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Natural Mechanisms for Optimizing Waste-to-Energy Performance in Gresik

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ABSTRACT

The increasing volume of waste in Gresik Regency indicates the need for a more effective and sustainable waste management system. A Waste-to-Energy Power Plant (WtE) based on gasification is proposed as an integrated solution to reduce waste volume while utilizing the energy potential from local resources. This study aims to formulate architectural design strategies for a WtE facility that can enhance operational performance while minimizing environmental impacts. The research employs a biomimicry approach by adapting filtration mechanisms, morphological adaptations, and flow control systems found in mangrove ecosystems. The results show that the application of these biomimetic principles generates design strategies that improve operational efficiency, optimize airflow management, and reduce odor dispersion in the surrounding area. These findings indicate that the biomimicry approach not only supports the technical performance of waste treatment facilities but also strengthens the educational function and public acceptance of the facility. Therefore, the WtE can be positioned not only as energy infrastructure but also as a representation of ecological design in sustainable environmental management.

***Keywords**: Waste-To-Energy, Biomimicry, Odor Filtration, Ecological Design,*

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INTRODUCTION

The increasing volume of waste in Gresik Regency has exceeded the capacity of existing management systems, posing risks to environmental quality and public health. This condition aligns with findings emphasizing that population growth and urbanization significantly increase waste generation when not supported by adequate infrastructure (Hoornweg & Bhada-Tata, 2012). In this context, Waste-to-Energy (WtE) technology offers a strategic solution by reducing waste volume while generating renewable energy, as highlighted in studies on integrated waste processing systems (Ragossnig & Schneider, 2015).

However, the implementation of WtE facilities faces architectural and social challenges, including odor control, environmental comfort, and limited public understanding of waste-to-energy processes. These factors significantly influence public acceptance and long-term sustainability. The built environment can function as a communicative medium when designed in an informative and contextual manner (Zeisel, 2006).

To address these challenges, this study adopts a biomimicry approach by using the mangrove ecosystem of Gresik's coastal area as a primary reference. The natural ability of mangroves to filter pollutants, regulate airflow, and adapt to extreme environments is translated into architectural strategies, including mass configuration, ventilation systems, and natural filtration elements.

The novelty of this research lies in applying mangrove-based biomimicry principles to the architectural design of a WtE facility, integrating technical efficiency with spatial environmental quality and public acceptance. Accordingly, this study investigates how biomimicry-inspired strategies can enhance operational performance, control odor impact, and support the educational function of WtE facilities.

METHOD

This study employs a descriptive-analytical method using secondary data obtained from Statistics Indonesia (Badan Pusat Statistik/BPS) of Gresik Regency, regional planning documents such as RPJMD, RKPD, and RENSTRA, as well as scientific literature on waste management and Waste-to-Energy (WtE) technology. These data provide the basis for understanding local waste conditions and identifying the need for energy-based waste treatment facilities.

The research is conducted in three main stages. The first stage involves analyzing regional waste conditions, including waste generation, composition, and existing management capacity. This analysis aims to identify functional challenges of WtE facilities, such as processing capacity requirements, potential environmental impacts, and surrounding environmental comfort, resulting in spatial and performance parameters for the facility.

The second stage focuses on biomimicry analysis by examining the ecological characteristics of mangrove ecosystems. Relevant natural mechanisms—such as filtration systems, airflow regulation, and adaptive morphology—are identified and translated into architectural principles applicable to design strategies.

The third stage is architectural design synthesis, where biomimicry principles are integrated into the design concept of the WtE facility. This includes the development of building massing, ventilation systems, and natural filtration elements to enhance operational efficiency and environmental quality. The outcome of this stage is a set of biomimicry-based architectural design strategies that support facility performance while improving public acceptance.

FINDING AND DISCUSSION

RESEARCH RESULT

Waste Management Analysis in Gresik Regency

Ngipik Landfill disposal facility, which has been operating since 2002, is the only final disposal facility in Gresik Regency. Its planned capacity of 400 m^3/day has been exceeded since 2017, with current waste generation reaching more than 800 m^3/day. This condition indicates that the existing system is no longer capable of accommodating the increasing waste volume.

