Multi-Sector Strategic Partnerships for Sustainable Waste-to-Energy Solutions: Addressing Environmental, Economic, and Social Impacts in Thailand

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***Abstract*—Identifying suitable partners is crucial as countries increasingly rely on Waste-to-Energy (WtE) solutions, particularly incineration technology, for effective waste management. This investigation aims to identify the optimal investment partner for WtE projects intended to remediate municipal solid waste for Local Administrative Organizations in northeastern Thailand. When assessing potential WtE partners, considering economically viable energy sources and protecting public health and the environment are essential. Integrating energy systems with efficient waste management is imperative in regions facing significant waste challenges to achieve sustainability. To address the complexity of selecting a suitable WtE partner, a model using the Fuzzy Analytic Hierarchy Process (FAHP) was devised with waste management specialists. This approach evaluates partners based on financial stability, technical proficiency, environmental impact, contributions to sustainability, and alignment with energy policy objectives. Implementing FAHP ensures a data-driven, equitable decision-making process that considers both economic and environmental factors. Results show Firm A as the most advantageous, followed by Firm C; Firm B is least preferable. Sensitivity analysis verified these findings, enhancing evaluation robustness. This study emphasizes WtE partnerships' role in mitigating waste, generating sustainable energy, and reducing reliance on non-renewable resources. It underscores the need for commercial and governmental collaboration to achieve energy objectives in regional and national plans. By providing a reproducible model for partner selection in energy initiatives, particularly waste management through incineration, this innovative approach contributes to environmental engineering. Insights from this study may influence similar initiatives elsewhere, promoting a more environmentally sustainable energy future.**

***Keywords*—Waste-to-Energy (WtE), sustainable waste management, Fuzzy Analytic Hierarchy Process (FAHP), renewable energy, resource management, environmental engineering**

I. Introduction

The management of Municipal Solid Waste (MSW) has emerged as a critical challenge in the context of rapid urbanization and growing global populations. This issue is particularly pronounced in developing regions, where sustainable waste management and energy security are pressing concerns. Simultaneously, the demand for renewable energy sources is increasing, driven by the need to reduce reliance on fossil fuels and mitigate climate change. Solid Waste-to-Energy (WtE) technologies present a promising solution that addresses both energy production and waste management, contributing to environmental sustainability and resource management. Among these technologies, incineration stands out as a widely adopted clean technology for reducing waste volumes and generating energy, especially in regions with limited land availability [1].

Thailand was selected as the focus point of this study because of its significant issues in managing municipal solid waste (MSW), especially in fast urbanizing regions such as the northeastern area. The country confronts significant challenges due to trash output rates beyond the capacity of current disposal systems, resulting in environmental deterioration, public health hazards, and an increasing demand for renewable energy integration. The scarcity of landfill capacity, along with the substantial amount of organic waste in the waste stream, highlights the pressing need for innovative and sustainable solutions. These circumstances provide Thailand an exemplary case for examining the adoption of Waste-to-Energy (WtE) technologies, which simultaneously tackle waste management and energy security requirements.

Moreover, Thailand's policy environment offers a conducive framework for the advancement of WtE initiatives. The Alternative Energy Development Plan (AEDP) advocates for renewable energy technologies, including Waste-to-Energy (WtE), within the national energy framework, whereas the National Solid Waste Management Master Plan emphasizes sustainable waste management methods to mitigate environmental and public health repercussions. These policies correspond with the objectives of this study, guaranteeing that the suggested framework is both contextually pertinent and pragmatically applicable. This study concentrates on Thailand, addressing the nation's particular concerns while offering insights and models applicable to other emerging nations encountering analogous issues.

The emphasis on Thailand is pertinent because of the nation's persistent difficulties in managing municipal solid Waste (MSW), especially in swiftly urbanizing areas. The northeastern region of Thailand, the focus of this study, is experiencing increasing trash creation rates that beyond the capacity of current disposal facilities. This scenario highlights the pressing necessity for creative waste management strategies, including Waste-to-Energy (WtE) initiatives, which not only facilitate waste reduction but also advance renewable energy goals.

The policy environment of Thailand further underscores the importance of this study. The Alternative Energy Development Plan (AEDP) advocates for the incorporation of renewable energy technologies, such as Waste-to-Energy (WtE), into the national energy portfolio. The National Solid Waste Management Master Plan concurrently emphasizes sustainable waste management strategies to mitigate environmental and public health effects. This study guarantees the practical application and contextual relevance of the proposed framework by connecting it with these policies. Moreover, the findings from this research can act as a framework for tackling analogous waste management and energy issues in other developing areas, underscoring its wider significance.

In the northeastern region of Thailand, Local Administrative Organizations face escalating levels of solid waste, necessitating sustainable management solutions to promote sustainable cities and environmental health (Fig. 1). Incineration has emerged as a viable alternative for managing large volumes of mixed waste due to its ability to generate electricity and heat while reducing waste bulk by up to 90%. Technological advancements and stricter environmental regulations have significantly enhanced the environmental performance of incineration, addressing concerns related to emissions and pollution. Despite challenges such as high capital and operational costs, incineration offers an effective substitute for conventional landfilling, which often leads to substantial greenhouse gas emissions and other environmental impacts.

Nonetheless, mitigating the dangers linked to incineration is essential for its effective execution. Potential emissions, such as particulate matter, dioxins, and furans, necessitate advanced air pollution control technology to assure adherence to environmental rules and safeguard public health. Moreover, the management of leftover ash, especially fly ash containing hazardous substances, necessitates secure disposal methods or novel reuse strategies, such as integrating ash into construction materials. By reconciling these issues with its considerable advantages, incineration continues to be an essential technology for areas pursuing sustainable waste management solutions.

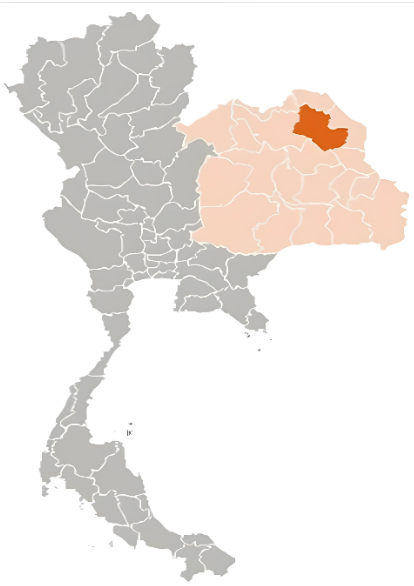

Fig. 1. Local Administrative Organization in the northeast region of Thailand.

However, the successful implementation of incineration technology hinges on the selection of appropriate investment partners, as these initiatives require substantial financial and technical resources. There exists a research gap in developing structured, data-driven frameworks for partner selection in WtE initiatives, particularly in emerging markets like northeastern Thailand. While numerous studies have explored the technical aspects of WtE technologies, few have incorporated comprehensive partner selection processes tailored to regions with unique energy and waste management needs, emphasizing the importance of an environmental systems approach.

This paper aims to address this gap by providing a framework for selecting suitable investment partners for implementing solid waste-to-energy incineration technology within Local Administrative Organizations. The framework is based on the Fuzzy Analytic Hierarchy Process (FAHP), an advanced decision-making methodology that aligns with integrated ecosystems management principles. This method meticulously evaluates potential partners based on critical criteria such as financial capacity, technological expertise, environmental impact, contributions to energy efficiency and sustainability, and alignment with regional energy and environmental policies. Incineration was chosen as the preferred WtE technology for this case study due to its effectiveness in managing MSW and its potential to contribute to Thailand's renewable energy objectives.

This study corresponds with policy frameworks including Thailand's Alternative Energy Development Plan (AEDP) and the National Solid waste Management Master Plan, highlighting its significance to national renewable energy and waste disposal initiatives. Global standards, such as those from the United Nations Environment Programme (UNEP) and the International Energy Agency (IEA), are also taken into account, offering an international viewpoint on optimal practices for Waste-to-Energy (WtE) initiatives. Integrating these policies and guidelines guarantees that the framework aligns with both local and global environmental goals.

The primary contribution of this study is the development of a structured, replicable model for collaborator selection in WtE initiatives using FAHP, reflecting an environmental systems approach. This methodology offers a transparent and equitable means of assessing potential partners, addressing the unique challenges faced by regions like northeastern Thailand, where energy generation and waste management are critical issues. By introducing this systematic decision-making framework, the research contributes to the broader literature on renewable energy, environmental sustainability, and clean technologies. It provides practical insights for policymakers and stakeholders involved in WtE initiatives worldwide, promoting sustainable resource management and the development of sustainable cities.

The following is the paper's structure: The literature reviews and criteria for partner selection in the WtE project are discussed in Sections II and III, which provide literature evaluations and an overview of waste-to-energy projects, with a particular focus on incineration. Section IV details the methodology employed to assess potential collaborators and introduces the FAHP. Section V summarizes the findings of the partner evaluation for the Local Administrative Organization case study and explores the potential applications of the framework in other regions. A summary of the main findings, contributions, and recommendations for future research is provided in Section VI, which concludes the paper.

