Developing an Architectural Spatial Integration Framework for Sustainable Waste Management Education Facilities

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Abstract.
The growing adoption of Waste-to-Energy facilities requires an architectural approach capable of integrating industrial operations, environmental education, and sustainable waste management within a coherent spatial system. However, existing studies primarily emphasize technological optimization, industrial building performance, or educational environments independently, leaving limited attention to architectural spatial integration as a design foundation. This study aims to develop an Architectural Spatial Integration Framework to support the design of Sustainable Waste Management Education Facilities. A Design-Based Research approach was employed through the synthesis of scientific literature, policy reviews, architectural precedent studies, and comparative analysis to identify transferable spatial design principles. The proposed framework consists of four integrated components, namely Spatial Organization Integration, Functional Integration, Environmental Integration, and Architectural Integration, which are translated into architectural design parameters including zoning, circulation, spatial hierarchy, building form, environmental systems, visual connectivity, and educational spaces. The framework is subsequently implemented through a conceptual architectural model demonstrating how industrial operations, visitor experiences, environmental learning, and sustainable building strategies can be integrated into a coherent spatial configuration. The findings establish Architectural Spatial Integration as the principal mechanism linking operational efficiency, environmental performance, and educational functions within Waste-to-Energy facilities. This study contributes a transferable architectural framework that advances the discourse on sustainable industrial architecture while providing practical guidance for the planning and design of future Sustainable Waste Management Education Facilities supporting circular economy principles and sustainable urban development.

Keywords: *Architectural Spatial Integration, Sustainable Waste Management, Waste-to-Energy Facility, Industrial Architecture, Environmental Education Facility, Sustainable Building Design and Spatial Design Framework.*

I. INTRODUCTION

The increasing generation of Municipal Solid Waste has become one of the most significant challenges to achieving sustainable development worldwide. Population growth, rapid urbanization, changing consumption patterns, and expanding economic activities have contributed to a substantial increase in waste generation, while the capacity of conventional waste management systems has become increasingly inadequate to accommodate these demands. Traditional waste management practices, which primarily emphasize waste collection, transportation, and disposal, are no longer sufficient to address the growing need for resource efficiency, carbon emission reduction, and environmental protection. Consequently, Sustainable Waste Management has evolved into a contemporary paradigm that recognizes waste as a valuable resource capable of generating economic, environmental, and energy benefits through the implementation of circular economy principles [1], [2]. Within this context, waste management is no longer intended solely to mitigate environmental pollution but also to improve resource efficiency, strengthen energy resilience, and support the achievement of sustainable development goals through the integration of environmental, economic, and social dimensions [3], [4].

In line with this paradigm shift, Waste-to-Energy (WtE) technology has emerged as one of the most promising approaches to modern waste management. Numerous studies have demonstrated that WtE technologies substantially reduce waste volume while simultaneously generating electricity and thermal energy, thereby contributing to renewable energy diversification and reducing dependence on fossil fuels [5], [6]. The advancement of WtE technologies has also transformed waste management facilities from conventional public service infrastructure into integral components of urban energy systems that support the transition toward low-carbon cities. Recent bibliometric evidence indicates a substantial increase in global Waste-to-Energy (WtE) research, particularly in relation to energy conversion technologies, operational optimization, and the integration of WtE systems into sustainable waste management strategies [7]. These developments suggest that WtE has become a major research focus in addressing future waste management challenges and advancing sustainable urban development.

Despite these developments, the implementation of WtE systems in many countries, including Indonesia, continues to face substantial challenges that extend beyond technological, financial, and regulatory issues to include public acceptance of waste treatment facilities. National policies have increasingly promoted the acceleration of sustainable waste management through the adoption of advanced waste treatment technologies; however, their implementation remains constrained by limited public literacy regarding modern waste management processes, persistent negative perceptions of waste treatment facilities, and the lack of approaches capable of integrating industrial operational functions with public environmental education [3], [4], [8]. These conditions indicate that the success of sustainable waste management depends not only on the sophistication of treatment technologies but also on the capacity of waste management facilities to enhance public understanding, experience, and participation in sustainable waste management practices. Consequently, the future development of WtE facilities should no longer focus exclusively on improving technological efficiency but should also adopt an architectural approach capable of bridging industrial operational requirements with environmental education functions as an integral component of sustainable waste management systems.