Based on waste composition analysis, municipal solid waste in Gresik is dominated by organic fractions (approximately 55.29%). However, the waste exhibits relatively low moisture content and a significant proportion of inorganic materials, categorizing it as medium-quality municipal solid waste (MSW).

These characteristics present both challenges and opportunities for Waste-to-Energy (WtE) development. On one hand, the high volume and accumulation rate necessitate an alternative treatment system with higher processing capacity. On the other hand, the relatively dry composition supports the feasibility of thermal conversion technologies such as gasification. Therefore, the key problem lies not only in increasing processing capacity but also in designing a facility that can effectively manage environmental impacts, particularly odor dispersion and surrounding environmental quality.

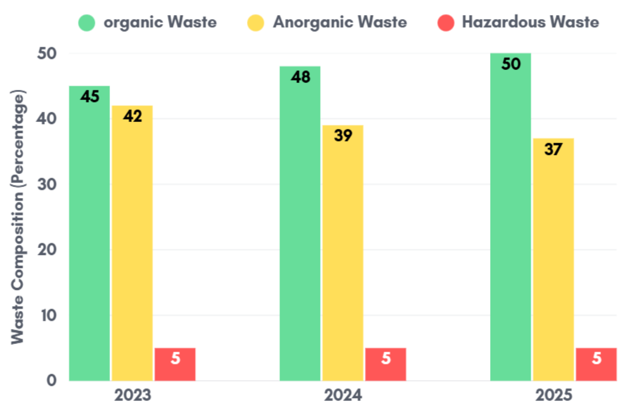

Chart 1. Percentage of waste composition at the Ngipik Landfill, Gresik Regency over the last 3 years

Source: (BPS Gresik Regency, 2025)

The identified waste characteristics indicate an energy conversion potential of approximately 700 kWh/ton, supporting the feasibility of Waste-to-Energy (WtE) implementation. This finding is consistent with global studies showing that municipal solid waste in developing countries is generally dominated by organic fractions exceeding 50%, making it suitable for energy recovery processes (Hoornweg & Bhada-Tata, 2012). Furthermore, research highlights that mixed organic–inorganic MSW can still be utilized as an alternative energy source when supported by appropriate treatment systems (Ragossnig & Schneider, 2015).

However, the high volume of waste generation and the low rate of source separation increase management complexity, particularly in terms of material flow, gas emissions, and odor dispersion. This condition requires facility design strategies that extend beyond processing technology to include integrated spatial and environmental management.

Based on these findings, the primary challenge of waste management in Gresik Regency lies in the imbalance between infrastructure capacity and the continuously increasing waste generation. The overcapacity of TPA Ngipik indicates that conventional disposal approaches are no longer adequate. Furthermore, the heterogeneous waste characteristics—dominated by organic fractions yet relatively dry—demand adaptive treatment systems alongside effective environmental control strategies.

In this context, the implementation of Waste-to-Energy (WtE) facilities must be integrated with architectural design approaches capable of managing material flows, airflow, and environmental impacts holistically. Therefore, a biomimicry approach, which adopts natural mechanisms as design strategies, becomes relevant to enhance operational performance while minimizing environmental impacts in waste treatment facilities.

Social Issues and Public Perception

Social challenges in waste management in Gresik Regency extend beyond technical and volumetric issues to include negative public perceptions of waste treatment facilities. Waste-to-Energy (WtE) plants are often perceived as sources of odor, air pollution, and health risks, largely influenced by community experiences with the overcapacity of TPA Ngipik. These perceptions are further reinforced by low levels of waste segregation at the source and limited public understanding of waste-to-energy conversion processes.

This phenomenon aligns with the concept of the Not In My Backyard (NIMBY) effect, where communities resist environmental infrastructure due to perceived risks. Studies in the context of NIMBY and social resistance (Bulkeley, 2013) indicate that such resistance is often driven by concerns over health impacts, air quality, and lack of transparency, rather than actual technological performance. In the context of WtE facilities, perceived risks are frequently shaped more by prior environmental experiences than by current technological standards.