II. Literature Review

Municipal solid waste management continues to be a significant obstacle in numerous urban areas, particularly those that are experiencing accelerated growth. The increased population and urbanization have led to a significant increase in waste generation, which has necessitated the implementation of effective waste management strategies. Waste-to-Energy (WtE) initiatives have acquired significant momentum as a sustainable solution for the concomitant generation of energy and the management of Municipal Solid Waste (MSW). The integration of WtE technologies into waste management systems provides a dual benefit: the production of renewable energy and the reduction of landfill dependence. The significance of strategic partnerships in the successful implementation of WtE initiatives has been emphasized in a multitude of studies.

Waste-to-Energy (WtE) technologies have emerged as viable solutions for the management of Municipal Solid Waste (MSW) and the generation of renewable energy as a result of the global escalation in population and waste generation. The economic benefits of various WtE scenarios at the Rajbandh open dumpsite in Khulna are evaluated by Mondal and Rafizul [2]. The study reveals that mass-burn incineration has the highest electricity generation capacity (207,799.73 MWh/year) and the greatest Net Present Value (NPV) of approximately 41.378 million USD. Their results underscore the potential of WtE to substantially reduce greenhouse gas emissions while simultaneously optimizing energy recovery from waste.

Emara *et al.* [3] make a significant contribution to this discipline by developing novel methodologies for characterization of MSW in Egypt, with an emphasis on organic content. Their research illustrates that seasonal fluctuations have a substantial impact on the calorific values and composition of waste, emphasizing the importance of precise waste characterization in order to optimize WtE conversion processes. These methodologies are indispensable for augmenting the energy recovery potential of developing nations. In Bangladesh, Rahman *et al.* [4] Compare Hydrothermal Carbonization (HTC) with traditional landfilling in order to further expand the discourse on sustainable waste management. Their life cycle assessment demonstrates that HTC's viability as an alternative to conventional MSW disposal methods is demonstrated by the substantial reduction of climate change impacts and other environmental hazards that HTC achieves when combined with energy generation.

In Brazil, Gonçalves Mollica *et al.* [5] demonstrate an integrated urban waste management model that integrates a variety of energy generation technologies. They conclude that gasification offers substantial economic advantages, particularly for larger facilities. The results of their study suggest that the integration of multiple WtE technologies can improve the overall efficiency and financial viability, particularly when combined with waste-collecting levies. De La Cruz and Bernal [6] conduct an analysis of WTE initiatives in the National Capital Region of the Philippines, emphasizing the substantial processing costs relative to conventional landfilling. The potential land savings and sustainable energy production benefits in densely populated urban areas are emphasized, and they advocate for policy interventions, such as subsidies, to make WtE projects economically competitive.

Oliveira *et al.* [7] investigate sustainability indicators for MSW treatment processes, demonstrating that incineration and gasification encounter economic feasibility challenges despite their environmental advantages. Their research emphasizes the necessity of a nuanced approach to the selection of WtE projects, which should include both economic viability and sustainability indicators. Farooq *et al.* [8] conduct an economic feasibility assessment of a variety of WtE technologies in Thailand, identifying anaerobic digestion as the most economically viable option. According to their analysis, the alignment of WtE initiatives with national sustainable energy objectives is crucial for long-term success, suggesting that there is a substantial potential for positive socio-economic outcomes.

The evaluation of WtE projects has become increasingly prevalent due to the integration of Multi-Criteria Decision-Making (MCDM) methods, particularly the Fuzzy Analytic Hierarchy Process (FAHP). In Cape Town, Alao *et al.* [9] employ a hybrid FAHP model to determine the most sustainable WtE technology, concluding that anaerobic digestion is the most viable option. Their research underscores the effectiveness of FAHP in capturing both subjective and objective evaluations during the decision-making process. Chattopadhyay *et al.* [10] underscore the significance of selecting appropriate indicators for effective decision-making by utilizing FAHP to evaluate centralized versus decentralized MSW management facilities in India. Their results substantiate the utilization of FAHP as a reliable instrument for traversing the intricacies of facility selection in integrated municipal solid waste management systems.

Basha *et al.* [11] demonstrate the applicability of fuzzy logic in augmenting decision-making processes related to waste management by combining FAHP with GIS techniques to identify suitable sites for WtE plants in urban areas. Their findings facilitate improved planning and site selection, thereby mitigating adverse environmental consequences. Ilbahar *et al.* [12] employ a modified Fuzzy SCEA approach to investigate risk assessment in WtE facilities, identifying critical risks such as equipment malfunctions and inappropriate waste storage. Their results underscore the significance of prioritizing risks as determined by expert judgments, thereby enhancing the operational reliability and safety of WtE facilities.

A hybrid fuzzy decision-making approach for the site selection of WtE facilities in Turkey is discussed by Albayrak [13]. This approach incorporates a variety of criteria from the political, social, technological, and economic perspectives. The investigation introduces a novel methodology that underscores the significance of effective decision-making tools and the intricacy of municipal solid waste management. Suvitha *et al.* [14] concentrate on the packaging sector's contribution to overall waste generation, emphasizing the importance of an optimal plastic waste management system that is based on an enhanced MCDM technique. Their discoveries provide valuable insights into the selection of effective waste collection technologies in uncertain environments.

Aghad *et al.* [15] emphasize the importance of geographic information systems in waste management decisions by integrating fuzzy-AHP and GIS for the selection of solid waste disposal sites in Kenitra province, Morocco. Their methodology enhances the selection of sites, thereby making a positive impact on environmental outcomes. Recent research suggests that there is an increasing interest in the economic and environmental implications of WtE technologies. Kop *et al.* [16] concentrate on the recovery methods for end-of-life tires in Turkey, employing a fuzzy extended AHP approach to ascertain the most appropriate recovery methods. This illustrates the adaptability of MCDM techniques in a variety of waste contexts.

Christensen and Bach [17] emphasize the Danish-Vietnamese partnership as a paradigm for collaboration in the improvement of waste management systems. Their research demonstrates the distinct challenges that developing countries encounter in the implementation of effective waste management solutions, as well as the potential for partnerships to facilitate technology transfer and innovation. In their analysis of incineration as a sustainable waste management solution in Kuwait, AlMokmesh *et al.* [18] underscore its significance in the conversion of municipal solid waste (MSW) into electricity and the reduction of landfill usage. Their discoveries emphasize the necessity of customized waste management strategies that prioritize public health and sustainability.

Suvitha *et al.* [19] investigate an optimal plastic waste management system that is predicated on improved MCDM techniques. This system prioritizes successful segregation to facilitate efficient recycling and facilitates the transition to a circular economy. Finally, Aghad *et al.* [20] demonstrate the practicality of advanced decision-making frameworks in the optimization of waste management strategies by combining fuzzy-AHP with GIS techniques for the selection of solid waste disposal sites in Kenitra province.

This literature demonstrates a thorough comprehension of WtE technologies and their potential to generate renewable energy while managing municipal solid waste. The economic and environmental assessments emphasize the significance of strategic decision-making frameworks such as FAHP, which improve the partner selection process in WtE initiatives. To ensure the successful implementation of sustainable waste management practices on a global scale, it will be essential to address the economic challenges and optimize decision-making methodologies as research continues to progress.

III. Waste-to-Energy Incineration Project

The Local Administrative Organization (LAO) in the northeastern region of Thailand encompasses twenty districts that are experiencing rapid urbanization and population growth. This expansion has led to the generation of approximately 1,500 tons of municipal solid waste (MSW) per day, posing significant challenges for resource management and environmental sustainability. Many local entities have relied on unregulated trench excavating and open-air disposal methods, resulting in adverse environmental impacts and public health concerns. The absence of sustainable waste management procedures has resulted in heightened environmental degradation, underscoring the necessity for new solutions. In response to these urgent issues, the LAO has signed a memorandum with 43 sub-local administrative organizations across all districts to collaborate on sustainable waste management strategies, administering a centralized waste disposal facility.

Currently, this facility processes about 500 tons of waste daily but struggles to manage the cumulative accumulation of residual waste, which exceeds 450,000 tons. This excessive volume strains the existing disposal system, highlighting the need for innovative clean technologies to enhance waste processing capabilities. Notably, organic waste constitutes the largest portion of the waste stream, surpassing other categories like paper, plastics, glass, and metal (Fig. 2). The significant amount of organic waste offers a chance for solutions centered on biodegradable material processing, which can bolster local sustainability efforts and renewable energy generation. The predominance of organic waste underscores the necessity for waste management solutions that can handle biodegradable materials efficiently, contributing to the development of sustainable cities.

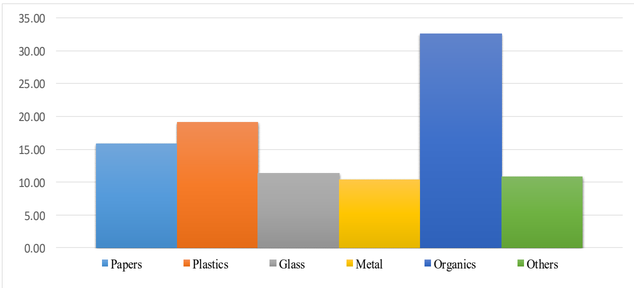

Fig. 2. Types of waste in the local administrative organization in the northeast region of Thailand.

This study concentrates on incineration, recognized for its effectiveness in handling substantial quantities of mixed Municipal Solid Waste (MSW) and producing energy; however, various Waste-to-Energy (WtE) technologies offer feasible alternatives, each possessing distinct benefits and drawbacks. Anaerobic digestion is especially appropriate for waste streams rich in organic material, such as food and agricultural waste. This method transforms biodegradable garbage into biogas, a renewable energy source, and digestate, an organic fertilizer. In comparison to incineration, anaerobic digestion is more environmentally sustainable for organic waste management, generating reduced emissions and facilitating nutrient recovery.

