	2018-2025	<2018
Source	Peer reviewed journals, Governments reports, and official policy documents	Media opinions, articles without empirical data or analytical content
Geographical Focus	Indonesia, or global studies with clear relevance	Global studies without local relevance
Topic	Policies, governance, and environmental performance of PLTSa/WtE	Purely technical studies with no policy or Environmental and Economy context

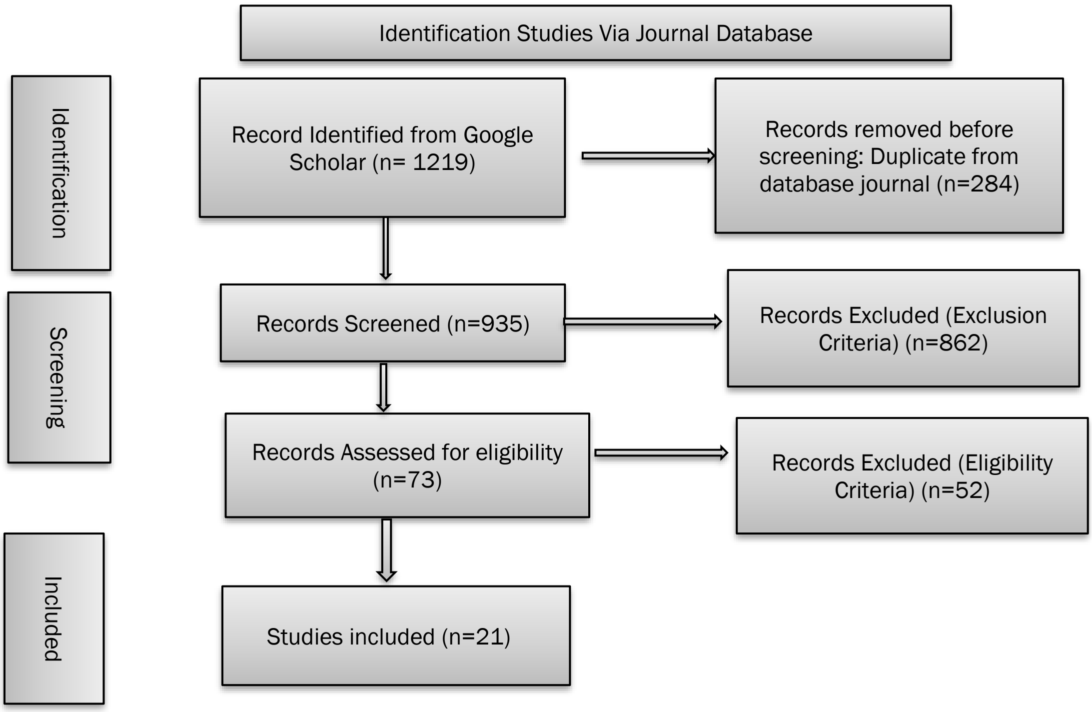


Figure 4. PRISMA flow diagram of the study selection process (2018–2025)

The data obtained from the selected articles were extracted using a data extraction sheet that included the following elements: article number, author, year of publication, study focus, key findings, moderating factors, and geographic context. The extracted findings were then organized into pre-defined categories aligned with the review objectives (governance, environmental performance, and economic aspects) and synthesized using a thematic, comparative descriptive approach to identify recurring patterns and cross-case differences between the Benowo and Putri Cempo pilots.

Result and Discussion

Benowo WtE Facility

The first facility in Indonesia to successfully operate commercially in converting municipal waste into electrical energy is the Benowo Waste-to-Energy Plant. The facility is located in Surabaya, occupying approximately 37.4 hectares of landfill area, of which 10 hectares are allocated for WtE operations and residual waste storage (see table 2). The Benowo WtE facility is operated under a Public Private Partnership (PPP) scheme with PT Sumber Organik (PT SO) as the implementing entity through a Build–Operate–Transfer (BOT) agreement, which is valid for 20 years starting from August 8, 2012 (Sucahyo & Fanida, 2021).

The Benowo WtE facility processes approximately 1,500 tons of waste per day and generates around 11 MW of electricity (see figure 5). The thermal gasification system combusts inorganic waste at temperatures above 850 °C, producing 9 MW of power, while an additional 2 MW is generated from the landfill gas recovery system (Affandi et al., 2024). Of the total output, about 10 MW is supplied to the PLN grid, and 1 MW is utilized for the facility's internal operational needs. In terms of waste input composition, approximately 60–65% of the incoming waste consists of organic materials (primarily from households and markets), while the remaining 35–40% comprises inorganic waste such as plastics, textiles, and non-recyclable residues. Waste is collected from all areas of Surabaya through the TPS 3R network and compacted at transfer stations before being transported to the Benowo landfill (Sucahyo & Fanida, 2021). This logistics system is supported by the digital-based Solid Waste Application Transportation (SWAT), developed by the Surabaya Department of Sanitation and Green Open Space (DKRTH), which enables real time monitoring of waste volume and transportation routes.

Policy and Governance Framework of the Benowo WtE Facility within the Context of National Regulatory Standards

The implementation of the Benowo WtE project in Surabaya has generally adhered to the governance framework stipulated in Presidential Regulation (Perpres) No. 35 of 2018. This regulation outlines five key components of governance, funding sources, contractual arrangements, construction location and implementing entities, electricity purchase schemes, and the allocation of authority among the central government, local governments, and PLN.