The growing body of research addressing these challenges indicates that existing solutions remain predominantly sector-oriented, with limited integration across disciplines. Within the field of Waste-to-Energy (WtE), most studies have concentrated on improving energy conversion efficiency, optimizing waste treatment systems, and integrating WtE technologies into sustainable waste management strategies. These studies have consistently demonstrated that the conversion of municipal solid waste into energy contributes significantly to waste volume reduction, improved resource efficiency, and the achievement of low-carbon development objectives [5], [6], [7]. In parallel, research on Industrial Building Design has evolved toward the development of industrial facilities that are increasingly flexible, adaptive, and capable of accommodating changes in production processes and technological advancements. Studies on industrial architecture have identified spatial flexibility as a key determinant of industrial building performance [9], [10]. Complementing this perspective, the integration of structural and architectural systems has been recognized as essential for achieving both functional efficiency and high spatial quality [11]. Previous studies have documented a gradual transformation in industrial building typologies from facilities designed solely for production activities toward environments that emphasize energy efficiency, spatial adaptability, and the overall quality of the built environment [12]–[16]. Meanwhile, research on Environmental Education Facilities has increasingly recognized architecture as an active medium for environmental learning by shaping users' experiences through spatial organization, visual connectivity, environmental interpretation, and interaction with the built environment. Studies on environmental education have increasingly recognized architecture as an active learning medium. The concept of the building as a teaching tool [17] has subsequently evolved into broader investigations demonstrating that spatial organization, circulation patterns, visual connectivity, and users' spatial experiences play significant roles in enhancing the effectiveness of sustainability education [18]–[22]. Despite these advances, these three research domains have largely developed independently, resulting in the absence of an architectural approach capable of systematically integrating industrial operations, environmental education, and sustainable waste management strategies within a unified design framework.

This fragmentation reveals a clear research gap (Tabel 1) within contemporary architectural scholarship. Existing Waste-to-Energy research continues to prioritize technological efficiency and waste treatment performance, whereas studies on Industrial Building Design primarily focus on production efficiency, building flexibility, and industrial spatial organization. Conversely, investigations into Environmental Education Facilities have concentrated on learning behavior, visitor experience, and educational environments without considering the operational complexity inherent in industrial facilities. Consequently, there remains a lack of research that systematically examines how these three domains can be integrated through a spatial approach as the foundation of architectural design. From an architectural perspective, relationships among building functions are determined not merely by physical proximity but also by spatial organization, circulation patterns, activity hierarchy, visual connectivity, and the continuity of users' spatial experiences in understanding the processes occurring within the building.

Table 1. Comparative Research Matrix of Previous Studies and Their Contribution to the Proposed Architectural Spatial Integration Framework

Authors	Waste-to-Energy	Industrial Building	Environmental Education	Spatial Integration	Used in This Study
Kothari et al. (2010)	✓	–	–	–	Establishes the role of Waste-to-Energy as a sustainable waste management strategy and defines the operational characteristics of WtE facilities
Lisbona et al. (2023)	✓	–	–	–	Provides recent developments in Waste-to-Energy technologies and their contribution to circular waste management systems.
Rachmawatie et al. (2024)	✓	–	–	–	Demonstrates the increasing global research trend and strategic importance of Waste-to-Energy development.
Reisinger et al. (2021)	–	✓	–	✓ (Partial)	Introduces spatial flexibility and integrated planning principles for industrial buildings.
Ilkovičová & Ilkovič (2024)	–	✓	–	✓ (Partial)	Explains the integration of architectural and structural systems in industrial buildings.
Goncikowski (2020)	–	✓	–	✓ (Limited)	Describes the evolution of industrial building typologies and spatial organization.
Cole (2014)	–	–	✓	✓ (Partial)	Introduces the concept of architecture as a teaching tool through spatial experience.
Tascı (2015)	–	–	✓	✓ (Partial)	Demonstrates the relationship between sustainable architecture and environmental learning environments.
Bradecki et al. (2024)	–	–	✓	✓	Highlights the importance of ecological architectural design in supporting environmental education.
Medaković et al. (2024)	–	–	✓	✓	Demonstrates how spatial configuration and visitor movement influence learning experiences and spatial perception.
Shaliha & Nugroho (2026)	✓	✓	✓	✓ (Limited)	Integrates Waste-to-Energy, green architecture, and educational functions into an architectural design proposal but does not develop a transferable spatial integration framework.

Source: synthesized from References [5]–[22].