Gasification is a promising waste-to-energy technique that converts non-recyclable and heterogeneous trash into syngas, a versatile energy carrier. Gasification presents numerous environmental benefits compared to conventional incineration, notably reduced emissions of dioxins and furans, attributable to its regulated working conditions. Furthermore, the by-products of gasification, including slag, tend to be more inert and manageable than the ash produced by incineration. Gasification necessitates uniform feedstock quality and elevated initial investment expenditures, which may restrict its use in areas with diverse waste streams.

These comparative findings emphasize the necessity of matching technology choices with regional waste composition, policy priorities, and sustainability objectives.

Regions with substantial organic waste may derive greater advantages from anaerobic digestion, whereas areas with restricted land availability and rigorous emission laws may prefer gasification or incineration employing modern emission control systems. By evaluating these alternatives in conjunction with incineration, decision-makers can customize WtE project designs to more effectively address local requirements, improve environmental outcomes, and conform to global sustainability goals.

The use of sophisticated emission control systems is essential for ensuring that Waste-to-Energy (WtE) projects adhere to environmental requirements and reduce their impact. Technologies such as Continuous Emissions Monitoring Systems (CEMS) and Selective Catalytic Reduction (SCR) are helpful in mitigating detrimental emissions, including particulate matter and nitrogen oxides. Moreover, scrubber systems and filters facilitate the elimination of acid gases and fine particles, enhancing air quality and assuring adherence to environmental regulations.

By using these technologies, WtE facilities can markedly diminish emissions and conform to international sustainability criteria. These approaches not only improve the environmental efficacy of incineration but also foster public trust and acceptance, hence reinforcing the overall sustainability of Waste-to-Energy operations. This integration strengthens the study's focus on sustainable waste management and renewable energy alternatives.

This study evaluates relationships across several sectors, including government agencies, business organizations, and Non-Governmental Organizations (NGOs), to guarantee a comprehensive and inclusive approach to Waste-to-Energy (WtE) project execution. Government entities are essential in establishing regulatory frameworks, integrating projects with regional policies, and guaranteeing adherence to environmental standards. The private sector provides technical experience, innovative technologies, and financial resources critical for the success of large-scale waste-to-energy operations. Moreover, NGOs and community-based groups provide essential insights into local requirements, promote community involvement, and foster public trust and acceptance.

This multi-sector collaboration guarantees that the suggested framework adeptly tackles the intricate issues of WtE projects by utilizing the assets of many stakeholders. The integration of private sector efficiency with public sector oversight guarantees operational effectiveness and compliance with environmental goals. Incorporating NGOs and other community leaders enhances the social aspect of sustainability, guaranteeing that initiatives are equitable and inclusive. This comprehensive partnership approach improves the scalability and replicability of the framework, rendering it adaptable to various socio-economic and policy environments.

The relationships formed for this study are directly linked to the execution of Waste-to-Energy (WtE) projects, tackling urgent issues in waste management and renewable energy production. These collaborations aim to guarantee that WtE projects directly reduce municipal solid waste (MSW) while producing power, so conforming to Thailand's national energy and environmental policies. The agreements concentrate on incineration technology to provide prompt solutions for trash reduction and energy security in areas experiencing increased waste production and restricted landfill availability.

In addition to these immediate objectives, the collaborations correspond with overarching sustainable development efforts. These encompass diminishing greenhouse gas emissions, promoting community involvement, and improving local resource management. By incorporating environmental, economic, and social factors into the WtE framework, these collaborations guarantee conformity with Thailand's Alternative Energy Development Plan (AEDP) and the National Solid Waste Management Master Plan. Furthermore, the collaborations foster community-oriented results, including enhanced waste management techniques, job development, and educational programs on sustainability. This dual emphasis highlights the enduring dedication of these partnerships to sustainable urban development and environmental resilience.

To address these pressing challenges, the LAO is exploring sustainable waste management solutions that align with an environmental systems approach. The proposed strategy involves implementing an efficient direct combustion system to convert community waste into electricity within a closed-loop system. This WtE method aims to manage effluents effectively and minimize air pollution, thereby reducing the environmental impact of waste disposal. Recognizing the urgency for this transition, local authorities are committed to improving waste management practices to better handle the increasing waste volume and contribute to renewable energy generation.

Although incineration provides significant advantages, including a reduction in waste volume by up to 90% and the production of renewable energy, it also entails certain dangers that necessitate meticulous control. Emissions from incineration, such as particulate matter, dioxins, and furans, provide significant environmental and health risks. To alleviate these hazards, the project incorporates sophisticated air pollution control technology, such as Continuous Emissions Monitoring Systems, to guarantee adherence to rigorous air quality regulations. Likewise, the management of bottom and fly ash, potentially containing hazardous elements, necessitates secure disposal methods and, when feasible, the recycling of ash for incorporation into construction materials. These strategies reduce environmental and public health risks while optimizing the project's sustainability.

The congruence of Waste-to-Energy (WtE) projects with regional energy and environmental policies is essential for their effective execution and enduring viability. These regulations significantly impact essential elements of project development, such as design, partner selection, and operational frameworks. Waste management rules delineate the permissible technological standards for such projects, whereas energy policies—such as renewable energy quotas and feed-in tariffs—are crucial in assessing their economic feasibility.

Compliance with air quality requirements and the execution of thorough environmental impact assessments (EIAs) are essential for obtaining project clearances and enhancing public trust. Furthermore, linking Waste-to-Energy (WtE) programs with Thailand's Alternative Energy

Development Plan (AEDP) guarantees their significant contribution to the attainment of national renewable energy goals. This alignment not only tackles the urgent issues of waste management but also integrates the projects into a wider policy framework, promoting sustainable development and enhancing both environmental and economic resilience.

By addressing both the benefits and risks of incineration, the proposed WtE strategy ensures a balanced approach to tackling northeastern Thailand's waste management challenges. This thorough evaluation reinforces the project's conformity with environmental and energy goals, improving its viability and acceptance among stakeholders and the community.

The Ministry of the Interior has evaluated a proposal for a WtE initiative at the LAO, integrating incineration technology capable of processing 500 tons of waste daily. This technology is expected to generate up to 20 MW of electricity, with 5 MW available for sale to the grid, supporting energy conservation objectives and reducing reliance on non-renewable energy sources. The initiative anticipates a gratuity fee of 500 baht per ton, with a projected 30% increase every three years, making the project economically viable over a 25-year period, which includes 5 years for construction and 20 years for operation. This financial model highlights the long-term viability of the project while ensuring economic incentives for private investors. The total investment required is estimated at 15 billion baht. By involving the private sector, the LAO aims to attract private investment for the WtE project to ensure compliance with legal standards and promote environmentally friendly practices.

To enhance transparency and competitiveness in partner selection, the initiative plans to implement an electronic procurement process, utilizing 100% private investment to produce a power capacity of 9.9 MW. This approach aligns with integrated ecosystems management by considering economic, environmental, and social factors in the decision-making process. The Fuzzy Analytic Hierarchy Process (FAHP) will be employed to comprehensively assess potential collaborators based on criteria such as alignment with regional policies, financial capacity, technical expertise in clean technologies, and environmental impact. By integrating FAHP, the project ensures an equitable, data-driven approach to partner selection, aligning with sustainable development goals. This environmental systems approach ensures that the selected partner is well-equipped to support the municipality's objectives of sustainable waste management and renewable energy generation.

By adopting this structured methodology, the LAO enables informed decision-making that contributes to the development of sustainable cities and promotes a greener environment in the region. The initiative represents a crucial step toward improving waste management practices, enhancing resource management, and integrating renewable energy solutions. Ultimately, this project aims to mitigate environmental challenges associated with waste accumulation, reduce greenhouse gas emissions, and advance the region's progress toward sustainability goals.

IV. RELATED METHODS

In addressing the complex challenges associated with selecting suitable partners for solid waste-to-energy (WtE) projects, it is essential to employ systematic and robust methodologies that facilitate informed decision-making. The selection process involves multiple criteria that often conflict, necessitating a structured approach to evaluate and prioritize options effectively. Various decision-making methodologies have been developed to address these complexities, among which Multi-Criteria Decision Making (MCDM) techniques have gained prominence.

MCDM provides a comprehensive framework for evaluating alternatives based on multiple criteria, enabling stakeholders to consider various factors simultaneously. This approach is particularly beneficial in scenarios where decisions must balance economic, environmental, and social dimensions. The flexibility of MCDM methodologies allows for the incorporation of both qualitative and quantitative assessments, providing a holistic view of the alternatives.

One of the most widely used MCDM methods is the Analytic Hierarchy Process (AHP), which facilitates structured decision-making by breaking down complex problems into simpler components organized in a hierarchical structure. However, traditional AHP may struggle to address the uncertainty and imprecision often encountered in expert evaluations. To overcome these limitations, the Fuzzy Analytic Hierarchy Process (FAHP) has emerged as an effective enhancement of AHP, integrating fuzzy logic to better capture the nuances of expert judgment and subjective preferences.