Financing Mechanism and Waste Management Service Fee (BLPS)

Presidential Regulation (Perpres) No. 35/2018 Articles 4 and 15 stipulate that the Waste Management Service Fee (BLPS) shall be financed through regional government budgets (APBD) and may be supplemented by the national budget (APBN). At the Benowo facility, this scheme is implemented through a tipping fee of IDR 200,000 per ton, paid by the Surabaya City Government to the operator, PT Sumber Organik (Fatima et al., 2025). The tipping fee refers to the fee paid by local governments to the project developer for processing municipal waste as part of electricity generation activities. Meanwhile, the electricity selling price is the tariff at which electricity produced by the WtE facility is sold to PT Perusahaan Listrik Negara (PLN). According to Perpres No. 35/2018, the tipping fee is capped at a maximum of IDR 500,000 per ton of waste, while the electricity purchase price is set at US$0.1335 per kWh. This arrangement results in a tipping fee obligation for local governments. The applied scheme at Benowo is consistent with Article 4 of Perpres No. 35/2018, as the financing is sourced from the regional budget (APBD) and the tipping fee remains below the regulatory ceiling specifically at IDR 200,000 per ton

Table 2. Summary of Waste-to-Energy (WtE) Studies: Technological Performance, Environmental Impact, Financial Feasibility, and Moderating Factors

No	Author(s)	Year	Study Focus	Key Findings	Moderating Factors	Geographic Context
1	Affandi et al.	2024	waste-to-energy conversion mechanisms and contribution to emission mitigation.	Benowo utilizes LFG and gasification (11 MW) and contributes to emission mitigation and NZE targets.	Technology capacity & waste characteristics	Indonesia
2	Liem et al.	2024	Emission reduction of Benowo WtE (LCA approach)	Gasification reduces emissions by 57.1%; electricity generation saves 119,953 tons CO_2-eq	Recycling rate & landfill proportion	Indonesia
3	Putra & Sarasi	2025	Financial feasibility of Benowo WtE	BCR 2.58, ROI 157%; tipping fee removal highly impactful.	PPP scheme & operational cost structure	Indonesia
4	Sucahyo & Fanida	2021	WtE innovation at Benowo	PPP model, SWAT system, LFG 2 MW & gasification 12 MW.	Governance quality & operator capability	Indonesia
5	Fatima et al.	2025	BOT/PPP implementation at Benowo	Govt pays Rp200k/ton, 11 MW; high land-use efficiency.	BOT structure & policy incentives	Indonesia
6	Arifianti et al.	2025	hybrid WtE system integrating plasma gasification + anaerobic digestion	CCS significantly reduces emissions (including negative emissions for biogenic CO_2) but greatly increases costs.	CAPEX/OPEX dominated by gas turbine size, CCS costs, carbon transport–storage, discount rate, tipping fee, and carbon credit levels	Indonesia
7	Novria & Surjosatyo	2022	MSW gasification optimization	AFR 0.3, 600–800°C optimal syngas yield.	AFR & reactor temperature	Southeast Asia
8	Raharja et al.	2024	PPP model for Putri Cempo	DBFOT without tipping fee, by-products maintain financial viability.	Financial innovation & PPP structure	Indonesia
9	Nurcahyati et al.	2025	LCA of Putri Cempo	Key impacts: carcinogens & heavy metals, 8 MW/day electricity.	Emission control & filtration systems	Indonesia
10	Roswulandari et al.	2019	Financial analysis of Putri Cempo	Positive NPV, IRR > SOCC; B/C >1.	Investment scale & technology efficiency	Indonesia
11	Amaral et al.	2023	Socio-economic impact of Putri Cempo	Positive social benefits, livelihood concerns remain.	Community perception & social inclusion	Indonesia
12	Aprilianto et al.	2024	Local government role	Govt as entrepreneur–coordinator–facilitator; no subsidies.	Local government capacity	Indonesia
13	Romadhoni & Setyowati	2025	Noise & odor impact study	47% affected by noise, 41% by odor.	Operational conditions & population density	Indonesia
14	Khalifa, Haddin & Marwanto	2021	Carbon emission reduction potential of WtE using LCA	LCA shows reduction CO_2, CH_4 & CO_2 emissions at 2.08 tons/day, optimal waste reduces impacts up to 60–98%.	Material composition, emission control systems, LCA scenario assumptions	Indonesia
15	Mudofir et al.	2025	Development and performance of WtE plants in Indonesia	Indonesia's WtE potential reaches, low segregation, regulatory overlap, and high investment costs.	Policy framework, waste segregation rate, financial incentives	Indonesia

No	Author(s)	Year	Study Focus	Key Findings	Moderating Factors	Geographic Context
16	Azis et al.	2021	Techno-economic evaluation of MSW-to-energy system in Indonesia	MSW processed produces 19.7 MW; electricity price and tipping fee heavily determine feasibility.	Electricity price regulation, tipping fee level, waste composition & calorific value	Indonesia
17	Shen et al.	2024	Environmental regulation & PPP WTE subsidies	Environmental regulation shows an inverted-U effect on government subsidies	Urbanization rate, regional GDP, R&D intensity, project scale, education level	China
18	Cui et al.	2020	PPP implementation in China's WtE	PPP WtE sector is expanding rapidly; strong policy support and technological innovation	MSW composition & supply stability, regulatory environment, public acceptance, subsidy level, market competition	China
19	Abedin et al.	2025	Advances in energy recovery technologies for MSW	Comprehensive comparison of WtE technologies	Waste composition, (TRL), calorific value, moisture content, regulatory & financial incentives	Global
20	Cao et al.	2022	Risk analysis of PPP WtE incineration projects	Identified 20 critical risks in PPP WtE, Risk clustering shows regulatory and financial risks as most dominan	Regulatory quality, MSW supply stability, subsidy, PPP contract structure, community acceptance	China
21	Ouedraogo	2024	Comparative LCA of landfilling vs sustainable MSW management	landfilling has the highest GHG emissions and environmental burden, AD, composting, and WtE reduce GWP, acidification, and ecotoxicity.	Waste composition, recycling rate, LCA boundary conditions, energy recovery efficiency, landfill gas capture rate	Global

Figure 5. Location of the Benowo Landfill and WtE Benowo WtE Facility (7°12'25.4" S, 112°36'45.6" E)

of waste (Kurniawan, 2016).

