

Waste Management for Environmentally Sustainable Cities: A Quadruple Helix Collaboration in Practice

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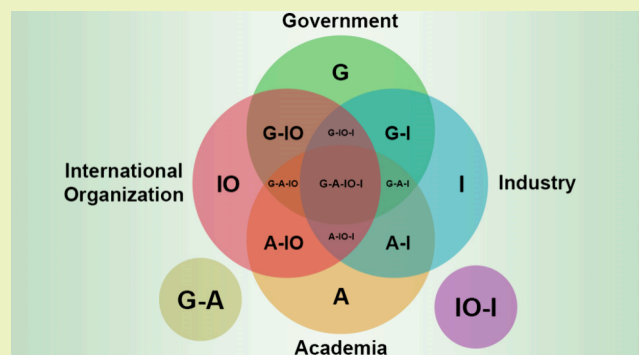
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ABSTRACT: This paper discusses a sustainable waste management initiative in ASEAN nations, utilizing a unique Quadruple Helix model that includes an international organization as an active fourth actor. This collaboration among academia, government, industry, and the international organization focuses on strategic policy alignment, advanced waste management technologies, and project creation through an interactive multi-stakeholder knowledge-sharing digital platform. The project is leading to a significant reduction in carbon and methane emissions, mitigating approximately 6 million tons of CO₂ equivalent and creating around 1,300 green jobs. Nearly 4 million ASEAN citizens are benefiting from improved access to solid waste management services, enhancing their quality of life and environmental health.

Universities play a crucial role by establishing the ASEAN-Korean Integrated Green Technology Platform (AKIGTP), which bridges next-generation research and practical applications. NTU's contributions in advanced research, knowledge dissemination, and fostering multi-stakeholder partnerships were instrumental in addressing complex challenges and advancing innovation within the Quadruple Helix framework. Taken together, the project not only showcases the potential of the Quadruple Helix model in driving sustainable development but also sets a precedent for similar initiatives globally. This comprehensive approach ensures effective and sustainable solutions to municipal solid waste management challenges, promoting a resilient and environmentally conscious future for the ASEAN region.

KEYWORDS: *Quadruple Helix, Triple Helix, Innovation, Cross Economy, Beyond Sustainability*



1. INTRODUCTION

In the dynamic landscape of research and innovation, collaboration models have evolved from the triple helix to the quadruple and quintuple helix, encompassing diverse actors like civil society, media, and environmental considerations. Originally emphasizing the pivotal role of universities, these models now extend to interdisciplinary perspectives, fostering collaboration for socio-economic development. Notable success stories demonstrate the effectiveness of bringing academia, industry, government, and others together to address complex challenges. The helix models align with sustainable development goals, as highlighted in recent research.^{1–3} Despite its noteworthy effort of helix model collaboration and innovation, its practical application and tailoring within the specific ASEAN regional context, particularly in the realm of solid waste management (SWM), have been notably constrained. As of 2023, the ASEAN population stands at 671.6 million, nearly constituting 9% of the global population.⁴ The annual municipal solid waste (MSW) generation for the entire ASEAN region was 149.62 million tons in 2017, reflecting a substantial environmental

challenge. Notably, most countries in the region have experienced a high increase in MSW projection.⁵ The burgeoning challenge of municipal solid waste management in the ASEAN region requires innovative, collaborative solutions that tap into the rich wellspring of expertise available both within the region and internationally.

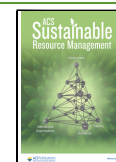
Current approaches to MSW management in various developing countries are often fragmented and lack the integration necessary to address the scale and complexity of the problem. Many countries in the region have seen a significant increase in MSW production, yet their waste management systems have not kept pace with this growth.⁶ Existing strategies frequently not sufficient to adopt a holistic perspective, missing opportunities for resource recovery and

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circular economy practices. This inadequacy highlights the critical need for innovative, collaborative solutions that leverage diverse expertise and technologies. Moreover, waste management practices vary significantly across countries, reflecting different levels of infrastructure, technological adoption, and policy implementation. Waste management technologies also encompass a broad spectrum of activities, categories, and stages along the value chain, from initial waste generation to final disposal or recycling.⁷ This comprehensive term integrates various strategies for handling, treating, and valorizing waste, aiming to minimize environmental impacts while maximizing resource recovery. Significant efforts have been made to systematically categorize these processes within the waste management framework, reflecting a diverse array of practices tailored to different types of waste and treatment technologies.⁸ Such categorizations are crucial for enhancing the efficiency and sustainability of waste management systems by clearly defining the roles and interactions within this complex network.