FAHP enables decision-makers to express their assessments using linguistic terms, which are then converted into fuzzy numbers. This approach not only accommodates uncertainty but also enhances the reliability and validity of the decision-making process. By leveraging the strengths of MCDM and FAHP, this research aims to develop a structured and replicable model for selecting suitable investment partners for implementing solid waste-to-energy incineration technology.

This study employed both primary and secondary data sources to establish a thorough and data-driven evaluation methodology. Primary data were gathered via structured interviews and surveys administered to 20 key stakeholders, comprising representatives from local government agencies, private sector firms specializing in waste management technologies, and Non-Governmental Organizations (NGOs) engaged in community involvement and environmental advocacy. The respondents were chosen for their experience in technical feasibility, financial management, and community relations, assuring equitable representation across essential domains of Waste-to-Energy (WtE) project execution.

Secondary data were sourced from official publications, environmental impact assessments, policy papers including Thailand's Alternative Energy Development Plan (AEDP) and the National Solid Waste Management Master Plan, as well as peer-reviewed scholarly literature. These sources offered significant insights into the legal environment, technological innovations, and global best practices pertinent to WtE initiatives.

The Fuzzy Analytic Hierarchy Process (FAHP) approach was utilized to rank criteria and sub-criteria for assessing possible investment partners. Expert assessments were employed to allocate weights, and these inputs were corroborated through subsequent interviews and cross-verified with documented case studies of WtE initiatives in analogous circumstances. This methodology guaranteed uniformity and dependability in the decision-making framework.

The application of the FAHP paradigm to different contexts is affected by regional disparities in waste composition, regulatory frameworks, socio-economic conditions, and stakeholder demands. Regions with a significant amount of organic waste may prioritize anaerobic digestion technology, while those with constrained territory and elevated non-biodegradable waste levels may consider incineration more appropriate. Moreover, legislative frameworks, like more stringent air quality regulations or subsidies for renewable energy, could profoundly influence the choice of Waste-to-Energy (WtE) technologies and the criteria for assessing prospective investment partners.

Moreover, public acceptance of waste-to-energy initiatives differs by geography and cultural environment. Areas exhibiting significant community opposition to incineration may necessitate an increased focus on public involvement and educational programs to ascertain project viability. The FAHP framework can include these geographical variations by adjusting the weightings of criteria and including other context-specific elements, such as localized stakeholder feedback, regulatory assessments, and waste characterization.

To improve the framework's adaptability, subsequent study might incorporate case studies from various geographical regions to assess how these aspects influence the decision-making process. This iterative process would enable the FAHP methodology to develop into a more adaptable and generally applicable instrument, capable of tackling various issues and priorities in WtE project execution. By incorporating regional variations, the framework guarantees its pertinence and efficacy across diverse socio-economic and environmental environments.

In the following sections, we will explore the principles and applications of MCDM, with a particular focus on FAHP, and detail the methodology employed in this study for evaluating potential partners. This examination will provide the necessary context for understanding how these methods contribute to effective decision-making in the realm of waste management and renewable energy.

A. Multi-criteria Decision Making (MCDM)

Multi-Criteria Decision Making (MCDM) has emerged as a potent strategy in the context of complex decision-making scenarios, particularly in the context of energy production and waste management. MCDM offers a structured framework for the assessment of multiple conflicting criteria, allowing decision-makers to consider a variety of factors and reach a fair conclusion. This methodology is especially pertinent in environments that are marked by subjectivity and uncertainty, necessitating the integration of qualitative evaluations with quantitative data.

The implementation of MCDM in waste-to-energy initiatives enables stakeholders to conduct a comprehensive evaluation of potential partners on a variety of criteria, including financial stability, technological proficiency, environmental impact, and compliance with local policies. MCDM provides a robust mechanism to navigate the trade-offs implicit in selecting the most appropriate investment partners, given the intricate character of these projects.

The Fuzzy Analytic Hierarchy Process (FAHP) has garnered substantial attention among the diverse MCDM techniques because of its capacity to manage uncertainty and imprecision during the decision-making process. The traditional Analytic Hierarchy Process (AHP) is expanded by the FAHP, which incorporates fuzzy logic, enabling decision-makers to express their preferences and judgments in a more flexible manner. This is especially advantageous in situations where the subtleties of expert opinions may not be effectively captured by precise numerical values.

FAHP initially organizes the decision problem into a hierarchy, identifying pertinent criteria and sub-criteria for the selection process. Decision-makers subsequently conduct pairwise comparisons of alternatives using linguistic variables, which are subsequently transformed into fuzzy numbers. By addressing the inherent uncertainties associated with expert judgments, this approach not only facilitates a more exhaustive evaluation of potential collaborators but also improves the reliability of the decision-making process.

The FAHP methodology will be implemented in this study to assess and identify appropriate investment partners for the implementation of solid waste-to-energy incineration technology in the LAO of the northeast region of Thailand. This research endeavors to establish a structured and systematic framework that addresses the distinctive challenges of energy generation and waste management in the region by capitalizing on the strengths of MCDM and FAHP.

B. Fuzzy Analytic Hierarchy Process (Fuzzy AHP)

In the context of multi-criteria decision-making (MCDM), the Fuzzy Analytic Hierarchy Process (FAHP) is a robust methodology that is capable of managing the inherent uncertainties and complexities that are frequently encountered when evaluating firm performance across economic and environmental dimensions. FAHP enhances the traditional Analytic Hierarchy Process (AHP) by incorporating fuzzy set theory, which allows decision-makers to more effectively communicate the imprecision and vagueness of their judgments. This is particularly advantageous when dealing with subjective assessments or qualitative criteria that are not precisely quantifiable.

In the context of this investigation, which is designed to identify the most sustainable regional development-oriented firms in Thailand, FAHP is indispensable. It is employed to prioritize firms according to their performance across a range of criteria, such as the qualifications of the proposal submitter, technical proposals, investment proposals, and pricing proposals that are advantageous to the government and community.

The incorporation of public acceptability as a vital element in the partner evaluation framework guarantees that the social aspects of Waste-to-Energy (WtE) projects are thoroughly considered. Community involvement and societal approval are essential for the effective execution of Waste-to-Energy projects, especially in areas where incinerator technologies face skepticism due to perceived health and environmental hazards. Partners will be assessed on their capacity to formulate and implement successful community involvement strategies, including conducting public discussions, delivering accurate information regarding project benefits and risks, and proactively resolving community concerns.

The framework includes criteria that evaluate the partner's strategies for informing the public about the environmental and economic advantages of WtE projects, together with their dedication to alleviating possible adverse effects. Proposals that incorporate initiatives to finance local environmental education programs or deliver immediate advantages to impacted communities, such as job creation or enhanced waste management services, will be prioritized. These initiatives not only boost public confidence and acceptability but also align with overarching sustainability objectives by promoting inclusive and equitable development.

Incorporating these social components into the FAHP model guarantees a comprehensive approach to partner selection, considering technical, environmental, economic, and social issues. This thorough methodology underpins the long-term viability and success of WtE initiatives, aligning them with community interests and facilitating their incorporation into sustainable urban development policies.

The FAHP process commences with the organization of the decision hierarchy, which facilitates and streamlines the evaluation of firms. In the fuzzy pairwise comparison process, decision-makers assess the relative significance of the primary criteria and sub-criteria by employing linguistic variables such as "much more important" or "slightly more important." The imprecise numbers that result from these linguistic judgments represent the degree of membership of each firm in relation to each criterion. This transformation facilitates the aggregation of fuzzy judgments by performing arithmetic operations on fuzzy numbers, resulting in comprehensive priority scores for each firm.

FAHP seamlessly incorporates qualitative and quantitative data, providing decision-makers with a comprehensive perspective on firm performance that includes both qualitative evaluations and concrete metrics. FAHP enhances the reliability and robustness of evaluations by capturing the nuances and uncertainties that are inherent in decision-making processes. This enables policymakers to make informed decisions that support sustainable and balanced regional development strategies.

The decision-making process is ensured to be effective and reliable by the implementation of several critical phases when FAHP is used to evaluate firms based on the identified criteria:

Structuring the Hierarchy: Organizing the criteria and sub-criteria for evaluation and establishing the decision hierarchy that defines sustainable regional development objectives.

Pairwise Comparisons: Employing pairwise comparisons to ascertain the significance of the criteria. Decision-makers assign linguistic variables to convey their preferences, and fuzzy numbers represent these linguistic judgments to quantify the degree of membership of each firm regarding each criterion.

Fuzzification Process: The process of converting linguistic variables into ambiguous numbers that represent the uncertainty of decision-making. This assessment employs imprecise numbers to calculate and aggregate the overall priority ratings of each firm across a variety of criteria.

Aggregation and Analysis: The calculation of firm priority scores using weighted averaging or fuzzy integrals, which are based on the fuzzy numbers generated for each criterion. This aggregation process combines a comprehensive understanding of the economic and environmental strengths and weaknesses of each firm.

Sensitivity Analysis: Conducting a sensitivity analysis to evaluate the robustness of FAHP findings. This analysis assesses the impact of modifications to input parameters on the final priorities designated to firms, thereby improving strategic policymaking and resource allocation.