Contractual Framework and Institutional Governance Structure

In accordance with Article 7 of Presidential Regulation (Perpres) No. 35 of 2018, there are two primary contractual arrangements in the management of Waste-to-Energy projects. The first is a waste management contract established between the local government, acting as the assigning authority, and the waste management operator as the technical executor. The second is a Power Purchase Agreement (PPA) for electricity procurement, executed between the WtE project developer and PLN as the energy off taker. In Surabaya, these provisions have been fully implemented in practice. The Surabaya City Government has entered into an operational cooperation agreement with PT Sumber Organik, which serves as the operator of the Benowo waste processing facility, while PLN has executed a PPA directly with the project developer for the purchase of 11 MW of electricity (Sucahyo & Fanida, 2021). The agreement follows the standardized format of the Power Purchase Agreement (PJBTL) as mandated in Article 11 of Perpres No. 35/2018, which stipulates the electricity tariff and procurement terms without requiring additional negotiation mechanisms.

Assignment and Project Implementing Entity

According to Article 6 of Presidential Regulation (Perpres) No. 35/2018, governors and mayors are authorized to assign Regional-Owned Enterprises (BUMD) or to open competitive bidding for Business Entities (BU) that meet the required technical and financial criteria. In the case of Surabaya, the city government opted to conduct an open tender. Four companies participated in the bidding process: PT Phoenix (Singapore), PT Medco (Malaysia), PT Imantata (France), and PT Sumber Organik. The Surabaya City Government ultimately selected PT Sumber Organik as the winning bidder to manage the project under a 20-year Build–Operate–Transfer (BOT) scheme (Sucahyo & Fanida, 2021). Since this selection was based on competitive procurement, the decision is legally valid and consistent with the regulatory provisions.

Electricity Purchase Scheme and Feed-in Tariff (FiT)

According to Articles 10 and 11 of Presidential Regulation (Perpres) No. 35 of 2018, PLN is required to purchase electricity from WtE developers at a fixed tariff. For facilities with a capacity below 20 MW, the purchase price is set at USD 13.35 cents per kWh. For capacities above 20 MW, the tariff is calculated as USD 14.54 – (0.076 × capacity). With the Benowo WtE facility operating at 11 MW, PLN purchases electricity at a rate of USD 13.35 cents per kWh, as stated in the Power Purchase Agreement (PPA) (Affandi et al., 2024).

Because the tariff does not increase annually, this pricing structure complies with the regulation and remains fixed from the Commercial Operation Date (COD) in 2021. Study by (Putra & Sarasi, 2025) notes that while this fixed tariff provides revenue certainty for developers, it also limits the project's financial flexibility, as it does not adjust for inflation or fluctuations in operational costs.

Government Support and Funding Sources

In terms of financing, Articles 14 and 15 of Presidential Regulation (Perpres) No. 35 of 2018 allow the use of regional government budgets (APBD), the national budget (APBN), and other lawful funding sources, including green financing and loans from international financial institutions. Although the Ministry of Energy and Mineral Resources (ESDM) and the Ministry of Environment and Forestry (KLHK) provided technical support to the Benowo project, most of the initial investment was funded entirely by private capital without direct APBN assistance (Sucahyo & Fanida, 2021). This positions the Benowo project as an example of a hybrid financing model that does not rely on central government subsidies while remaining compliant with the principles stipulated in Article 14.

A comparison with WtE project governance practices in other countries such as those described by (Cui et al., 2020) in their study on public–private partnerships (PPP) in China shows that the implementation model of the Benowo WtE facility broadly aligns with global governance frameworks. In China, PPP has become the dominant model for WtE development, with more than 60% of newly developed projects since 2015 adopting this scheme. Their success is strongly influenced by policy stability, clear risk-sharing arrangements, and direct fiscal support from the central government, including environmental subsidies and a fixed feed-in tariff of RMB 0.25/kWh. Local governments act as operational implementers and waste-supply guarantors, while the central government assumes policy-related risks and ensures electricity pricing through the State Grid Corporation of China. This integrated approach aligns China's WtE policy with its national energy strategy and enables sustained private sector investment. Furthermore, (Cui et al., 2020) highlight the importance of performance monitoring mechanisms and post-operation contractual evaluations to maintain transparency and accountability between public and private entities. In practice, oversight in China is carried out through annual evaluations based on technical and environmental indicators, the use of continuous emission monitoring systems (CEMS) with publicly accessible data, and independent financial audits conducted every five years to assess contract effectiveness and risk sharing arrangements. Such open monitoring models may serve as a reference for strengthening governance of the Benowo WtE facility, particularly in relation to post operation performance reporting and transparency. In addition to performance monitoring and evaluation, risk management is also a key determinant of PPP WtE project success. In this regard, the work of (Cao et al., 2022) provides a complementary perspective by emphasizing the importance of managing policy, financial, technical, and social risks in China's WtE projects. Their study finds that regulatory stability, contractual clarity, and public engagement have a direct influence on project sustainability and private-sector investor participation. A proportional risk-sharing approach between government and operators has been shown to reduce financial uncertainty while simultaneously increasing public trust in WtE projects.

Benowo's PPP governance can be linked to realized performance through a coherent causal pathway. The combination of a municipal tipping fee and the fixed feed-in tariff under the PLN power purchase arrangement provides a comparatively predictable cashflow for the operator (Affandi et al., 2024; Fatima et al., 2025). This revenue predictability, in turn, supports the continuity of operations and maintenance and strengthens process reliability, which is essential for sustaining stable waste throughput and consistent electricity delivery to the grid (Affandi et al., 2024; Putra & Sarasi, 2025). In line with this mechanism, the economic assessment indicates that the project remains viable under field conditions; however, the sensitivity analysis shows that feasibility deteriorates sharply when tipping-fee revenues are removed, underscoring that governance-linked revenue design is a critical determinant of the facility's realized performance rather than its design potential alone (Putra & Sarasi, 2025).