Previous studies on spatial integration across various building typologies have demonstrated that well-integrated spatial configurations enhance operational efficiency while simultaneously strengthening users' engagement with the built environment [24], [22]. However, these concepts have not yet been specifically developed for sustainable waste management facilities, which are characterized by highly complex operational systems, stringent safety requirements, and the simultaneous integration of educational functions. Accordingly, the principal research gap addressed in this study is the absence of a comprehensive architectural framework capable of integrating Waste-to-Energy operational systems, industrial building functions, environmental education, and sustainability strategies into a coherent spatial system that serves as the foundation for the design of Sustainable Waste Management Education Facilities.

Based on this research gap, the present study aims to develop an Architectural Spatial Integration Framework as a conceptual model that explains the principles of spatial integration for the design of Sustainable Waste Management Education Facilities. The proposed framework is developed through the synthesis of theoretical perspectives on Waste-to-Energy, Industrial Building Design, Environmental Education Facilities, and Sustainable Waste Management, which are subsequently translated into a set of architectural spatial principles capable of integrating industrial operational requirements, environmental learning systems, and sustainable design strategies within a coherent spatial organization. The novelty of this study does not lie in the advancement of Waste-to-Energy technologies, innovations in waste treatment systems, or the isolated application of green building principles. Rather, its contribution resides in the development of an Architectural Spatial Integration Framework that establishes a conceptual architectural foundation for systematically integrating industrial and educational functions through spatial design. Accordingly, this study contributes to the advancement of architectural knowledge, particularly within the field of sustainable industrial architecture, while providing a transferable conceptual framework that can guide the planning and design of sustainable waste management facilities across diverse geographical and institutional contexts.

II. METHODS

This study employed a Design-Based Research (DBR) approach because its primary objective was not to evaluate the performance of an existing building or to develop Waste-to-Energy (WtE) technologies, but rather to establish a conceptual architectural framework that can serve as a foundation for the design of Sustainable Waste Management Education Facilities. The DBR approach facilitates the generation of design knowledge through the systematic synthesis of theoretical concepts, architectural precedents, and practical design considerations, thereby producing a conceptual artifact applicable across various design contexts. Within architectural research, this approach is particularly relevant because design is regarded as a medium for knowledge generation through design rather than merely the production of a physical artifact [14]. Accordingly, the research process was structured as an iterative sequence comprising problem identification, literature review, knowledge synthesis, extraction of spatial design principles, development of the Architectural Spatial Integration Framework, and the subsequent translation of the framework into architectural design principles. This approach is also consistent with contemporary studies on industrial architecture, which recognize design integration as a critical process for achieving adaptive, flexible, and operationally efficient industrial buildings [9], [10], [11]. Consequently, the primary outcome of this research is a conceptual framework that systematically explains the relationships among spatial components within sustainable waste management facilities rather than a conventional architectural design proposal.

The research data were collected from four complementary sources, namely literature review, policy and regulatory review, precedent studies, and architectural document analysis. The literature review encompassed international scientific publications addressing Waste-to-Energy, Industrial Building Design, Environmental Education Facilities, Sustainable Waste Management, and spatial organization in architecture. The policy and regulatory review examined national and international policies related to sustainable waste management and the development of Waste-to-Energy facilities to establish the normative context supporting the proposed framework. Subsequently, precedent studies were conducted to identify architectural approaches adopted in waste management facilities, industrial buildings, and environmental education facilities. Architectural document analysis focused on identifying patterns of spatial organization, functional relationships, circulation systems, spatial hierarchy, and strategies for integrating industrial and educational functions. All data sources were analyzed using a comparative synthesis approach to identify similarities, differences, and recurring spatial principles that served as the basis for constructing the proposed framework. Similar synthesis-based approaches have been widely employed in studies of industrial buildings and educational facilities to formulate transferable architectural design principles [17], [10], [20], [22].

The Architectural Spatial Integration Framework was developed through a sequential synthesis process that integrated findings from the reviewed literature and architectural precedents into four principal components: Spatial Organization Integration, Functional Integration, Environmental Integration, and

Architectural Integration. Spatial Organization Integration establishes the spatial relationships among operational areas, educational spaces, public zones, and supporting facilities to create a logical, safe, and efficient spatial configuration. Functional Integration connects the operational requirements of the Waste-to-Energy system with educational activities through the organization of zoning, spatial relationships, and user activity sequences. Environmental Integration incorporates sustainable design strategies, including daylight optimization, passive ventilation, energy efficiency, rainwater management, green infrastructure, and environmentally responsible material selection as integral components of the building's spatial system. Meanwhile, Architectural Integration unifies building form, massing, structural systems, circulation, and spatial experience into a coherent architectural composition that simultaneously supports industrial operations and environmental education. These four components were subsequently synthesized into a conceptual framework that systematically defines the relationships among spatial elements and translates them into architectural design principles for Sustainable Waste Management Education Facilities. Through this approach, the proposed framework functions not only as a design guideline but also as a conceptual contribution that can be replicated, adapted, and further developed in future research and professional practice concerning sustainable waste management facilities [24], [11], [20].