The Fuzzy Analytic Hierarchy Process (FAHP), which integrates fuzzy logic with the Analytic Hierarchy Process (AHP), was created to manage ambiguous expert views using fuzzy numbers [21]. The criteria weights in this study were determined using the Fuzzy Analytic Hierarchy Process (FAHP). Fuzzy pairwise comparisons were performed utilizing Triangular Fuzzy Numbers (TFNs) to address uncertainty in decision-making. A TFN is defined by three parameters, $M_i = (m_{i1}, m_{i2}, m_{i3})$, $i \in \{1, 2, \cdots, n\}$, where $i \in \{1, 2, \cdots, n\}$. These parameters represent the minimum value, the most likely value, and the maximum value, respectively, defining the range of possible values for a fuzzy number. This approach effectively captures expert opinions when precise judgments are challenging to obtain.

Utilizing the extent analysis methodology, each item was assessed, and the extent for each objective, g_i, was determined. As a result, the m extent analysis results for each item were obtained as Eq. (1):

$$M_{g_i}^1, M_{g_i}^2, \cdots, M_{g_i}^m;\ i = 1, 2, \cdots, n \tag{1}$$

where $M_{gi}^{\,j} (j = 1, 2, \ldots, m)$ are triangular fuzzy numbers. The first is to generate merit of fuzzy synthetic extent (Eqs. (2) and (3)) in relation to the object, i, and then calculate the inverse of the vector in Eq. (4). The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as $V(M_2 \geq M_1) = \sup[\min(\mu_{M_1}(x), \mu_{M_2}(y)]$ which can be equally defined as Eq. (5).

To differentiate M_1 and M_2, it requires the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$. The degree of the possibility for a convex fuzzy number to be better than k convex fuzzy numbers, $M_i (i = 1, 2, \ldots, k)$, could be described as Eq. (6). The weights vector is calculated via Eq. (7). The normalized weight vectors were calculated by Eq. (8).

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \text{and} \tag{2}$$

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{3}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{4}$$

$$V(M_2 \geq M_1) = \begin{cases} 1 & \text{if } m_2 \geq m_1, \\ 0 & \text{if } l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{5}$$

$$V(M \geq M_1, M_2, \ldots, M_k) = \min V(M \geq M_i): i = 1, 2, \ldots, k \quad (6)$$

$$d(S_i) = \min V(S_i \geq S_k)\ k=1,2,\ldots,n;\ k \neq i \quad (7)$$

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \text{ and } W' = (d(S_1), d(S_2), \ldots, d(S_n))^T \quad (8)$$

C. Sensitivity Analysis (SA)

A statistical methodology known as Adjusted Mixture Design (AMD) combines both fundamental and advanced techniques, such as experimental design, statistical analysis, and optimization. Experimental design entails the meticulous execution of experiments to gather data on the efficacy of a variety of variable combinations. This approach is indispensable for the purpose of optimizing process parameters and comprehending the complex interrelations between various components and their intended results. Organizations can achieve their desired outcomes while adhering to established constraints by implementing these research findings to identify optimal combinations. It is an essential instrument for acquiring a deeper understanding of systems, particularly when utilizing restricted component proportions or determining the precise combination of elements [22].

Mixture design is a particular application of experimental design that is used to address circumstances in which the response is contingent upon the proportions of the mixture's components. In this context, the components of a mélange are used to represent the factors, and conventional design methods are frequently inappropriate. In mathematical terms, a q-component mixture can be described as the sum of proportions equal to one. The selection of the appropriate mixture design necessitates the consideration of a variety of factors, such as the number of interactions to be investigated, the complexity of the design, the statistical validity, the feasibility of implementation, and the associated costs.

The simplex-lattice design is a mixture design method that is frequently employed. It is characterized by its node configurations, which enable the evenly spaced proportions of components. This design allows practitioners to systematically evaluate a variety of compositions. The simplex-centroid design is an alternative that is employed when all components are within the same range and there are no design space limitations. A center-point run is incorporated into this method, which represents equal portions of all components.

The AMD methodology is divided into numerous stages. The process commences with the establishment of major and minor criteria weights, which is followed by the collection of data for the simplex-lattice or simplex-centroid mixture designs. Subsequently, modifications are implemented to accommodate constraints, and the weights of criteria are revised. The sensitivity analysis computes adjusted values for these weights, culminating in iterations that refine the weights of major and minor criteria. This structured approach not only optimizes mixtures but also guarantees that the chosen designs are in accordance with the specified requirements and outcomes.

V. RESULTS AND DISCUSSION

The evaluation criteria for the Waste-to-Energy (WtE) project are meticulously crafted to ensure a comprehensive assessment of proposals, reflecting essential factors that substantiate the qualifications and capabilities of candidates. The ultimate goal is to identify the most suitable partner for the project's successful implementation by assessing technical proposals, performance and experience, project location preparedness, and investment and pricing strategies that benefit both the government and the community (Table 1 and Fig. 3).

Table 1. Main criteria (MC) and subcriteria (SC) for evaluating WtE project partner

Main Criteria	Subcriteria	Description
MC_1: Environmental and Technical Qualifications	SC_1: Environmental Site Preparedness	Assesses the site's environmental suitability and readiness for sustainable operations.
	SC_2: Environmental Quality Certifications	Evaluates certifications related to environmental management and sustainability standards.
	SC_3: Experience in Sustainable Projects	Assesses prior experience with sustainable waste management and WtE projects.
MC_2: Sustainable Technology Proposals	SC_4: Sustainable Construction Management Plan	Requires plans that incorporate sustainable practices in construction and operation.
	SC_5: Innovative Sustainable Design	Involves submission of designs that enhance environmental performance.
	SC_6: Sustainable Operations and Maintenance Plan	Includes strategies for ongoing sustainable operations and maintenance.
	SC_7: Qualified Environmental Personnel Plan	Evaluates the qualifications of personnel in environmental and sustainability roles.
MC_3: Sustainable Investment and Financial Viability	SC_8: Investment in Renewable Technologies	Reviews investment proportions dedicated to renewable and clean technologies.
	SC_9: Financial Sustainability and Capital	Evaluates financial stability and commitment to sustainable investments.
	SC_10: Efficiency in Sustainable Investment Management	Assesses effective management of investments towards sustainability goals.
MC_4: Community Engagement and Environmental Impact	SC_11: Community Sustainable Waste Services	Evaluates the effectiveness of proposed sustainable waste services for the community.
	SC_12: Fair Waste Disposal Pricing	Considers proposals for waste disposal charges that encourage sustainable practices.
	SC_13: Stakeholder Environmental Engagement	Proposals regarding engagement with contractors and users in sustainability efforts.
	SC_14: Environmental Education and Relations Budget	Evaluates budgets for community education on environmental sustainability.

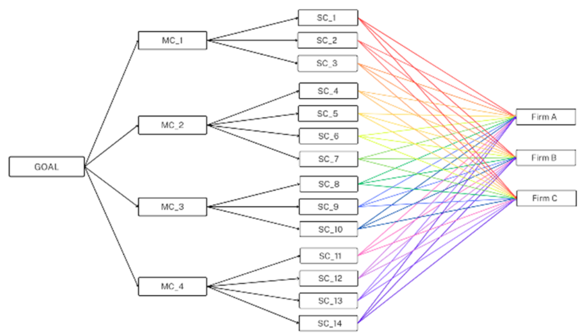

Fig. 3. Criteria for assessing investment partner for WtE incineration projects.

The first main criterion, environmental and technical qualifications, evaluates candidates' preparedness and capacity to adhere to the environmental and technical standards essential for WtE projects. Under Environmental Site Preparedness, bidders must demonstrate their ability to provide a comprehensive land-use plan outlining the site's intended use, supported by clear documentation substantiating ownership or access to the land. The availability of land title documents and proximity to existing waste disposal sites are critical factors ensuring proper project sanctioning and environmental suitability for sustainable operations. Additionally, bidders must address the availability of water resources for operational requirements and implement effective waste byproduct management strategies, such as ash handling, to guarantee adherence to environmental regulations and community standards.

Environmental quality certifications assess certifications pertaining to environmental management and sustainability standards. These certifications reflect the company's commitment to environmental stewardship and compliance with international standards, bolstering their ability to implement clean technologies and contribute to environmental sustainability. Experience in Sustainable Projects focuses on the bidders' history of operating waste incineration facilities, particularly those utilizing advanced technologies like Stoker incineration. Bidders are required to demonstrate their ability to effectively manage community waste systems by showcasing successful participation in sustainable waste management initiatives over the past decade. This reflects their operational capability and dedication to quality and safety, essential for a reliable partnership.

The second main criterion, Sustainable Technology Proposals, assesses technical proposals by emphasizing the importance of practical and environmentally conscious project designs that are clear and effective. The sustainable construction management plan mandates that candidates submit plans integrating sustainable practices into construction and operation phases, thereby reducing environmental impact during development. Innovative sustainable design requires the submission of designs that enhance environmental performance. Bidders must provide precise and comprehensible technical designs, including infrastructure plans and process flow diagrams, demonstrating their ability to contribute to renewable energy generation and achieve the project's environmental objectives.

Additionally, the sustainable operations and maintenance plan includes strategies for ongoing sustainable operations and maintenance. To ensure long-term efficiency and environmental compliance, bidders must consider factors such as waste transportation logistics, thermal balance calculations, and water and effluent management. The qualified environmental personnel plan evaluates the qualifications of personnel in environmental and sustainability roles. It is imperative that the team possesses the requisite expertise to effectively manage sustainable waste management practices, ensuring the project's success.