Economic Performance of the Benowo WtE Facility

The Benowo Waste-to-Energy facility in Surabaya, operated by PT Sumber Organik in collaboration with the Surabaya City Government and PT PLN (Persero), is the first Public–Private Partnership WtE project in Indonesia. PT Sumber Organik serves as the provider and operator of the technology that converts municipal waste into electrical energy, while PT PLN (Persero) functions as the offtaker, purchasing the electricity generated for distribution to the public (Sucahyo & Fanida, 2021). From an economic perspective, the project is supported by a combination of private investment and local government assistance. The fixed electricity tariff guaranteed by the government (feed-in tariff) was established through a Power Purchase Agreement (PPA) with PLN, which is consistent with Presidential Regulation No. 35/2018. PLN is required to purchase electricity from WtE facilities at a rate of US$0.1335/kWh (13.35 US cents/kWh). The evaluation conducted by (Azis et al., 2021) indicates that, both technically and economically, the 1,000-ton/day WtE model referenced in Perpres 35/2018 falls into the highly feasible category, with an Internal Rate of Return (IRR) of 25.3% and a payout time of approximately 3.4 years.

These findings align with the investment analysis by (Putra & Sarasi, 2025), who report that the Benowo WtE project demonstrates strong financial performance under ideal design conditions, although its performance declines under actual operating conditions. The facility is designed to process 1,000 tons of waste per day and generate 78,840 MWh of electricity annually. However, field observations show that the effective operating capacity has reached only about 44% of its design capacity. This underperformance can be explained by interrelated feedstock, process, and governance constraints. Variations in waste quality particularly heterogeneous composition and high moisture content reduce the stability of thermal conversion and raise the risk of downtime. At the same time, limitations in pre-treatment and source separation constrain the supply of suitable combustible fractions, while inconsistent waste delivery and coordination challenges between local actors (collection, transport, and facility operation) further suppress utilization rates. These constraints collectively translate the design level financial potential into lower realized operating performance under field conditions.

This reduced operational capacity directly affects economic performance, with total projected revenue decreasing from IDR 4.15 trillion (design capacity) to IDR 2.95 trillion (effective capacity). Net profit also declined, from IDR 2.54 trillion to IDR 1.34 trillion a reduction of approximately 47.3% from the initial potential. Nevertheless, the project continues to generate a positive Return on Investment (ROI), reaching 157.7% under the design scenario and 83.1% under actual field conditions (Putra & Sarasi, 2025).

The sensitivity analysis shows that an increase in operational costs by 10–50% can reduce the Benefit Cost Ratio (BCR) from 2.58 to 2.01 under the design-capacity scenario and from 1.83 to 1.43 under the effective-capacity scenario, although the project remains economically viable (BCR > 1). However, if tipping-fee revenue from the local government is removed, economic feasibility declines sharply, the BCR drops to 1.34 under design capacity and to 0.60 under effective capacity, with the Return on Investment (ROI) turning negative (−40.41%) (Putra & Sarasi, 2025). These findings affirm that tipping-fee income plays a critical role in maintaining the project's financial sustainability.

From a global perspective, the economic feasibility of Waste-to-Energy (WtE) projects is largely determined by the balance between operational costs, technological efficiency, and the fiscal policy support provided by governments. According to a review by (Abedin et al., 2025), waste-management costs in WtE systems can exceed USD 100 per ton in developed countries, while in developing countries they typically range around USD 35 per ton, but often face challenges in revenue recovery. This underscores the importance of incentive mechanisms such as feed-in tariffs and tipping fees to ensure the financial viability of WtE projects. Furthermore, the study highlights that each WtE technology has distinct cost structures and efficiency profiles. In lifetime cost assessments, gasification and incineration require high upfront investment but offer relatively strong Energy Return on Investment (EROI) values (1.5–3.5), compared with conventional landfill based systems, which exhibit very low EROI values (< 0.5). Conversely, anaerobic digestion (AD) is considered the most economically sustainable option due to its low carbon footprint (100–300 g CO_2/kWh) and minimal demand for non-renewable resources (0.1–0.3 kg/ton), making it an economically viable model for regions with high proportions of organic waste. In addition, (Abedin et al., 2025) emphasize that feed-in tariff schemes, carbon pricing mechanisms, and landfill taxation represent the three most effective economic policy instruments for stimulating WtE investment. These global insights reinforce the economic evaluation of the Benowo WtE facility in Surabaya, which shows that the project's financial sustainability is highly dependent on the tipping fee provided by the local government.

Environmental Performance of the Benowo WtE Facility

The Benowo WtE facility operates using a hybrid system combining landfill gas (LFG) recovery and thermal gasification which enables the simultaneous conversion of two different waste streams, organic and inorganic, into electrical energy. Both technologies contribute significantly to reducing greenhouse gas (GHG) emissions and strengthening the energy security of Surabaya City (Affandi et al., 2024). Based on a Life Cycle Assessment (LCA) conducted by (Arifianti et al., 2025), the total emissions generated from this system amount to approximately 0.45 tons of CO_2-eq per MWh of electricity, or about 40% lower than conventional incineration facilities in Southeast Asia, which average around 0.75 tons CO_2-eq/MWh.

Furthermore, according to (Liem et al., 2024), LCA-based analysis shows that Surabaya's GHG emissions decreased from 1.13 million tons CO_2-eq in the pre-2015 period to 430,839 tons CO_2-eq after the operation of the LFG system and the Benowo WtE facility equivalent to a total reduction of 57.1%. Of this reduction, the largest contribution comes from diverting 1,000 tons of waste per day to the gasification reactor (approximately 454,000 tons CO_2-eq) and from the utilization of electricity generated by the WtE facility (approximately 120,000 tons CO_2-eq). With additional policies on recycling, composting, and RDF production, emission reduction projections could reach 84.4% from the baseline level, positioning Surabaya as a national model for transitioning toward low-carbon waste management.