The MSW management value chain encompasses a series of interconnected stages, each critical to ensuring effective waste management. The process begins with waste collection, which involves the systematic gathering of waste from residential, commercial, and industrial sources. Efficient collection and routing systems are vital for minimizing environmental impacts and ensuring subsequent stages are properly supplied.⁹ Following collection, the waste undergoes processing, where it is sorted and treated to separate recyclable materials from non-recyclable ones. This stage may involve automated mechanical sorting, manual picking, and various treatment technologies such as shredding and compacting.^{10–12} Recycling is a key component, involving the reprocessing of materials like paper, plastic, glass, and metals into new products, thus conserving resources and reducing landfill demand.^{13–16} Composting is another processing method,¹⁷ where organic waste is biologically decomposed to produce nutrient-rich compost for agricultural use. Four representative composting technologies include Windrow Composting, suitable for large-scale operations with long, narrow piles; In-Vessel Composting, which uses enclosed containers for faster, controlled composting; Aerated Static Pile Composting, involving large heaps with forced aeration systems; and Vermicomposting, utilizing specific worms to produce nutrient-rich compost from organic waste.^{18–24} Non-recyclable and non-compostable waste often proceed to disposal. Landfilling remains a common method, where waste is deposited in engineered sites designed to minimize environmental contamination. Hybrid method of combining the landfilling and partial composting is another practice to reduce the pollution in the landfilling site. Alternatively, incineration involves burning waste at high temperatures to reduce volume and potentially generate energy, though it requires stringent emission controls.^{25–29} These technologies and methods vary significantly by region and country, reflecting differences in infrastructure, technological adoption, regulatory frameworks, and local policies, leading to diverse approaches and effectiveness in managing MSW globally and locally.^{30,31} Such diversified geology, living conditions, industrial activities, and consumption patterns across the ASEAN region necessitate a varied application of waste management technologies, leading to significant regional disparities.³² Although numerous studies are underway, such as those addressing gaps in plastic pollution and optimizing the waste

composition change by the e-waste increase, there remain critical gaps and a lack of fully optimized technologies tailored to the specific needs of each region.^{33,34} To address complex challenges, “Advancing ASEAN-Korean Cooperation in Integrated Municipal Solid Waste Management (IMSWM) for Environmentally Sustainable Cities” project has been jointly proposed by the consortium that represents the quadruple helix model. This project targets to transition the ASEAN Member States (AMS) towards a resource-efficient, circular society model, capitalizing on the extensive experience and learning of the advanced waste management technologies in IMSWM by 2026. Central to this initiative is the endeavor to enhance the national and local capacity of AMS to implement integrated solid waste management practices, thereby paving the way for catalytic waste investment projects in line with ASEAN’s vision toward the environmentally sustainable cities.³⁵ What makes this project particularly unique is the enhanced model of collaboration among government, industry, academia, and international organization, evolving into a Quadruple Helix. Each entity contributes a distinct set of interventions, encompassing strategic alignments, engagement with green technology platforms, knowledge sharing, capacity building, and waste management projects, among others. The four key partners, each representing one of the quadruple helix actors:

1. **Academia:** Nanyang Technological University (NTU) takes on the academia role, establishing the ASEAN-Korean Integrated Green Technology Platform (AKIGTP) to bridge the next generation research and practical application.
2. **Government:** The National Institute of Green Technology (NIGT) played a pivotal role in initiating the project proposal to the main funder, the ASEAN-Korean Cooperation Fund (AKCF), ensuring the introduction of best practices and performance standards aligned with local and national goals.
3. **Industry:** Korea Environment Cooperation (K-ECO) plays a crucial role in delivering technological knowledge to ASEAN Member States (AMS) through a focused capacity development program.
4. **International Organization:** Global Green Growth Institute (GGGI) provides vital support, offering customized solid waste management strategies and guidelines for each ASEAN country. GGGI lead collaboration among all partners to develop a strong, unified project pipeline aligned with global sustainability goals.