The third main criterion, sustainable investment and financial viability, requires investment proposals to provide a transparent financial framework illustrating the project's feasibility in terms of anticipated returns, operational expenses, and initial costs. Investment in Renewable Technologies reviews investment proportions dedicated to renewable and clean technologies, demonstrating the bidders' commitment to advancing renewable energy initiatives and supporting energy conservation objectives. Financial sustainability and capital evaluates financial stability and commitment to sustainable investments. Bidders must showcase their financial capacity to support the project's long-term objectives and dedication to sustainable financial practices. Efficiency in sustainable investment management assesses the effectiveness of investment management strategies towards sustainability goals, including cost management, anticipated revenue from electricity sales, gratuity fees, and construction costs, ensuring alignment with environmental sustainability and resource optimization.

The fourth main criterion, community engagement and environmental impact, acknowledges the importance of benefiting both the government and the community by incorporating pricing strategies and community relations. Community Sustainable Waste Services evaluates the effectiveness of proposed sustainable waste services for the community. Bidders must illustrate how their services will enhance sustainable waste management practices and positively impact community well-being. Fair waste disposal pricing considers proposals for waste disposal fees that promote sustainable practices. Strategies may include equitable rates for community waste disposal services and proposals to waive fees for contractors, fostering community acceptance and participation.

Stakeholder environmental engagement involves proposals for sustainability initiatives that engage contractors and consumers. Bidders are required to specify methods to encourage collaboration and support among stakeholders, fostering the development of sustainable cities and enhancing community relations.

Bidders are urged to conduct regular public discussions and workshops to transparently communicate the project's aims, operational procedures, and anticipated outcomes, thereby addressing community concerns effectively. These programs seek to mitigate apprehensions over health effects, air quality, and the adoption of incineration technology. Community forums function as a medium for collecting public feedback, which may be methodically integrated into the project's design and execution stages. Adherence to stringent air quality regulations, along with the implementation of sophisticated emissions control systems, mitigates health hazards and enhances public confidence.

Finally, the environmental education and relations budget assesses the budgets allocated for community education on environmental sustainability. Bidders are expected to allocate resources for community relations, manage the disposal of accumulated old waste, and determine the sharing of waste disposal fees, thereby reinforcing their commitment to environmental sustainability and promoting environmental awareness. Community benefit initiatives, such as direct funding in local environmental projects, scholarships, or subsidies for enhanced waste management services, exemplify the concrete advantages of the project. These activities not only improve community welfare but also bolster local backing for the project, guaranteeing its sustained success. These approaches guarantee that community concerns are addressed and that public approval and sustained support for the project are obtained.

Decision-makers often make unclear, imprecise, and vague decisions. Descriptive scales like high, medium, and low help decision-makers communicate their opinions on certain traits better than exact numbers. Fuzzy sets were created to negotiate imprecise and confusing information. A membership function may represent a fuzzy number, which is a mapping x: $\Re \rightarrow [0, 1]$. Triplets (l, m, u) represent triangular fuzzy numbers (TFNs). The criteria l, m, and u represent the smallest, most probable, and highest crisp numerical values. The membership function $(\mu_M(x))$ of a triangular fuzzy number is defined as follows.

$$\mu_M(x) = \begin{cases} (x-l)/(m-l) & l \leq x \leq m \\ (u-x)/(u-m) & m \leq x \leq u \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

Fuzzy membership functions with the incorporation of upper and lower bounds can generate fuzzy numbers with values ranging from 0 to 1 (TFN □[0, 1]), whereas crisp values are defined by the binary logic [0, 1]. Various "shapes" can be used to define fuzzy numbers, such as uniform, triangular, and trapezoidal, dependent on the circumstances. Nevertheless, TFNs are frequently employed in practical applications due to their simplicity of computation, and they are therefore employed in this context to assess the selection of strategic investment partners. After obtaining the fuzzy values, the defuzzification process is applied to transform them into a single crisp value for each criterion's weight. This conversion enhances interpretability, making the results more suitable for decision-making. The final weights of the main and sub-criteria for bidder selection are presented in Table 2.

Table 2. Final prioritization of the main and sub-criteria for evaluating WtE project partner

MC	Weight (CR)	SC	Weight (CR)	Firm	Geometric mean Weight	Total Weight
1	0.4959	1	0.5556	A	0.58	0.1605
	(0.0158)		(0.0464)	B	0.13	0.0360
				C	0.28	0.0771
		2	0.1235	A	0.57	0.0346
			(0.0158)	B	0.16	0.0101
				C	0.26	0.0157
		3	0.3209	A	0.60	0.0958
			(0.0464)	B	0.10	0.0165
				C	0.29	0.0454
2	0.3601	4	0.2145	A	0.18	0.0136
	(0.0345)		(0.0465)	B	0.59	0.0455
				C	0.23	0.0177
		5	0.5719	A	0.21	0.0423
			(0.0464)	B	0.36	0.0735
				C	0.34	0.0693
		6	0.0990	A	0.61	0.0219
			(0.0158)	B	0.12	0.0042
				C	0.26	0.0092
		7	0.1146	A	0.53	0.0220
			(0.0213)	B	0.12	0.0051
				C	0.33	0.0135
3	0.0397	8	0.1454	A	0.10	0.0006
	(0.0158)		(0.0032)	B	0.66	0.0038
				C	0.23	0.0013
		9	0.2415	A	0.12	0.0012
			(0.0158)	B	0.54	0.0052
				C	0.33	0.0032
		10	0.6131	A	0.12	0.0029
			(0.0079)	B	0.61	0.0148
				C	0.26	0.0064
4	0.1043	11	0.5215	A	0.54	0.0294
	(0.0308)		(0.0213)	B	0.11	0.0060
				C	0.35	0.0189
		12	0.1058	A	0.29	0.0033
			(0.0158)	B	0.10	0.0011
				C	0.59	0.0065
		13	0.1058	A	0.10	0.0012
			(0.0158)	B	0.65	0.0072
				C	0.24	0.0026
		14	0.2669	A	0.22	0.0062
			(0.0032)	B	0.36	0.0099
				C	0.26	0.0072

The Sankey diagram visualizes the decision-making framework by illustrating the relationships between primary and secondary evaluation criteria. The nodes represent key assessment categories, while the thickness of the connecting lines signifies the relative weight of each subcriterion. A greater line thickness indicates a stronger influence or higher assigned weight in the evaluation process, highlighting the most impactful factors in selecting a Waste-to-Energy (WtE) project partner. Additionally, the size of the nodes reflects the significance of each criterion, with larger nodes corresponding to those with a greater impact on the final decision (Fig. 4).

This diagram provides a structured representation of the partner selection process, emphasizing the key evaluation categories: Environmental and Technical Qualifications, Sustainable Technology Proposals, Sustainable Investment and Financial Viability, and Community Engagement and Environmental Impact. The weight distribution across these categories underscores the importance of Environmental Site Preparedness (0.5556) and Innovative Sustainable Design (0.5719) in assessing an investment partner's capability. Sustainable Technology Proposals (0.3601) and Environmental and Technical Qualifications (0.4959) emerge as the dominant factors in the evaluation. Other influential criteria, such as Financial Sustainability and Capital (0.2415) and Community Sustainable Waste Services (0.5215), contribute significantly to ensuring the long-term viability of the project and alignment with stakeholder expectations. This comprehensive evaluation framework integrates technical, financial, environmental, and social dimensions, ensuring a well-rounded approach to decision-making in WtE project implementation.

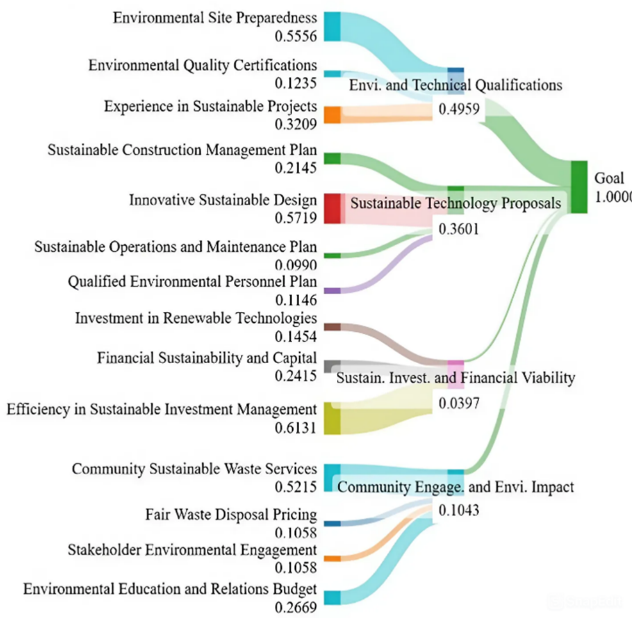

Fig. 4. Sankey diagram illustrating the relationship between the FAHP categories of main criteria and subcriteria.

The main criteria' consistency ratios (CR) indicate that the pairwise comparisons are generally acceptable, with all values falling below 0.05. In particular, the CRs of MC_1, MC_3, and MC_4 are 0.0158 and 0.0308, respectively. MC_2 has a slightly higher CR of 0.0345, which suggests a marginally greater inconsistency. Conversely, the sub-criteria demonstrate exceptional consistency, with all CR values remaining below 0.05. Notably, SC_8 and SC_10 exhibit exceptionally low CRs of 0.0032 and 0.0079, respectively, which implies that their evaluations are exceptionally consistent. Generally, the analysis indicates that the decision-making framework is highly reliable, which enables the selection of the evaluation alternatives with confidence.