III. RESULT AND DISCUSSION

Development of the Architectural Spatial Integration Framework

The development of Waste-to-Energy (WtE) facilities over recent decades indicates that the majority of existing research has primarily focused on improving energy conversion efficiency, optimizing waste treatment technologies, and strengthening sustainable waste management systems. These approaches have made substantial contributions to waste volume reduction and the utilization of renewable energy as integral components of Sustainable Waste Management strategies [5], [6], [1], [7]. However, as identified in the introduction, most of the research still places buildings as operational containers for technological systems, so aspects of spatial organization and spatial relationships have not developed as the focus of research. On the other hand, the study of Industrial Building Design is developing towards increasing building flexibility, spatial organization efficiency, and integration between structural systems and industrial functions [14], [9], [10], [11]. Meanwhile, research on Environmental Education Facilities shows that the quality of space organization, visual relationships, and user experience play an important role in building environmental learning processes through architecture [17], [19], [20]. A synthesis of these three research domains reveals a significant conceptual gap, namely the absence of an architectural framework capable of systematically integrating the operational requirements of Waste-to-Energy systems, the characteristics of industrial buildings, and the educational functions of environmental learning within a unified spatial system.

In response to this research gap, this study develops an Architectural Spatial Integration Framework through a conceptual synthesis of three principal knowledge domains, namely Waste-to-Energy, Industrial Building Design, and Environmental Education Facilities, as described in the methodology section. The framework was developed by identifying recurring spatial principles across these domains and integrating them into a unified conceptual structure capable of guiding the architectural design of sustainable waste management facilities. This approach adopts design integration principles established in industrial building research, which regard spatial organization as the primary mechanism for connecting multiple building functions efficiently [10], [11]. At the same time, it incorporates the concept of architecture as a medium for environmental education, emphasizing the importance of spatial experience, process legibility, and users' interaction with the built environment [17], [18], [22]. Unlike previous studies that have addressed these domains independently, the proposed framework is conceived as an integrated architectural model that positions spatial organization as the principal medium for connecting industrial operations, environmental learning systems, and sustainability strategies.

Fig. 1. Proposed Architectural Spatial Integration Framework and Spatial Design Parameters for Sustainable Waste Management Education Facilities
Source: Authors' Analysis, 2026.

Figure 1 presents the proposed Architectural Spatial Integration Framework, which constitutes the principal outcome of this research. The framework is organized hierarchically, with Architectural Spatial Integration serving as the core that represents the fundamental principle of spatial integration in the design of sustainable waste management facilities. The second layer, referred to as the integration layer, comprises Spatial Organization Integration, Functional Integration, and Environmental Integration, representing the three primary dimensions that collectively establish the building's spatial system. These dimensions are subsequently translated into spatial design parameters, including zoning, building form, daylighting, visitor flow, waste flow, and circulation, which function as operational design parameters throughout the architectural design process. These parameters interact systematically to generate a Sustainable Waste Management Education Facility that not only supports the operational efficiency of Waste-to-Energy systems but also promotes environmental learning through an integrated spatial organization. Accordingly, the proposed framework positions spatial integration as the conceptual foundation that links technical requirements, functional performance, and educational objectives within a coherent architectural system, while providing the basis for the discussion of framework components and their translation into architectural design presented in the following sections.

Framework Components and Spatial Design Parameters

The Architectural Spatial Integration Framework was developed through the integration of four principal components that establish a systematic relationship among the operational requirements of Waste-to-Energy (WtE) facilities, the spatial organization of industrial buildings, the functions of environmental education, and sustainable design strategies. The first component, Spatial Organization Integration, structures the spatial system by organizing industrial zones, educational zones, public zones, and service zones according to the principles of zoning, spatial adjacency, and spatial hierarchy. Studies on industrial building design have consistently identified spatial organization as a key determinant of industrial building flexibility while emphasizing the integration of structural systems, building functions, and architectural design as essential for achieving efficient industrial facilities [9]–[11]. Furthermore, the evolution of industrial building typologies has increasingly shifted toward spatial organizations capable of accommodating functional transformation, technological advancement, and changing operational requirements [12]–[15]. The second component, Functional Integration, establishes relationships among waste flow, operational flow, visitor flow, and learning flow through the design parameters of circulation, visibility, and safety, thereby enabling industrial operations and educational activities to coexist without compromising operational efficiency or user safety. This perspective extends previous Waste-to-Energy research, which has primarily emphasized technological optimization and waste treatment performance [5]-[7], by introducing spatial organization as the principal mechanism for integrating industrial systems with user experience.