As a key stakeholder in this initiative, epitomizes the indispensable role of academic institutions in sustainable development projects. As one of the leading technological universities, NTU not only brings to the table cutting-edge research and technological advancements but also serves as a hub for knowledge dissemination, fostering multi-stakeholder partnerships, shedding light on areas that have not been extensively explored. A pivotal role in improving waste management and energy recycling in Singapore through its Smart Campus and EcoCampus initiatives can integrate sustainable practices and smart technologies, serving as a model for scalable solutions in the ASEAN region.³⁶ In the recent research that it provides a crucial exploration of how universities play a pivotal role in advancing innovation within the quadruple helix framework, emphasizing the university’s



Figure 1. Project architecture and operational flow diagram. This project is supported by the ASEAN-Korea Cooperation Fund (AKCF) and implemented by the project consortium (Nanyang Technological University, Global Green Growth Institute, National Institute of Green Technology, and Korea Environment Cooperation).

integral contribution to fostering more effective and comprehensive innovation processes. In light of the recent research, it demonstrated the pivotal role of the university in driving innovation and sustainable development, particularly in social innovation projects. Their unique position as centers of research and knowledge expansion makes them key to the success of such initiatives.³⁷ As such, the participation of a university enriches the project with depth, rigor, and a unique perspective that seamlessly melds theory with practice. In the following sections, this paper will delve deeper into the unprecedented nature of the quadruple helix collaboration model in the ASEAN context and elucidate why the involvement of a university is not just beneficial but crucial for the success and sustainability of such a monumental project.

2. ASEAN WASTE MANAGEMENT STATUS QUO

The ASEAN region, home to a diverse set of economies, cultures, and environments, is currently grappling with a pressing and multifaceted challenge: escalating municipal solid waste management (MSWM) issues such as ground, water and air contaminations, as well as ecological problems.³⁸ Rapid urbanization, bolstered economic growth, and an ever-increasing consumerist culture have led to an exponential rise in waste generation across the member states. This increase is often accompanied by outdated and inefficient waste management infrastructures that are not capable of processing the volume and complexity of the waste. Consequently, landfills are overflowing, many of which lack proper environmental safeguards, leading to soil, air, and water pollution. This not only jeopardizes the ecological balance but also poses significant health risks to local communities.³⁹

ASEAN countries are experiencing a significant increase in municipal solid waste (MSW) generation due to rapid

urbanization, industrialization, and population growth. The per capita MSW generation in ASEAN is 1.14 kg/capita/day. Indonesia generates the highest quantity of municipal waste at 64 million tons/year, followed by Thailand, Vietnam, the Philippines, Malaysia, Singapore, Myanmar, and Lao PDR. Organic waste is the highest fraction of MSW in all ASEAN countries except Singapore, where it accounts for only 10.5% of total MSW. Common waste management practices in the region include open dumping and burning, with composting and recycling often handled by the informal sector. Singapore is an exception with a well-structured system that relies on waste-to-energy incineration.⁴⁰ Despite efforts, challenges in technology, infrastructure, financing, and policy persist, highlighting the need for integrated and sustainable waste management solutions.⁵