From an architectural perspective, these negative perceptions represent a critical challenge, as they may lead to social resistance despite the technical necessity of such facilities. The dense industrial context of Gresik further heightens public sensitivity to issues of air quality and odor. Therefore, WtE facilities should not be designed as closed and exclusive systems, but rather as communicative and adaptive environments that manage odor, regulate airflow, and present waste processing activities in an educational manner.

This approach is consistent with the perspective that the built environment can function as a medium of communication between technical systems and users (Zeisel, 2006), who argues that the built environment can function as a medium of communication between technical systems and users. In this regard, architectural design plays a dual role—not only as an operational container but also as a tool to enhance public understanding and trust.

Accordingly, the social challenges in Gresik demand a WtE facility that operates efficiently while fostering public acceptance. A biomimicry approach becomes relevant in this context, as it offers natural strategies for filtration, environmental adaptation, and emission control, enabling the building to act as a mediator between waste-processing technology and community perception.

Application of Biomimicry Mechanisms in the Design of PLTSa Gresik

The application of biomimicry in the design of the Gresik Waste-to-Energy (WtE) facility is positioned as a strategic approach to address spatial and system performance issues arising from high waste loads, odor problems, and negative public perception. In this study, biomimicry is not limited to visual imitation of nature, but is understood as the adaptation of natural mechanisms in managing flows of materials, energy, and emissions in an efficient and sustainable manner.

This approach aligns with the perspective that biomimicry in architecture extends beyond biological form to include ecological systems and processes (Pawlyn, 2011), who emphasizes that biomimicry in architecture extends beyond biological form to include ecological systems and processes that underpin environmental performance.

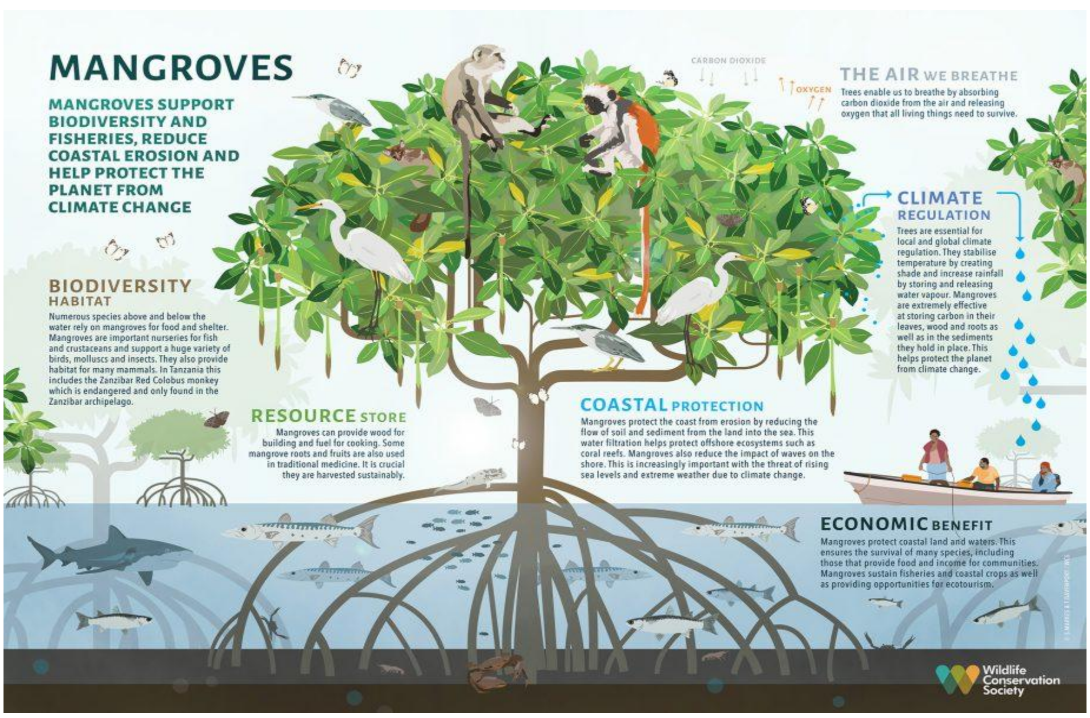

Figure 1. Mangrove Ecosystem
Source: *https://blog.wcs.org/photo/2021/09/27/the-value-of-mangroves-education-tanzania/*

Mangrove-Based Biomimicry Design Strategies

Mangrove ecosystems are selected as the primary reference due to their ecological and functional relevance to Gresik's coastal context. Mangroves demonstrate resilience in extreme environments, accommodate high material loads such as sediments and organic waste, and perform natural filtration of water, air, and particulates. These characteristics position mangroves as an ecological model capable of managing material flows in a sustainable manner. This approach differs from conventional biomimicry studies in architecture, which often emphasize biological form, as this research focuses on translating ecosystem mechanisms into environmental control strategies.