The remaining components, Environmental Integration and Architectural Integration, collectively translate sustainability principles into the building's spatial system and architectural expression.

Environmental Integration incorporates daylighting, natural ventilation, green infrastructure, water management, and energy efficiency as integral elements of passive design strategies that simultaneously enhance building performance and environmental quality. This approach aligns with the principles of Sustainable Waste Management, which regard resource efficiency and environmental impact reduction as inseparable components of contemporary waste management systems [1]-[4]. This perspective is further supported by studies demonstrating that the environmental performance of industrial buildings is strongly influenced by the integration of architectural design strategies from the earliest stages of the design process [16], [25]. Meanwhile, Architectural Integration establishes the relationship among building form, morphology, visual connectivity, spatial experience, and façade design as architectural elements that shape the identity of the facility while simultaneously reinforcing its educational function. This principle is founded on the understanding that architecture serves not merely as a container for activities but also as a medium for learning through spatial experience and visual engagement with the processes occurring within the building [17]-[20]. Furthermore, the organization of visual connections, spatial sequences, and user movement adopts the concept of spatial integration enabling the resulting architectural expression to represent not only the operational functions of an industrial facility but also a coherent educational narrative that promotes sustainable waste management through an integrated spatial organization [22], [24].

Architectural Translation of the Framework

The Architectural Spatial Integration Framework is translated into architectural design by transforming each integration component into a set of design parameters applicable to spatial organization and building configuration. At this stage, Spatial Organization Integration is translated into strategies for zoning, spatial adjacency, and spatial hierarchy, which regulate the relationships among industrial, educational, public, and service zones. This spatial arrangement enables waste treatment operations to be conducted efficiently while maintaining accessibility and spatial legibility for visitors. Such an approach is consistent with studies on industrial building flexibility, which identify spatial organization as a fundamental basis for architectural decision-making [9], [10], as well as research on industrial building typologies that emphasizes the interrelationship among function, structure, and spatial organization in determining overall building performance [14], [13], [12], [11]. Furthermore, Functional Integration is translated through the organization of circulation, waste processing sequence, visitor flow, and operational flow, allowing industrial operations, logistics, and educational activities to coexist within an interconnected yet safe circulation system. This arrangement employs the principles of visibility and user flow separation to create an educational experience that enables visitors to understand each stage of the waste treatment process without disrupting industrial operations, reflecting the evolving role of Waste-to-Energy facilities that increasingly requires both operational efficiency and enhanced public engagement in sustainable waste management [1], [5]-[7].

The implementation of Environmental Integration is achieved through the incorporation of daylighting, natural ventilation, green infrastructure, energy-efficient systems, and water management strategies as integral components of the building's spatial organization. Simultaneously, Architectural Integration is translated into the configuration of building mass, façade, visual connectivity, educational corridors, and observation spaces, which collectively establish a direct relationship between industrial processes and users' learning experiences. This approach conceptualizes architecture as an interpretive medium through which waste treatment processes become integral components of environmental learning. The concept of the building as a teaching tool [17] provides the theoretical foundation for this approach, while subsequent studies have demonstrated that spatial experience, visual relationships, and environmental quality significantly enhance learning effectiveness in environmental education facilities [18]-[21]. The development of educational corridors and observation spaces also adopts the principles of spatial integration, whereby spatial configuration and movement sequences function as mechanisms for shaping users' experiences through continuous visual engagement with activities occurring within the building [24], [22]. Consequently, the translation of the framework extends beyond the organization of building functions to generate an architectural configuration that integrates building expression, massing composition, circulation systems, and spatial experience as the physical manifestation of the relationship among Waste-to-Energy processes, environmental education, and the principles of Sustainable Waste Management.

Proposed Architectural Model

The proposed architectural model represents the physical realization of the Architectural Spatial Integration Framework through the integration of spatial organization, functional systems, environmental strategies, and educational facilities into a unified architectural composition. Rather than treating industrial operations and environmental education as separate entities, the proposed model organizes both functions within an interconnected spatial system that enables operational efficiency while simultaneously facilitating public learning. The building configuration applies hierarchical zoning to distinguish industrial processing areas, educational facilities, public spaces, and supporting services, while maintaining visual and functional connectivity through coordinated circulation and observation routes (Figure 2). This approach reflects the concept of industrial architecture as an adaptive spatial system capable of accommodating complex operational requirements while providing flexible spaces for human interaction and learning [9]-[11].