Compounding waste management issue in the region is causing the inadequate segregation of waste, leading to a mixed disposal of organic, recyclable, and non-recyclable waste. This intensifies landfill pressures and increases the release of harmful greenhouse gases like methane.⁴¹ If not properly treated, waste can lead to severe environmental pollution, including the contamination of water bodies and soil, posing significant risks to human health and ecosystems.^{42,43} Moreover, informal sectors largely manage waste collection and disposal, leading to inconsistent service quality, a lack of data transparency, and environmental degradation from unregulated dumpsites. With urban populations in the ASEAN region projected to rise even further in the coming decades, these waste management challenges threaten to escalate into full-blown crises, with ramifications far beyond city limits. Addressing the MSWM issue is not just a matter of environmental urgency but also of socio-economic importance. Proper waste management can create numerous green jobs, promote sustainable industries, and pave the way for a circular

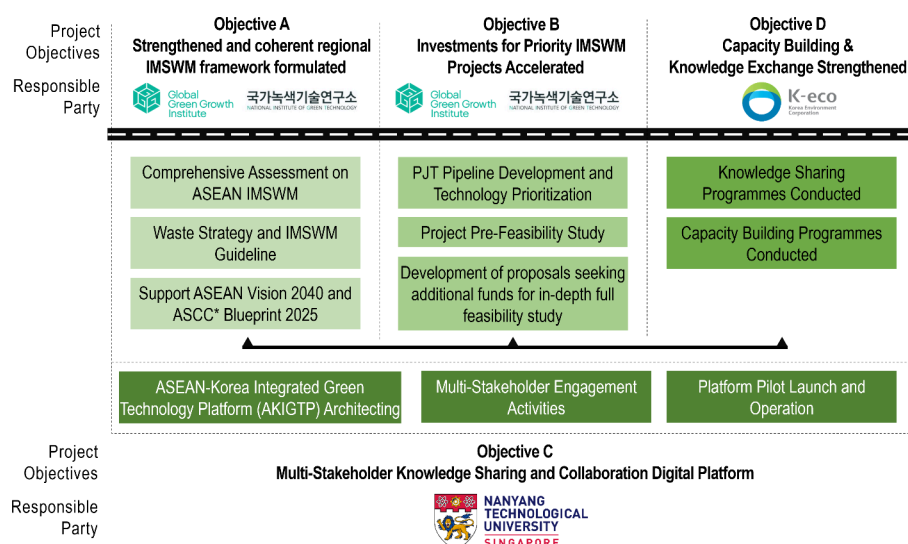


Figure 2. Project objectives and responsibilities. This project is supported by the ASEAN-Korea Cooperation Fund (AKCF) and implemented by the project consortium (Nanyang Technological University, Global Green Growth Institute, National Institute of Green Technology, and Korea Environment Cooperation).

economy, reducing resource overexploitation. Furthermore, the ASEAN region is a significant contributor to marine plastic pollution, largely due to the numerous small rivers that carry plastic waste into the ocean. These rivers, influenced by the geographical characteristics and climatic conditions of their catchment areas, face high rainfall and are often located near urban drainage systems along coastlines. This combination increases the likelihood of plastic waste entering the rivers and subsequently being carried into the ocean. Therefore, streamlining waste management in the ASEAN region can play a pivotal role in conserving marine ecosystems.⁴⁴ ASEAN is setting strategic goals to enhance the circular economy through financial aid, improvements in the regulatory framework, and encouragement of behavior change. However, there are various challenges standing in the way that will require time and persistent effort to overcome.⁴⁵

Advancing a comprehensive waste management framework in the ASEAN region is fundamental for ensuring a sustainable, prosperous, and resilient community. Given the complex challenges of escalating municipal solid waste issues, the active and rich participation of universities is crucial. Their expertise in research, innovation, and technology development & transfer can drive effective solutions for waste management, fostering a transformative shift towards sustainable practices and reinforcing ASEAN's commitment to building a resilient and environmentally conscious community.^{46,47} Therefore, we have convened a diverse array of international stakeholders to develop an innovative waste management improvement model, as illustrated (Figure 1). This collaborative effort aims to integrate best practices and cutting-edge technologies to address the unique challenges faced by the ASEAN region, ultimately promoting a sustainable and efficient waste management system.