At the architectural scale, biomimicry is applied through building massing, airflow systems, and functional zoning. The multi-rooted and dispersed structure of mangroves is translated into a fragmented yet interconnected massing strategy, enabling adaptive functional distribution while preventing odor concentration in a single zone. The layered filtration principle is adapted into a sequence of transitional spaces, filtering elements, and buffer zones that reduce odor dispersion before air is released into the surrounding environment.

Furthermore, the flow regulation observed in mangrove ecosystems—driven by tidal dynamics—is translated into passive airflow control strategies. Cross-ventilation and pressure differentials are utilized to direct contaminated air toward processing zones rather than public or surrounding areas. In this way, natural mechanisms form the basis of passive environmental control, complementing mechanical building systems.

Beyond performance, the biomimicry approach also shapes the building's educational narrative. Similar to mangroves as transitional ecosystems between land and sea, the WtE facility is conceived as a transitional space between waste and energy. Waste processing is not entirely concealed but spatially layered to allow public understanding without causing discomfort. This strategy reinforces the facility's educational role while enhancing public acceptance of waste treatment infrastructure.

Formulation of Facility Requirements for WtE in Gresik

The facility requirements for the Gresik Waste-to-Energy (WtE) plant are formulated based on a waste generation rate of approximately 395 tons/day, the overcapacity condition of TPA Ngipik, and the need for environmental control and social acceptance. The facility is designed as an integrated system capable of managing material, energy, and emission flows efficiently, with processing flexibility through gasification technology and the potential production of Refuse Derived Fuel (RDF).

In general, the facility structure follows the main components of WtE systems, including waste reception, energy conversion units, and emission control systems. This framework aligns with classifications emphasizing the importance of integrating waste processing operations with environmental impact control in the design of energy recovery facilities (Ragossnig, 2015).

1. **Core Functional Requirements**

   The primary functions include waste reception and weighing, pre-treatment zones, gasification reactor units, energy recovery systems (boiler, turbine, and generator), and residue management areas for ash and slag. This functional sequence ensures stable waste-to-energy conversion despite fluctuations in waste composition and calorific value.

2. **RDF Facility as a Complementary System**

   As a complementary processing option, an RDF facility is incorporated to handle high-calorific dry fractions such as plastics, paper, and industrial residues that are less suitable for gasification. The facility includes advanced sorting, drying, shredding, and storage prior to distribution to external users such as cement industries. This strategy aligns with findings by Felix Schneider (2015), highlighting that RDF integration enhances system flexibility and optimizes energy recovery from dry waste fractions.

3. **Odor and Emission Control Systems**

   Odor and emission control are critical requirements, particularly in pre-treatment and RDF zones. The design incorporates exhaust treatment systems and a chimney integrated with building massing and airflow strategies. A biomimicry approach is applied through layered transitional spaces and buffer zones, inspired by mangrove filtration mechanisms, to retain and filter polluted air before release into the environment.

4. **Operational and Support Spaces**

   Supporting facilities include control rooms, operator areas, maintenance workshops, storage, and utilities. These spaces are designed with separated circulation from public and waste-handling routes while maintaining functional integration for efficient and safe operations.

5. **Educational and Public Interface**

   To enhance public acceptance, the facility includes educational spaces and controlled visitor pathways that present waste-to-energy and RDF processes in a sequential manner. These spaces are spatially layered to ensure visibility without exposing visitors to odor or noise disturbances.

6. **Massing and Zoning Strategy**

   Spatially, the facility adopts a fragmented yet interconnected massing configuration, separating “dirty zones” (pre-treatment, RDF, reactor) from “clean zones” (education and administration). The chimney and emission system function as central organizing elements. This configuration reflects a macro-level biomimicry approach, where the building operates as an artificial ecological system that adaptively regulates material and airflow.