The implementation of environmental strategies is demonstrated through the expansion of vegetated buffer zones and ecological landscapes, the optimization of passive environmental systems through daylight utilization and climate-responsive building orientation (Figure 3), and the application of ecological, locally available, and recycled construction materials that reinforce both environmental performance and industrial architectural identity (Figure 4). These design decisions are consistent with sustainable building principles emphasizing resource efficiency, environmental quality, and long-term operational performance [17], 1], [2], [25].

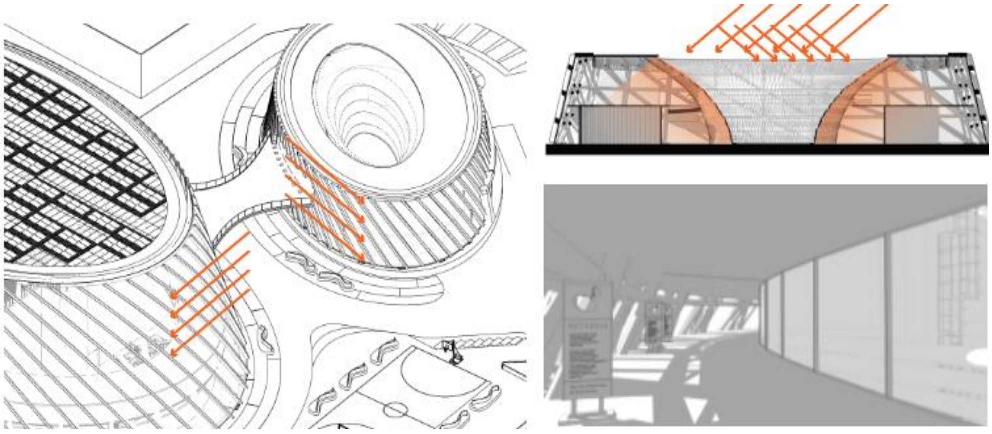

Fig. 3. Implementation of the Principle of Energy-Efficient Building Systems through Passive Design Strategies Adapted to Local Climate Conditions

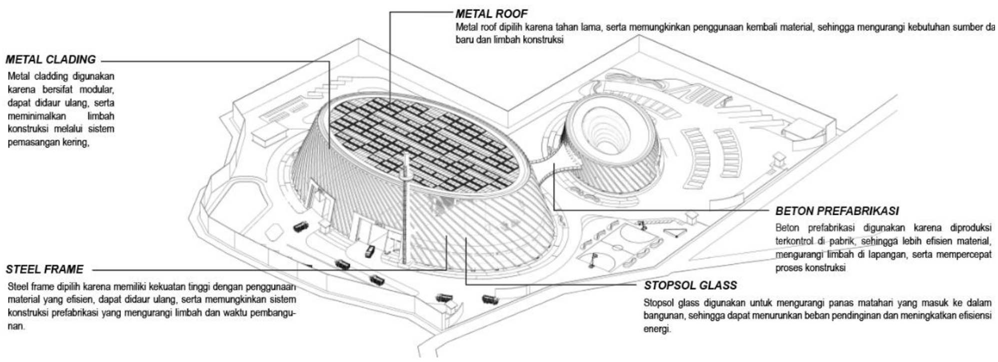

Fig. 4. Architectural Implementation of the Proposed Architectural Spatial Integration Framework at the Building Scale

The proposed model also translates the educational dimension of the framework into a continuous spatial learning experience integrated throughout the architectural environment rather than being confined to dedicated exhibition spaces. The educational interior (Figure 5) is organized as an interactive learning environment where visitors can observe waste management processes through direct visual relationships, controlled circulation, and sequential spatial experiences that strengthen understanding of Waste-to-Energy systems. Complementing this approach, interpretive educational signage distributed along visitor circulation routes functions as an architectural information system that guides users through successive stages of waste processing while reinforcing environmental awareness and the identity of the facility as a Sustainable Waste Management Education Facility. This spatial learning sequence aligns with previous studies emphasizing that environmental education becomes more effective when learning is embedded within users' direct interaction with architectural space rather than relying solely on conventional instructional methods [18]-[20]. Consequently, the proposed architectural model demonstrates that the Architectural Spatial Integration Framework is capable of generating an integrated design in which industrial operations, environmental performance, and educational experience are synthesized into a coherent architectural system, thereby extending previous Waste-to-Energy facility studies that have predominantly focused on technological efficiency without systematically incorporating architectural spatial integration as the primary design framework.