These figures demonstrate the high effectiveness of the hybrid system in reducing emissions from the municipal solid waste sector, which has long been a significant contributor to national GHG levels. These findings are consistent with the study by (Ouedraogo et al., 2024) in the United States, which compared landfilling with Integrated Waste Management (IWM) systems incorporating recycling, anaerobic digestion, and gasification. Their analysis recorded a decrease in global warming potential from 899 kg CO_2-eq to 14.6 kg CO_2-eq per ton of MSW, indicating a net-negative emission condition.

The energy efficiency achieved by the Benowo WtE facility is also relatively competitive. The facility's electricity output of approximately 11 MW corresponds to a conversion ratio of around 700 kWh per ton of waste processed, which is higher than the average performance of similar facilities in developing countries, typically reaching only 400–500 kWh per ton (Affandi et al., 2024), and also higher than the output of Integrated Waste Management (IWM) systems (approximately 584 kWh per ton). Both systems demonstrate high efficiency due to their ability to recover residual energy through thermochemical and bioconversion processes, thereby reducing dependence on fossil fuels. This indicates that the integration of gasification technology within the Benowo waste-processing system provides a significant added value in terms of energy efficiency and urban waste utilization.

Putri Cempo WtE Facility

The Putri Cempo landfill, located in Surakarta City, has been in operation since 1987. It occupies an area of 17 hectares with an initial design capacity intended to accommodate municipal waste for 20 years from the start of its operation. Initially, the landfill operated using a sanitary landfill system; however, because it has continued operating for more than 20 years, it has become overloaded, with waste piles reaching a height of up to 28 meters (Badan Litbangda Kota Surakarta, 2023). The development of the Putri Cempo Waste-to-Energy (WtE) facility represents a significant initiative by the Surakarta City Government to address the escalating waste accumulation and overcapacity at the landfill. The Putri Cempo WtE plant is one of the 12 pilot cities designated by the Indonesian government to implement WtE projects as a strategy to resolve landfill-related issues. The facility is located within the Putri Cempo landfill area, situated in Mojosongo Village, Jebres District, Surakarta City, Central Java.

Various types of waste entering the Putri Cempo landfill are first sorted (see figure 6). Materials such as metals, glass, wood, and plastics must be separated because they cannot be processed using gasification technology. After sorting, the waste is dried and mixed with bio-activators to accelerate the drying process until the moisture content decreases to 20% (Romadhoni & Setyowati, 2025). The sorted waste is then processed using a wet pyrolysis method to produce a more homogeneous feedstock suitable for use as fuel in the gasification process. The output of the wet pyrolysis process is known as biochar (BC). This product is subsequently processed through gasification to generate syngas, which is then used as fuel for a gas diesel engine to drive the generator during

Figure 6. Location of the Putri Cempo Landfill and WtE Facility (110°51'21.74" E, 07°32'8.11" S)

electricity production (Badan Litbangda Kota Surakarta, 2023). The Putri Cempo WtE facility uses gasification technology capable of processing up to 545 tons of waste per day to generate 8 MW of electrical energy. Approximately 5 MW is sold to PLN as the national electricity utility, while the remaining output is used for the facility's internal operational needs (Romadhoni & Setyowati, 2025).

Policy and Governance Aspects of the Putri Cempo WtE Facility within the Framework of National Regulations

The governance of the development and operation of the Putri Cempo WtE facility generally adheres to the provisions of (Peraturan Presiden Nomor 35 Tahun 2018 Tentang Percepatan Pembangunan Instalasi Pengolah Sampah Menjadi Energi Listrik Berbasis Teknologi Ramah Lingkungan, 2018). This regulation serves as the legal foundation for Waste-to-Energy projects in Indonesia, clearly outlining the distribution of roles and responsibilities among local governments as land providers and waste-supply guarantors, business entities as technical implementers and holders of investment risks, and PLN as the offtaker purchasing the electricity generated. This policy framework guides the formulation of funding structures, contractual arrangements, construction mechanisms, and electricity-purchase schemes, ensuring that the Putri Cempo WtE project operates within a standardized public private governance model.

Funding Sources

Project funding for Waste-to-Energy (WtE) facilities may originate from regional budgets (APBD), the national budget (APBN), or other lawful sources, as stipulated in Chapter VI, Articles 14–15 of Presidential Regulation (Perpres) No. 35/2018. To support the acceleration of WtE development, the central government may provide a Waste Management Service Fee (BLPS) of up to IDR 500,000 per ton of waste (Article 15, paragraph 3). However, for the Putri Cempo WtE project, the entire financing structure is sourced from private investment through a Public Private Partnership using a Design–Build–Finance–Operate-Transfer (DBFOT) scheme (Badan Litbangda Kota Surakarta, 2023). The tipping fee scheme is not applied by the Surakarta City Government in order to avoid financial burdens on the municipality, particularly considering the potential for changes in local administration in the future. The total investment cost of the project is estimated at IDR 336.4 billion. The project financing structure consists of 30% capital from PT SCMPP and 70% third-party loans. The loan was provided to PT SCMPP by PT China Construction Bank Indonesia Tbk (CCB Indonesia) amounting to USD 16,567,000 or approximately IDR 231.94 billion, based on an exchange rate of IDR 14,000 per USD at the time (Raharja et al., 2024). Putri Cempo's DBFOT-based PPP governance shapes realized performance through a revenue–risk configuration that differs from BOT models. Because the project is fully financed by the private partner and does not apply municipal tipping-fee payments, fiscal exposure for the Surakarta City Government is minimized, while revenue and cost-recovery risks are largely transferred to the developer (Badan Litbangda Kota Surakarta, 2023; Raharja et al., 2024). Under a fixed, non-escalating tariff and a PPA of approximately 5 MW, cashflow becomes highly sensitive to operational efficiency and to the reliability and quality of the municipal waste supply (Raharja et al., 2024). This context elevates the importance of upstream sorting and moisture reduction (targeting 20% moisture) to stabilize the gasification chain and secure electricity generation, while financial sustainability is further supported through by-product commercialization that helps compensate for the absence of tipping-fee revenues (Badan Litbangda Kota Surakarta, 2023; Raharja et al., 2024; Romadhoni & Setyowati, 2025; Roswulandari et al., 2019). Accordingly, feasibility indicators remain positive, but the DBFOT design implies greater sensitivity to waste-supply disruptions, operating-cost escalation, and the effectiveness of revenue diversification as determinants of realized performance (Roswulandari et al., 2019).