DISCUSSION

The findings of this study indicate that integrating biomimicry principles into the design of a Waste-to-Energy (WtE) facility provides a comprehensive response to both technical and socio-environmental challenges in Gresik Regency. The identified waste characteristics—high generation rates, a dominant organic fraction, and relatively low moisture content—support the feasibility of thermal conversion technologies such as gasification, while also necessitating adaptive environmental control strategies. The application of mangrove-inspired biomimicry demonstrates that spatial configuration, airflow management, and layered filtration systems can enhance operational efficiency and reduce odor dispersion. More importantly, the results highlight that architectural design plays a critical role not only in optimizing system performance but also in mediating public perception, positioning the facility as both infrastructure and a communicative space.

These findings are consistent with global waste management studies emphasizing the energy potential of municipal solid waste (Hoornweg & Bhada-Tata, 2012), which emphasize the energy potential of municipal solid waste in developing countries. The integration of RDF as a complementary system also aligns with research highlighting flexible waste processing systems (Schneider, 2015), highlighting the importance of flexible waste processing systems. From a design perspective, this study extends the framework of biomimicry in architecture framework emphasizing ecological processes in design (Pawlyn, 2011) by shifting the focus from formal imitation toward the application of ecological processes as operational strategies. In addition, the role of architecture as a communicative medium supports the role of architecture as a communicative medium (Zeisel, 2006), particularly in addressing social resistance to environmental infrastructure, as also discussed in the context of NIMBY and social resistance (Bulkeley, 2013), where public perception is often shaped more by prior environmental experiences than by actual technological performance.

However, this study has several limitations. The research adopts a qualitative and design-oriented approach based primarily on secondary data and the theoretical translation of ecological principles into architectural strategies. Consequently, the proposed design has not been quantitatively validated, particularly in terms of airflow behavior, odor dispersion, and emission control performance. Furthermore, the focus on the specific context of Gresik Regency may limit the generalizability of the findings to other regions with different environmental and waste characteristics.

Despite these limitations, the study offers important implications for both research and practice. It suggests that biomimicry can function not only as a conceptual design approach but also as an operational environmental control strategy that enhances both technical performance and public acceptance. This approach is particularly relevant for urban-industrial contexts where environmental sensitivity and social perception are critical. Future research is recommended to incorporate quantitative validation methods, such as computational fluid dynamics (CFD) simulations, as well as comparative studies with conventional WtE facility designs. Further exploration of alternative ecological models beyond mangrove ecosystems may also provide additional insights into adaptive and resilient design strategies for sustainable waste management infrastructure.

CONCLUSION

Based on the analysis of waste conditions, existing infrastructure, and social aspects in Gresik Regency, this study demonstrates that the increasing volume of waste—exceeding the capacity of TPA Ngipik—requires a more adaptive and sustainable treatment system. In this context, a gasification-based Waste-to-Energy (WtE) facility is identified as a relevant solution, capable of reducing waste volume while generating energy.

This study addresses the research problem by demonstrating that biomimicry principles derived from mangrove ecosystems—particularly filtration, environmental adaptation, and flow regulation—can be translated into architectural design strategies. These include fragmented building massing, controlled airflow and ventilation systems, as well as layered transitional spaces and buffer zones for odor and emission control. Through these strategies, the WtE facility is positioned not only as a technical infrastructure but also as an integrated spatial system capable of managing material flows, airflow, and environmental impacts holistically.

In addition to improving operational performance, the biomimicry approach contributes to the development of educational spaces that enable the public to understand waste-to-energy processes in a gradual and controlled manner. This has the potential to enhance public acceptance of waste treatment facilities, which are often perceived negatively.

Therefore, the design of WtE facilities in Gresik should not solely focus on processing technology but also on the integration of biomimicry-based architectural strategies at the macro level. This integration can be achieved through adaptive zoning, passive environmental control systems, and processing flexibility through Refuse Derived Fuel (RDF). Ultimately, the proposed approach positions the Gresik WtE facility as both energy infrastructure and an ecological design model that supports sustainable and context-responsive environmental management.

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