Fig. 5. Human-Scale Application of the Proposed Architectural Model Based on the Architectural Spatial Integration Framework

Discussion: Comparison with Previous Studies

The proposed Architectural Spatial Integration Framework extends the existing body of knowledge by synthesizing three research domains that have generally evolved independently, namely Waste-to-Energy systems, Industrial Building Design, and Environmental Education Facilities. Previous studies on Waste-to-Energy have primarily concentrated on technological performance, energy recovery, environmental efficiency, and integrated waste management strategies, emphasizing the optimization of treatment technologies and resource recovery rather than the organization of architectural space [5], [6], [1]. Although these studies acknowledge the importance of sustainable infrastructure, architectural design is generally treated as a supporting physical container for technological systems rather than as an active component influencing operational performance and public engagement. Conversely, studies in industrial architecture have emphasized flexibility, adaptability, and spatial organization as key determinants of industrial building performance [14], [13], [9], [10], [11], [15], while research on environmental education has demonstrated that learning effectiveness is significantly influenced by spatial experience, visual accessibility, environmental quality, and user interaction with the built environment [17]-[20]). However, these research streams have remained largely disconnected, leaving limited understanding of how industrial operations, educational functions, and environmental performance can be integrated through architectural spatial organization.

Compared with previous studies, the framework proposed in this research introduces a different conceptual perspective by positioning Architectural Spatial Integration as the principal mechanism linking operational systems, environmental strategies, and educational functions within a single architectural model (Tabel 2). Existing studies have primarily addressed technological integration in Waste-to-Energy systems [5], [6] and spatial efficiency in industrial buildings [10] . In contrast, the proposed framework expands these perspectives by integrating Spatial Organization, Functional, Environmental, and Architectural Integration within a coherent architectural design framework. Likewise, existing studies have demonstrated that architectural space can enhance environmental learning through spatial experience, visual connectivity, and interpretive environments [17], [19], [20], [22]. Building upon these findings, the proposed framework integrates educational activities directly into industrial spatial sequences through observation corridors, educational interiors, interpretive signage, and continuous visual connectivity, thereby transforming industrial operations into an integral component of the learning experience rather than treating education as a separate function. This integration also differs from previous eco-friendly architectural approaches that primarily emphasize environmental performance through passive design strategies, renewable energy utilization, and material efficiency [1], because the proposed model treats spatial organization itself as the medium through which sustainability, industrial productivity, and environmental education are simultaneously achieved, thereby establishing an architectural design framework that extends the current discourse on sustainable Waste-to-Energy facilities beyond technological optimization toward an integrated spatial paradigm.

Table 2. Comparative Analysis of Previous Studies and the Proposed Architectural Spatial Integration Framework

Previous Study	Main Focus	Spatial Perspective	Main Contribution	Limitation	Contribution of This Study
Kothari et al. (2010)	Waste-to-Energy technology	None	Energy recovery	No architectural integration	Introducing spatial integration into WtE facility design
Lisbona et al. (2023)	Sustainable waste management	Limited	Circular waste management	Focus on operational system	Integrates operational and spatial systems
Reisinger et al. (2022)	Industrial building	Industrial spatial organization	Industrial flexibility	No educational integration	Connects industrial and educational spaces
Cole (2014)	Environmental education	Learning environment	Educational architecture	No industrial process	Integrates learning into industrial facilities
Bradecki et al. (2024)	Educational space	Spatial learning	User experience	No WtE context	Learning through industrial spatial sequence
Medaković et al. (2024)	Spatial integration	Spatial configuration	Spatial connectivity	No sustainable waste facility	Applies spatial integration to Waste-to-Energy architecture

Source: Authors' Analysis, 2026, Source: synthesized from References [5], [6], [10], [17], [20], [22].