The analysis indicates that Firm A has become the primary strategic investment partner for Waste-to-Energy incineration projects in Thailand, with a weight of 0.4366 and a normalized weight of 0.4458. This classification suggests that Firm A is the most suitable for the undertaking, as opposed to Firm C in second place and Firm B in third. In general, the combined weight of the alternatives indicates that a robust evaluation framework has been implemented, thereby guaranteeing that the most advantageous partners are chosen to improve the efficacy and effectiveness of solid waste management initiatives in the region.

This study primarily focuses on incineration as it effectively reduces substantial quantities of mixed municipal solid waste (MSW) and produces energy; however, other Waste-to-Energy (WtE) technologies offer viable alternatives, each tailored to particular waste compositions and regional needs. Anaerobic digestion is especially beneficial for waste streams abundant in organic matter, including food and agricultural waste. This method generates biogas, which can be transformed into electricity or employed directly as a renewable energy source, and also produces digestate, a by-product that serves as an organic fertilizer. Anaerobic digestion, in contrast to incineration, results in reduced greenhouse gas emissions and facilitates nutrient recycling, rendering it an ecologically sustainable option for the management of biodegradable waste.

Gasification is a sophisticated waste-to-energy technique that transforms non-recyclable and heterogeneous garbage into syngas, a multifunctional energy carrier suitable for electricity generation or chemical manufacturing. Gasification functions under regulated conditions, leading to markedly reduced emissions of dioxins and furans in comparison to incineration. Moreover, the by-products of gasification, including slag, are often inert and more manageable than the ash generated by incineration. Gasification systems necessitate uniform feedstock quality and entail substantial capital investment, thereby restricting their applicability in areas with varied and heterogeneous waste streams.

These comparative observations highlight the necessity of connecting Waste-to-Energy technology selection with local environmental, economic, and policy concerns. Regions with a significant amount of organic waste may get more advantages from anaerobic digestion, whereas areas with restricted acreage and strict emission rules may prefer gasification or incineration equipped with advanced emission control technologies. By evaluating these alternatives in conjunction with incineration, decision-makers can guarantee that the chosen waste-to-energy method effectively meets regional difficulties and sustainability goals.

The sensitivity analysis from the Adjusted Mixture Design (AMD) demonstrates the variable impact of main criteria (MC) on the selection of strategic partners for Waste-to-Energy (WtE) projects across multiple alternatives. Main Criterion 1 (MC_1) has the most significant impact, notably at alternative 1, with a weight of 0.790, underscoring its critical role in decision-making. Main Criterion 2 (MC_2) exhibits substantial variability, particularly at alternatives 6 and 11, where the weights reach their highest points at 0.547 and 0.790, respectively. Conversely, Main Criterion 3 (MC_3) maintains a consistent value of 0.040 across all alternatives, suggesting that it has minimal impact. The distribution of Main Criterion 4 (MC_4) is varied, with alternatives 3 and 7 both having weights of 0.547. In general, the analysis emphasizes the impact of fluctuations in criteria weights on the selection of partners, thereby ensuring that the project's objectives are met.

The sensitivity analysis for the Waste-to-Energy (WtE) project selection provides valuable insights into the performance of various firms across a variety of criteria. The radar chart clearly demonstrates that Firm A consistently achieves the highest scores across the majority of criteria, which suggests that it has a significant competitive advantage in the evaluation process (Fig. 5). The exhaustive qualifications and experience of this firm are the primary factors contributing to its robust performance, as demonstrated by its favorable metrics in the evaluation framework. Firm C, on the other hand, exhibits strengths in specific criteria that could be capitalized on in future proposals, despite its deficiencies in certain areas. This underscores the intricate competition among applicants.

Firm A remains in the lead, with Firm C and Firm B following in the second graphic, which positions the firms based on their scores across all criteria. This classification underscores the relative strengths and shortcomings of each firm, enabling stakeholders to identify potential voids in their proposals (Fig. 6). The fluctuating scores of Firm B indicate that its performance is unpredictable, which raises concerns regarding its overall efficacy and reliability in achieving the necessary project results. Therefore, the sensitivity analysis not only validates the selection process but also offers critical feedback to firms seeking to improve their competitive positioning in future proposals.

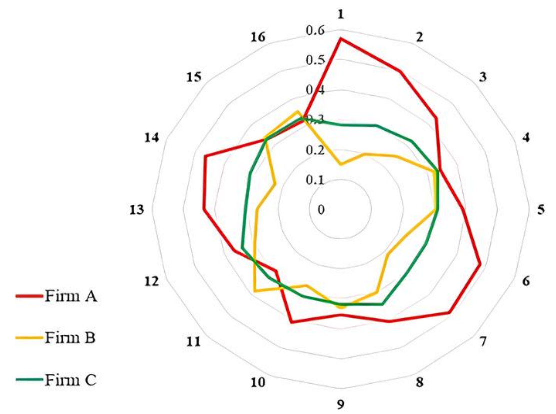

Fig. 5. Final weight of bidders for all scenarios.

The sensitivity analysis results emphasize the importance of bidders continuously refining their strategies and adapting to the changing expectations of the evaluation criteria. Firms can increase their appeal as potential partners for the WtE initiative by concentrating on the areas in which they can improve or differentiate themselves, such as demonstrating greater operational efficiency or enhancing technical proposals. Ultimately, the waste management sector benefits from this iterative approach, which contributes to more effective and sustainable solutions by fostering a competitive environment.

Firm A has been chosen as the strategic partner for the Waste-to-Energy (WtE) project for its exhaustive qualifications in the operational aspects of the incineration facility. The Stoker-Type incinerator's structural details and key components are essential for the efficient incineration of municipal waste. The system is designed to manage a minimum throughput of 4800 rpm daily and has a disposal capacity of at least 450 tons per day. The integration of a Heat Recovery Boiler complements this robust incineration capacity, and Firm A will furnish comprehensive information regarding its components, structural integrity, and selected model to guarantee optimal energy recovery performance.

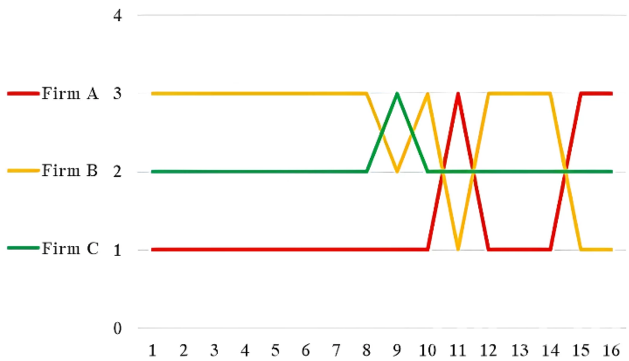

Fig. 6 Sensitivity analysis based on 16 scenarios from the AMD.

Furthermore, it is anticipated that Firm A will provide a comprehensive explanation of the operational efficiency-supporting performance indicators for both the incinerator and the heat recovery boiler. Utilizing a Nonautomatic Extraction Condensing Steam Turbine Generator, the Heat Recovery Utilization System is designed to produce electricity through steam. The proposal includes essential information regarding the components, selected equipment models, and performance parameters of this system, as well as its connection to the power distribution station.

Additionally, Firm A is required to comply with the Department of Industrial Works' standards and applicable laws by implementing an Air Pollution Control System. Comprehensive descriptions of operational processes, equipment models, and system components are included in the plan. A Continuous Emission Monitoring System (CEMS) is also required to assure compliance with air quality regulations by conducting continuous emission monitoring.

Firm A was chosen as the ideal partner due to its capacity to synchronize project goals with long-term environmental sustainability and Thailand's national renewable energy objectives. The company's incorporation of sophisticated emission control technologies, including Continuous Emissions Monitoring Systems (CEMS) and Selective Catalytic Reduction (SCR), guarantees adherence to rigorous air quality regulations, mitigating environmental issues typically linked to incineration methods. Moreover, Firm A's dedication to employing renewable energy technologies and effective energy recovery systems aligns with the objectives specified in Thailand's Alternative Energy Development Plan (AEDP).

Firm A's strategy promotes environmental resilience by reducing greenhouse gas emissions and improving waste-to-energy conversion efficiency, hence facilitating the production of renewable electricity. These initiatives correspond with the National Solid Waste Management Master Plan, guaranteeing that the project addresses both urgent waste management issues and broader national sustainability objectives. This congruence underscores the strategic significance of Firm A's choice in promoting sustainable urban development and energy saving goals in northeastern Thailand.

The project will include an Automatic Control System for the management of incinerator operations. The control levels, apparatus models, and scope of control will be thoroughly explained, including combustion control, auxiliary systems, air pollution treatment, and turbine safety mechanisms. Finally, the electrical system must ensure safety and reliability, which includes the implementation of all necessary electrical infrastructure, fallback systems, and an external power supply during initialization. In general, Firm A's proposal effectively manages and optimizes the operations of the WtE project as a comprehensive approach.

The findings indicate that Firm A's plan exhibits a robust alignment with national and regional policy frameworks, especially in achieving the objectives specified in Thailand's AEDP and Solid Waste Management Master Plan. This congruence highlights the framework's efficacy in incorporating policy issues into the decision-making process. Subsequent versions of the framework may integrate dynamic, policy-specific weighting systems to accommodate regulatory modifications, hence enhancing its effectiveness in policy-oriented environments.