Contractual Arrangements

According to Chapter I, Article 7 of Presidential Regulation (Perpres) No. 35/2018, there are two primary contractual mechanisms: (1) a waste-management service contract between the local government and the waste-management operator, and (2) a Power Purchase Agreement (PPA) between the WtE project developer and PLN. In the context of the Putri Cempo WtE facility, the Surakarta City Government established a cooperation agreement with PT Solo Citra Metro Plasma Power (SCMPP) as the main operator. Meanwhile, the electricity purchase contract is executed directly between SCMPP and PLN, with tariff provisions following the government-mandated fixed price, without negotiation.

Project Site and Implementing Entity

Referring to Chapter III, Article 6 of Presidential Regulation (Perpres) No. 35/2018, regional leaders may assign a Regional-Owned Enterprise (BUMD) or a private business entity through a competitive mechanism. The Surakarta City Government implemented this provision by appointing PT SCMPP as the sole project developer under a Public–Private Partnership (PPP) scheme. The municipal government serves as the land provider and guarantees a waste supply of approximately 450 tons per day from the Putri Cempo landfill. The construction of the main infrastructure including the gasification reactor, gas-processing system, and electricity distribution network is fully financed by the private sector (Aprilianto et al., 2024; Raharja et al., 2024).

Electricity Purchase Scheme

In accordance with Chapter V, Articles 10–11 of Presidential Regulation (Perpres) No. 35/2018, the Ministry of Energy and Mineral Resources (ESDM) mandates PLN to purchase electricity from WtE developers. The electricity purchase tariff is set at USD 13.35 cents/kWh for capacities up to 20 MW, with no negotiation and no price escalation throughout the contract period. PLN signed a Power Purchase Agreement (PPA) with SCMPP for an output capacity of approximately 5 MW when the project reached its Commercial Operation Date (COD) (Raharja et al., 2024).

Division of Authority

The collaborative governance framework among the central government, local government, and private sector is established in Presidential Regulation (Perpres) No. 35/2018, which outlines the division of authority for the Putri Cempo WtE project. The Ministry of Energy and Mineral Resources (ESDM) is responsible for setting the electricity tariff policy and mandating PLN to purchase electricity from WtE developers (Articles 10–11). Meanwhile, the Surakarta City Government is responsible for providing land and ensuring the waste supply for the Putri Cempo landfill, as well as facilitating coordination between institutions and surrounding communities. PT Solo Citra Metro Plasma Power (SCMPP) serves as both the project developer and operator, undertaking technical planning, financing, construction, and facility operation. This model of authority allocation reflects a collaborative public–private governance structure in which the roles of regulator, off-taker, and operator are clearly delineated to ensure transparency, accountability, and fiscal efficiency (Raharja et al., 2024; Roswulandari et al., 2019).

When compared with the Benowo WtE facility in Surabaya, the governance structure of the Putri Cempo WtE project demonstrates a different approach to financing and incentives. Benowo utilizes a Build–Operate–Transfer (BOT) scheme supported by a tipping fee of IDR 200,000 per ton, enabling financial risks to be shared between the local government and the operator. This scheme helps maintain the project's feasibility even when operational capacity frequently falls below its design level. In contrast, Putri Cempo adopts a Design–Build–Finance–Operate Transfer (DBFOT) model without a tipping fee, meaning that the entire investment cost of IDR 336.4 billion and all associated financial risks are borne by PT SCMPP. This model reduces the fiscal burden on the regional budget (APBD) but requires high operational efficiency and revenue innovation, including the utilization of gasification by-products.

According to (Ezeudu & Bristow, 2024), the financial viability of waste-to-energy and other municipal waste services commonly depends on structured cost-recovery mechanisms most notably tipping fees and service charges which form an essential part of the revenue needed to cover capital and operational expenditures. From a contractual and institutional perspective, both WtE facilities comply with Perpres No. 35/2018, which mandates two principal agreements: waste-management contracts and electricity-purchase agreements. However, Benowo selected PT Sumber Organik through a competitive tender process, whereas Putri Cempo was appointed directly through a PPP scheme as the sole implementing entity. In terms of electricity purchase schemes, both facilities apply the same fixed tariff of USD 13.35 cents/kWh, although Benowo operates at a larger capacity (approximately 11 MW) compared with Putri Cempo (approximately 5 MW), giving it a higher potential electricity-based revenue stream.

Economic Performance of the Putri Cempo WtE Facility

The Surakarta City Government and PT Solo Citra Metro Plasma Power (SCMPP) developed this project through a Public–Private Partnership (PPP) using a Design–Build–Finance–Operate-Transfer (DBFOT) scheme (Badan Litbangda Kota Surakarta, 2023). Under this model, all investment and operational costs are borne by the private sector, while the government provides only the landfill site, permits, and a guaranteed waste supply of 450 tons per day. The absence of a tipping-fee mechanism from the regional budget (APBD) makes the project financially less burdensome for the municipality. Consequently, the developer must implement business and technological innovations to maintain financial sustainability (Raharja et al., 2024). A financial feasibility assessment by (Roswulandari et al., 2019) indicates that the Putri Cempo WtE project is economically viable. Based on a Cost–Benefit Analysis (CBA) conducted using data from the Surakarta Environmental Agency (DLH) and the PT Solo Citra Metro Plasma Power consortium, the project achieves an Internal Rate of Return (IRR) of 8.174%. This reflects the real annual return generated by the investment over the project's lifetime, meaning that the project is expected to yield an average annual return of 8.174% on the total capital invested over its operational lifespan. For comparison, (Azis et al., 2021) report that a 1,000-ton/day WtE model such as that adopted at the Benowo facility achieved a significantly higher IRR of approximately 25.3% under ideal design conditions. This difference suggests that the financial performance of WtE facilities is strongly influenced by effective processing capacity, electricity tariff structures, the presence or absence of tipping fees, and the operational efficiency specific to each location.