Scientific Contribution and Practical Implication

The principal scientific contribution of this research lies in the development of the Architectural Spatial Integration Framework, which extends current discourse on industrial architecture by positioning spatial organization as the primary mechanism for integrating operational systems, environmental performance, and educational functions within a single architectural model. Previous studies on Waste-to-Energy have demonstrated the importance of technological optimization and energy recovery in supporting sustainable waste management [5]-[7], while research in Industrial Building Design has emphasized flexibility, functional efficiency, and the integration of structural and industrial systems [14], [9], [10], [11], [15]. In parallel, studies concerning Environmental Education Facilities have established that architectural space can actively facilitate environmental learning through spatial experience, visual interaction, and user engagement [17], [18]-[21]. Nevertheless, these domains have largely evolved independently, resulting in the absence of an architectural framework capable of systematically connecting industrial processes, educational activities, and sustainable environmental strategies. By integrating Spatial Organization, Functional Integration, Environmental Integration, and Architectural Integration within a unified conceptual structure, the proposed framework broadens the theoretical scope of industrial architecture from an operationally driven building typology toward an integrated spatial system that simultaneously supports production efficiency, environmental performance, and learning experiences. This contribution also expands the application of spatial integration concepts beyond museums and educational buildings to the context of sustainable waste management facilities, where industrial operations become part of the educational narrative rather than remaining isolated technical processes [22], [24].

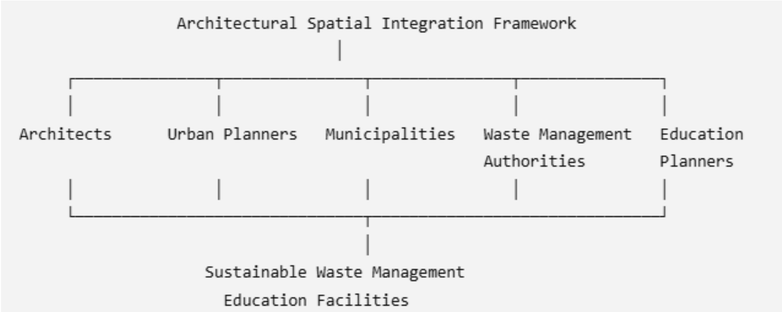

Fig. 6. Scientific Contribution and Practical Application of the Architectural Spatial Integration Framework

From a practical perspective, the proposed framework provides a transferable design reference that can support multidisciplinary decision-making throughout the planning and design process of Sustainable Waste Management Education Facilities. For architects, the framework offers a systematic basis for translating industrial requirements into coherent spatial configurations that integrate operational efficiency with educational functions. For urban planners and municipal governments, it provides spatial principles that can guide the planning of waste management infrastructure as part of sustainable urban development policies, complementing current policy directions that encourage integrated and circular waste management systems [1]-[4], [8]. Waste management authorities may utilize the framework to organize operational flows, visitor circulation, and environmental mitigation strategies within a single spatial system, while education planners can employ the educational components of the framework to develop learning environments that promote environmental awareness through direct interaction with industrial processes rather than relying solely on classroom-based instruction. Consequently, the framework functions not merely as a conceptual design model but also as an interdisciplinary planning instrument that connects architectural design, industrial operation, environmental education, and sustainable waste governance through an integrated spatial approach, thereby providing a practical foundation for future Waste-to-Energy facility development in diverse urban contexts.

IV. CONCLUSION

This study developed an Architectural Spatial Integration Framework that systematically integrates Waste-to-Energy operations, Industrial Building Design principles, Environmental Education Facilities, and Sustainable Waste Management strategies into a unified architectural model for Sustainable Waste Management Education Facilities. Unlike previous studies that primarily examined these domains independently, the proposed framework positions Architectural Spatial Integration as the principal design mechanism linking operational systems, educational functions, environmental strategies, and architectural expression within a coherent spatial organization. The framework is structured through four interrelated components, namely Spatial Organization Integration, Functional Integration, Environmental Integration, and Architectural Integration, which are subsequently translated into spatial design parameters and implemented through an architectural model incorporating hierarchical zoning, integrated circulation systems, passive environmental strategies, educational corridors, observation spaces, and environmentally responsive architectural elements. These findings demonstrate that spatial organization extends beyond functional arrangement to become an active architectural medium through which industrial processes, environmental learning, and sustainability objectives are simultaneously achieved

The principal contribution of this research lies in expanding the theoretical discourse of industrial architecture by introducing a transferable framework that systematically connects industrial production, environmental education, and sustainable waste management through architectural spatial integration. The proposed framework provides an interdisciplinary reference for architects, planners, municipalities, waste management authorities, and education planners in developing future Waste-to-Energy facilities that function not only as industrial infrastructure but also as educational environments supporting sustainable urban development. Because the present study develops a conceptual framework rather than evaluating an implemented facility, future research should validate the framework through empirical case studies, post-occupancy evaluations, user behavior analysis, and comparative applications across different geographical, technological, and socio-cultural contexts. Such investigations would enable further refinement of the framework and strengthen its applicability as a design decision-support model for sustainable industrial architecture.

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