This comprehensive strategy enhances partner selection for immediate project success while ensuring compatibility with long-term national sustainability objectives, thereby contributing to Thailand's overarching environmental and renewable energy initiatives.

This research is urgent because of its compatibility with Thailand's national environmental policies, including the Alternative Energy Development Plan (AEDP) and the National Solid Waste Management Master Plan. These policies emphasize the implementation of renewable energy technologies and sustainable waste management techniques, which are fundamental to the proposed FAHP framework. The framework assesses investment partners on their capacity to advance these objectives, so ensuring that WtE activities directly facilitate the attainment of national energy goals and environmental sustainability benchmarks.

The incorporation of WtE projects into these policy frameworks illustrates their capacity to diminish greenhouse gas emissions, enhance resource recovery, and mitigate the burdens on conventional waste disposal methods, including landfilling. The research demonstrates how sophisticated incineration technology, together with emission control systems, can reduce environmental effects while producing renewable energy. These contributions not only tackle local waste management issues but also establish WtE projects as important instruments in Thailand's comprehensive climate change and energy transition initiatives.

Furthermore, the framework offers a replicable model for policymakers to recognize and collaborate with stakeholders who are in accordance with these national priorities. The study emphasizes the importance of collaboration among local administrative bodies, private sector groups, and community stakeholders to enhance the incorporation of Waste-to-Energy technology into national development strategies. This method guarantees the effective implementation of policy objectives at the project level, connecting strategic goals with actionable results.

VI. Conclusion

This study established a structured framework for identifying suitable investment partners to implement solid waste-to-energy (WtE) incineration technology in Local Administrative Organizations in northeastern Thailand. Addressing the increasing demand for renewable energy solutions and efficient resource management, incineration was selected as a critical clean technology in WtE applications due to its capacity to generate heat and electricity while reducing waste volumes by up to 90%. The Fuzzy Analytic Hierarchy Process (FAHP) was implemented to assess potential collaborators based on critical criteria, including financial capacity, technological expertise, environmental impact, and alignment with regional energy and environmental policies. This framework offers decision-makers an environmental systems approach to systematically manage complex partnerships in WtE and environmental engineering projects, ensuring that partners align with project objectives.

The primary criteria in the FAHP model were Community Engagement and Environmental Impact, Sustainable Investment and Financial Viability, Sustainable Technology Proposals, and Environmental and Technical Qualifications. Sub-criteria under these categories included factors such as environmental site preparedness, environmental quality certifications, experience in sustainable projects, innovative sustainable design, efficient investment in renewable technologies, and strategies for community relations and environmental education. By evaluating potential partners against these comprehensive criteria, the model ensures that selected collaborators possess not only financial and technical capabilities but also a strong commitment to environmental sustainability, clean technologies, and community development. This alignment emphasizes the relevance of the model to contemporary environmental and energy challenges, such as renewable technologies, environmental sustainability, and sustainable cities.

The efficacy of Waste-to-Energy (WtE) initiatives depends on technical and financial viability, as well as public endorsement and conformity with environmental regulations. The social components of community trust and engagement are essential for the sustained success of such programs. This study incorporated community participation as a fundamental criterion inside the FAHP framework, evaluating potential partners based on their ability to promote openness and proactively address public issues. Strategies include public discussions, educational initiatives, and transparent communication regarding the advantages and protections of WtE projects are crucial for fostering trust and alleviating opposition, particularly in areas where incineration technologies may face mistrust.

The study's results largely correspond with Thailand's principal environmental policies, such as the Alternative Energy Development Plan (AEDP) and the National Solid Waste Management Master Plan. These policies prioritize the incorporation of renewable energy sources, sustainable waste management strategies, and community-oriented methodologies. By associating the evaluation framework with these policy objectives, the study guarantees that the suggested technique addresses local waste management requirements while simultaneously advancing national sustainability aims. This connection highlights the framework's significance in tackling overarching policy aims while guaranteeing community advantages.

Future research should investigate how particular policy incentives, such as tax advantages for improved pollution control systems or subsidies for community involvement projects, can further augment public participation and acceptability. Moreover, comprehensive case studies on public perceptions of WtE projects could yield significant insights for customizing methods to local social settings, thus enhancing the incorporation of social and policy aspects into WtE planning and execution.

The results underscore the significance of transparent and balanced partner selection in renewable energy initiatives, particularly in regions like northeastern Thailand, where waste accumulation and energy demand critically impact urban sustainability. Despite criticisms regarding emissions, incineration technology has demonstrated exceptional efficacy in reducing waste mass and generating energy, making it ideal for regions with limited land availability and contributing to the development of sustainable cities. Technological capacity and financial stability emerged as the most significant determinants of a partner's suitability, showcasing the FAHP's effectiveness in evaluating both quantitative and qualitative factors. This research emphasizes the importance of incineration as a waste management solution that promotes environmental sustainability and enhances energy efficiency.

The Fuzzy Analytic Hierarchy Process (FAHP) offers an effective foundation for assessing partners in Waste-to-Energy (WtE) projects; however, subsequent research could improve the framework by using supplementary techniques like Geographic Information Systems (GIS) and scenario simulations. Geographic Information Systems (GIS) can facilitate spatial analysis to determine appropriate facility placements by considering variables such as population density, waste generation rates, and environmental limitations. Likewise, scenario simulations could evaluate the sensitivity of partner selection results to variables such as variations in waste composition or regulatory alterations, facilitating more adaptable and robust planning.

These enhancements would convert the FAHP framework into a multi-method decision-support instrument, offering a holistic approach to tackling the intricacies of WtE project execution. This integration, while outside the current study's focus, signifies a viable avenue for future research aimed at enhancing the adaptability and robustness of waste-to-energy planning approaches.

To guarantee the effective execution of Waste-to-Energy (WtE) initiatives, various specific solutions are proposed. Initially, comprehensive risk management strategies must be formulated to tackle prospective technological and operational obstacles. This encompasses contingency strategies for machine malfunctions, variable waste input quality, and project deadline delays. Implementing sophisticated monitoring systems, such as Continuous Emissions Monitoring Systems (CEMS), can guarantee adherence to environmental rules and promote transparency with stakeholders. Moreover, public engagement tactics are crucial for alleviating opposition to WtE initiatives. Facilitating community meetings, disseminating accessible information regarding the advantages and protections of WtE technology, and integrating community comments into project design can bolster public confidence and acceptance.

Policy incentives are crucial for promoting investment and guaranteeing project feasibility. Governments may use tax incentives or subsidies to promote the adoption of sophisticated pollution control technologies and renewable energy projects. Feed-in tariffs for electricity produced by waste-to-energy facilities can offer economic stability to operators by ensuring a fixed price for energy sold to the grid. Additionally, providing low-interest loans or subsidies for waste-to-energy projects might stimulate private sector involvement, especially in areas where substantial initial costs may dissuade investment.

Ultimately, synchronizing WtE initiatives with national energy and waste management strategies can enhance their effectiveness. Integrating projects into frameworks like Thailand's Alternative Energy Development Plan (AEDP) and the National Solid Waste Management Master Plan guarantees that these initiatives support both local and national sustainability objectives. These indicators offer a framework for policymakers and stakeholders to effectively mitigate risks, encourage investment, and attain enduring environmental and economic resilience.

The primary contribution of this study is the creation of a replicable decision-making framework for selecting collaborators in WtE initiatives, based on an integrated ecosystems management approach that considers economic, environmental, and policy factors. While many studies focus on the technical aspects of WtE technologies, this paper highlights the critical role of strategic partnerships in ensuring the success of these initiatives. By introducing a data-driven method customizable to various waste management contexts and regions, with an emphasis on the efficacy of incineration in waste reduction and energy generation, the study offers practical insights into sustainable waste management and energy policy through the integration of waste treatment with renewable energy production.

The findings have significant implications for policymakers and stakeholders involved in the planning, implementation, and oversight of energy policies. The developed framework serves as a decision-support tool for governments and organizations investing in WtE partnerships, ensuring collaborations are based on comprehensive, data-driven criteria. In northeastern Thailand, where the urgent need for effective solid waste management is evident, incineration presents a strategic approach to sustainable WtE solutions aligned with environmental and energy conservation objectives. By utilizing this framework, stakeholders can establish holistic partnerships that not only address waste management challenges but also contribute to the realization of renewable energy goals.

Future research should focus on applying the FAHP framework to various contexts beyond incineration, including other WtE technologies like hybrid energy systems, gasification, and anaerobic digestion. Analyzing the performance of these technologies as WtE collaborators in regions with diverse waste compositions and energy demands can provide valuable insights into their adaptability and effectiveness, further promoting an integrated ecosystems management approach. Additionally, incorporating factors such as public acceptability, social engagement, and long-term sustainability impacts into the partner selection process could enhance the robustness of the decision-making framework, aligning with the objectives of environmental sustainability and the development of sustainable cities.

Exploring the integration of advanced emission control technologies can also enhance the environmental performance of WtE initiatives, addressing common criticisms associated with incineration and other waste management solutions. By broadening the scope of criteria and examining a diverse array of technologies, researchers can deepen their understanding of how WtE initiatives effectively promote environmental sustainability and social well-being in diverse regional contexts.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A.N. and, P.L. contributed to the data curation of the research design, conceptualization, methodology, software, validation, visualization of the research, to the analysis of the results and to the writing - review & editing of the manuscript

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