The Benefit–Cost (B/C) Ratio of 2.177 and the positive Net Present Value (NPV) indicate that the project generates substantial net benefits throughout its investment lifecycle. A B/C value greater than 1 confirms that every IDR 1 invested yields more than twice its value in economic benefits. Based on these parameters, the investment is estimated to be recovered within approximately 15 years, with continued revenue potential through electricity sales to PLN and by-products produced from the gasification process (Roswulandari et al., 2019). To cover operational margins without government subsidies, the developer optimizes the utilization of by-products such as synthetic diesel briquettes and paving blocks made from combustion residue, which are marketed commercially (Raharja et al., 2024). Additionally, social impact assessments show that the project provides measurable economic multiplier effects in surrounding communities: 67% of respondents reported increased household income, 77% believed that the WtE facility's CSR programs created new opportunities for local MSMEs, and the majority perceived the project as having a positive impact, particularly in terms of job creation (70%) (Amaral et al., 2023). Compared with the Benowo WtE plant, the DBFOT-based PPP scheme adopted by the Putri Cempo WtE project places the entire investment and operational burden on the private partner, without any tipping fee support from the local government. This arrangement increases the financial risk borne by the developer but significantly reduces the fiscal burden on the city. The financial assessment by (Roswulandari et al., 2019) shows that the project remains economically feasible, with an IRR of approximately 8.17%, a positive NPV, and a B/C ratio of 2.17 indicating that the economic benefits generated throughout the project's lifecycle exceed its total investment costs. Putri Cempo's IRR is slightly lower than the IRRs reported in comparable municipal PPP case studies documented by UNECE, such as the Porto Nacional Smart City PPP (IRR 9.18%) and the Belgrade urban bus-transport PPP (IRR 10.92–10.96%) (United Nations Economic Commission for Europe, 2025). This indicates a more modest return profile for Putri Cempo's DBFO arrangement, implying higher sensitivity to waste-supply reliability, tariff adequacy, and operating-cost escalation. The substantially lower IRR compared with the Benowo WtE plant which records 25.3% under ideal design capacity (Azis et al., 2021) highlights how differences in processing capacity, waste supply reliability, electricity tariff structures, and the presence of tipping fees play a decisive role in determining investment returns at each location.

Environmental Performance of the Putri Cempo WtE Facility

From an environmental perspective, the operation of the Putri Cempo WtE facility represents a concrete step toward integrating a low-carbon urban waste-management system. Unlike incineration, gasification operates under limited-oxygen conditions, producing more controlled emissions and a smaller volume of residual waste. Within the reactor, gasification occurs under low-oxygen conditions and generates synthetic gas (syngas) as its primary output. Syngas is a mixture of CO, H_2, and CH_4 with a calorific value of 4–6 MJ/Nm^3, and it serves as the main energy source at the Putri Cempo WtE facility, where it is combusted in a gas-engine generator to produce approximately 8 MW of electricity per day (Nurcahyati et al., 2025). Emissions of other pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), dioxins, mercury, and others are significantly lower compared with the flue gases produced by incineration systems (Badan Litbangda Kota Surakarta, 2023). However, LCA evidence for the Putri Cempo gasification system indicates that residual environmental and health risks remain, with human carcinogenic toxicity reported as one of the highest potential impact categories (41.647 kg 1,4-DCB eq). These risks are associated with incomplete/partial combustion pathways that may generate carcinogenic compounds such as dioxins/furans and PAHs (e.g., benzo[a]pyrene), particularly within temperature regimes linked to dioxin/furan formation (200–700°C; peak = 315°C). Therefore, the claimed emission advantages should be interpreted as conditional on stringent gas-cleaning systems, continuous monitoring, and safe management of solid residues to minimize toxic releases (Nurcahyati et al., 2025).

Based on a Life Cycle Assessment (LCA) conducted by (Khalifa et al., 2021) using SimaPro 8.3 software, the Putri Cempo WtE system demonstrates substantial potential to reduce carbon emissions and other environmental impacts. With a processing capacity of around 1,400 tons of waste per day, the facility generates total emissions of approximately 2,076.87 kg CO_2 and a climate-change index of 3,817.58 kg CO_2-eq over its life cycle. These values are significantly lower than the emission potential of open dumping or conventional incineration systems in Indonesia, which typically range from 6,000–8,000 kg CO_2-eq per ton of input. Inventory analysis shows that PVC-based materials are the largest contributors to carbon emissions and toxic gases, accounting for 57.7%, followed by corrugated board (15.2%) and injection-molded plastics (15.2%). This highlights the critical importance of pre-processing and waste segregation prior to gasification to further minimize climate impacts. Simulation results from optimized LCA scenarios show even more progressive outcomes, including an 80% reduction in carbon monoxide (CO) emissions, a 60% reduction in climate-change impacts, a 98% reduction in resource-depletion potential, and a 100% decrease in fossil-energy depletion impacts.