3. PROJECT PROPOSAL AND MAIN GOALS

The current landscape of waste management in the ASEAN region stands at a critical juncture due to escalating urbanization, consumerism, and inadequate infrastructure, which have led to increased waste generation and significant environmental challenges.⁵ While the challenges are multi-

dimensionally complex, so too are the opportunities for transformative action. Recognizing this, the “Advancing ASEAN-Korean Cooperation in Integrated Municipal Solid Waste Management (IMSWM) for Environmentally Sustainable Cities” project was conceived as a beacon of progressive change. Rooted in the principles of resource efficiency and circularity, this project aspires to harmonize the best of ASEAN and Korean experiences, bolstered by a history of significant ASEAN-Korean cooperation.⁴⁸ It aims to foster a collaborative environment that transcends borders and disciplines, initiated by the ASEAN Korean Cooperation Fund (AKCF) utilizing quadruple helix models of collaboration. The active participation of ASEAN member states in this project is essential, as they are the ultimate beneficiaries (Figure 1). The initiation of this project is a testimony to the ASEAN community's commitment to sustainability and resilience. With an increasing global spotlight on climate change, pollution, and urbanization challenges, the ASEAN region has the potential to demonstrate leadership and innovative solutions in the waste management domain. The considerable endeavors are reflected in the project with its scale, ambition, and the tangible anticipated benefits. These impacts will be realized through the initiation of the actual municipal solid waste management project, and when fully implemented, it will not only significantly reduce carbon and methane emissions (about 6 metric tons CO₂ equivalent) but will also generate approximately 1,300 green jobs. Moreover, nearly four million ASEAN citizens are poised to benefit from improved access to solid waste management services, elevating the quality of life and environmental health across the region.

The primary objectives of this initiative are multifaceted. Foremost, it seeks to align the waste management models of ASEAN Member States with the ASEAN Socio-Cultural Community Blueprint 2025 (ASCB 2025), laying down strategic interventions to realize the ASEAN Vision 2040 for Sustainable Urban Development.^{35,49} Through rigorous assessments, strategy formulation, capacity-building, and the establishment of a multi-stakeholder knowledge-sharing platform, the project endeavors to build a cohesive, region-wide framework for IMSWM. Ultimately, the aim is to catalyze long-

term capital for IMSWM in the ASEAN region, ensuring that cities are not only sustainable but also thriving hubs of innovation and collaboration for generations to come.

The project comprises four pivotal objectives (Figure 2). Objective A, with the main responsibility entrusted to the Global Green Growth Institute (GGGI), aims to establish a robust regional IMSWM framework in alignment with ASEAN Vision 2040 and the ASCC Blueprint 2025. GGGI's central role is attributed to its expertise in sustainable development, particularly in green growth strategies and environmental sustainability. With a track record of various environmental projects and policy advisement in various countries, including its collaboration with Indonesia from 2014-2020 which significantly advanced national environmental goals, GGGI possesses the necessary competencies and resources to conduct comprehensive waste management assessments and develop the 2030 Waste Strategy.^{50,51} Its experience in facilitating international cooperation and implementing practical green solutions positions it effectively to lead these tasks. Objective B, managed by GGGI and National Institute of Green Technology (NIGT), focuses on developing and accelerating a significant pipeline of waste management projects across ASEAN countries, with NIGT excelling in the development and promotion of sustainable waste management technologies and policies.⁵² The successful execution of this project pipeline is bolstered by the rich experience and extensive networks of all consortium partners. Their combined expertise and established connections ensure that innovative waste management initiatives are effectively transformed from conceptual ideas into practical solutions. Objective C, led by Nanyang Technological University (NTU), envisions the creation of the ASEAN-Korean Integrated Green Technology Platform (AKIGTP). This multi-stakeholder knowledge hub is designed to foster collaboration, knowledge exchange, and innovative partnerships across the region. NTU's leadership in this objective is pivotal, as academia possesses unique capabilities to architect the most effective and comprehensive platform structure, surpassing other entities in designing a system that best facilitates interdisciplinary communication and innovation among consortium partners as well as AMS, project stakeholders and participants.^{53–55} Lastly, Objective D focuses on capacity building, utilizing developed Integrated Municipal Solid Waste Management (IMSWM) experience to enhance the knowledge and practical expertise of ASEAN members. The Korea Environment Corporation (K-Eco) plays a pivotal role in this objective, leveraging its experience in nurturing environmental experts and track record includes dispatching staff to international organizations for sustainable development training and establishing a Human Resources Development Center to develop employee capabilities and educate external experts, effectively contributing to objective goals.^{56,57} Together, these objectives encapsulate a holistic, ambitious vision for waste management transformation within the ASEAN region.