Meanwhile, a Life Cycle Assessment (LCA) conducted by (Nurcahyati et al., 2025) using ISO 14040/14044 guidelines shows that the gasification technology used at the Putri Cempo landfill is capable of generating approximately 8 MW of clean energy per day while significantly reducing municipal solid waste. Operating with a reactor temperature of 600–800 °C and an air–fuel ratio (AFR) of 0.3, every 1,800 kg of waste entering the gasifier produces approximately 4,052 kg of combustible syngas, along with 486 kg of residual ash and char, and around 193,000 Kcal/hour of waste heat loss. This system demonstrates high mass efficiency and a waste-reduction rate exceeding 85%, making it more environmentally sound than conventional incineration. However, the LCA results also highlight several residual environmental impacts that require control. These include carcinogenic emissions resulting from incomplete combustion potentially producing dioxins, furans, and polycyclic aromatic hydrocarbons (PAHs) as well as freshwater and marine ecotoxicity caused by the leaching of heavy metals such as Cd and Pb from combustion ash. To address these risks, PT SCMPP separates combustion ash into fly ash and bottom ash, which are stored in enclosed facilities before being reused as paving-block materials through a solidification–stabilization process, thereby minimizing the potential release of heavy metals (Cd, Pb) (Hermawan et al., 2024; Raharja et al., 2024).

Global findings by (Abedin et al., 2025) further emphasize that gasification technology exhibits a cleaner environmental-emission profile than conventional incineration, particularly in reducing SOx, NOx, dioxins, and heavy metals, while maintaining higher energy efficiency (40–60%). Nevertheless, CO_2 emissions from gasification still require careful management due to the use of auxiliary materials and the combustion of syngas. Beyond gaseous emissions, Waste-to-Energy (WtE) processes also generate non-gaseous environmental impacts, including solid residues (fly ash, slag, and combustion by-products), water consumption, and potential soil and water pollution. According to (Abedin et al., 2025), gasification systems produce solid residues that are smaller in volume and more chemically stable compared with incineration. The risk of heavy-metal contamination in fly ash and slag is lower because the high reaction temperatures (800–1600°C) promote vitrification, effectively immobilizing hazardous metals such as Pb, Cd, and Hg within a glass-like matrix. As a result, gasification residues exhibit much lower leachability than incinerator ash, making them safer for reuse or landfilling without posing significant risks to soil or groundwater. The gasification system adopted at the Putri Cempo WtE facility has the potential to deliver substantial environmental benefits not only by reducing toxic air pollutants but also by enabling the beneficial reuse of solid residues as construction materials.

Nevertheless, LCA-based assessments indicate that residual environmental and health risks may persist in MSW gasification, including potential human carcinogenic toxicity linked to incomplete/partial combustion by-products (e.g., dioxins/furans and PAHs). To mitigate these trade-offs, the literature recommends strengthening process and emission control by optimizing operating conditions (e.g., temperature and combustion time), applying treatment and control technologies such as wastewater treatment plants and electrostatic precipitators, and conducting routine monitoring of emissions and environmental quality; air-pollution control devices may include gravity settlers or cyclones, fabric filters, electrostatic precipitator, and wet scrubber, and because toxicant monitoring is necessary, monitoring should cover environmental monitoring, biological monitoring and health surveillance (Nurcahyati et al., 2025).

Consistent with ISO 14040/14044 LCA interpretation principles, the environmental benefits of gasification should therefore be concluded alongside remaining burdens, meaning that net advantages are conditional on effective process control, verified emissions compliance, and safe, well-managed residues.

Conclusion

This review shows that the Benowo and Putri Cempo WtE facilities demonstrate Indonesia's progress toward a regulated, low-carbon waste-management system. Both projects operate under Presidential Regulation No. 35/2018, which provides a clear governance structure. However, differences in financing models create distinct risk profiles. Benowo's BOT scheme with tipping fee support enables stronger financial performance. In contrast, Putri Cempo's DBFOT model implemented without tipping fees, requires higher operational efficiency and alternative revenue strategies. Economically, both facilities are feasible, although Benowo achieves higher returns due to larger capacity and more stable revenue streams. Environmentally, LCA findings confirm that gasification and hybrid LFG–gasification systems significantly reduce GHG emissions and produce cleaner residues compared with landfilling and conventional incineration. These outcomes align with global evidence that policy stability, feed-in tariffs, and adequate cost-recovery mechanisms are essential for sustaining WtE operations. Overall, the two cases illustrate that WtE development in Indonesia can support national climate and energy goals, provided that governance transparency, waste-segregation practices, and multi-level policy coordination continue to be strengthened. This review has limitations. First, the evidence base is constrained by the number of included studies and the heterogeneity of methods, system boundaries, and performance indicators across the reviewed papers, which limits direct comparability between cases. Second, publication and reporting biases may be present, as studies with positive outcomes and better data availability are more likely to be published, while negative or operationally sensitive results may be underreported. Accordingly, the conclusions should be interpreted as synthesis of available evidence rather than definitive causal attribution.

Future research in Indonesia should focus on three practical priorities. First, operational evidence should be strengthened by establishing standardized national WtE performance indicators and analyzing long-term plant data to

capture capacity utilization, downtime, feedstock quality effects, and O&M reliability across technologies. Second, environmental robustness requires longitudinal emissions monitoring supported by consistent CEMS disclosure and routine residue testing, complemented by advanced LCA to assess performance stability over time. Third, economic and governance resilience should be evaluated through comparative studies of tipping-fee versus no-tipping-fee PPP models, including sensitivity to tariffs and cost-recovery assumptions under varying municipal capacities, while incorporating structured social-acceptance assessments on perceived risks, transparency, and stakeholder engagement. Integrating these strands with energy-system and policy-scenario modeling would provide actionable evidence for optimizing Indonesia's WtE strategy in the transition toward low-carbon waste management.

Author contributions

Author 1 led the study and had the primary role in the manuscript. Author 1 conducted the literature search, PRISMA screening and selection, data extraction, thematic synthesis, analysis and interpretation, and drafted the full manuscript, including tables and figures. Author 2 contributed through supervision and methodological guidance, reviewed the PRISMA workflow and methods reporting, and provided critical revisions to strengthen rigor and clarity. Author 3 provided supervision and substantive input on governance and policy interpretation, and reviewed the Discussion and implications for alignment with the reviewed evidence. All authors reviewed and approved the final version of the manuscript.

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