4. PROJECT METHODOLOGY BY QUADRUPLE HELIX FRAMEWORK

The methodology underpinning the “Advancing ASEAN-Korean Cooperation in Integrated Municipal Solid Waste Management (IMSWM) for Environmentally Sustainable Cities” project is both comprehensive and innovative, reflecting its ambitious goals and the intricate nature of the challenges it seeks to address. In this collaborative effort, each stakeholder

employs specific methodologies to contribute to the project's success. GGGI employs a comprehensive assessment methodology to evaluate existing waste management practices and infrastructure across ASEAN countries, using data-driven analysis to identify gaps and opportunities for improvement. This includes leveraging geographic information system technology and other analytical tools to map waste generation and management patterns.^{58,59} NIGT utilizes a participatory approach, engaging local stakeholders through workshops and consultations to develop tailored waste management solutions that align with local contexts. They also apply technology foresight and scenario planning to anticipate future waste management needs and innovations. NTU focuses on integrating advanced research and technological innovations into the project, using their expertise to design the ASEAN-Korean Integrated Green Technology Platform (AKIGTP). This involves creating a robust online platform that facilitates real-time knowledge exchange, data sharing, and collaborative project development among stakeholders. K-Eco implements capacity-building programs that include hands-on training, workshops, and the development of educational materials to enhance the skills and knowledge of waste management professionals in the ASEAN region. Their approach ensures that local practitioners are well-equipped to implement and sustain IMSWM practices. Together, these methodologies create a comprehensive and synergistic approach to transforming waste management practices across the ASEAN region. Furthermore, the integration of the AKIGTP digital platform bolsters the project's capacity for effective pipeline development, ensuring a more streamlined and collaborative approach to tackling the complexities of IMSWM. (Figure 3)

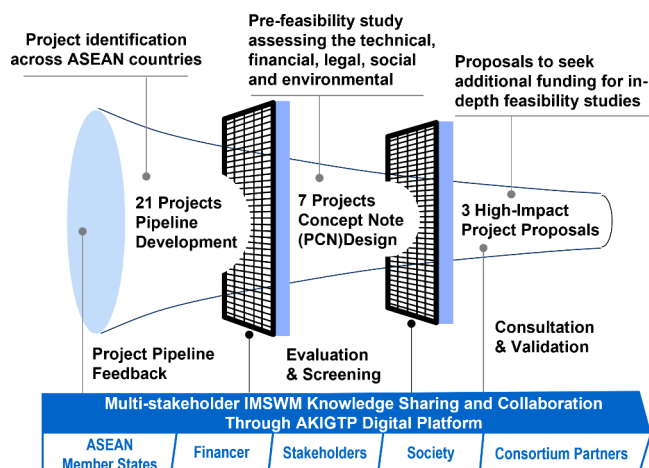


Figure 3. Project development methodology through multi-stakeholder digital platform.

The project starts with a systematic, phased approach. The initial stage entails the development of a detailed project pipeline, conceptualizing distinct waste management projects spanning ASEAN countries. Each project within this pipeline undergoes rigorous scrutiny, accounting for diverse factors ranging from environmental safeguards to investment strategies. Subsequent stages involve the design of Project Concept Notes (PCNs), incorporating elements like pre-feasibility studies and technical evaluations. These PCNs, serving as a blueprint for each project, play a crucial role in attracting

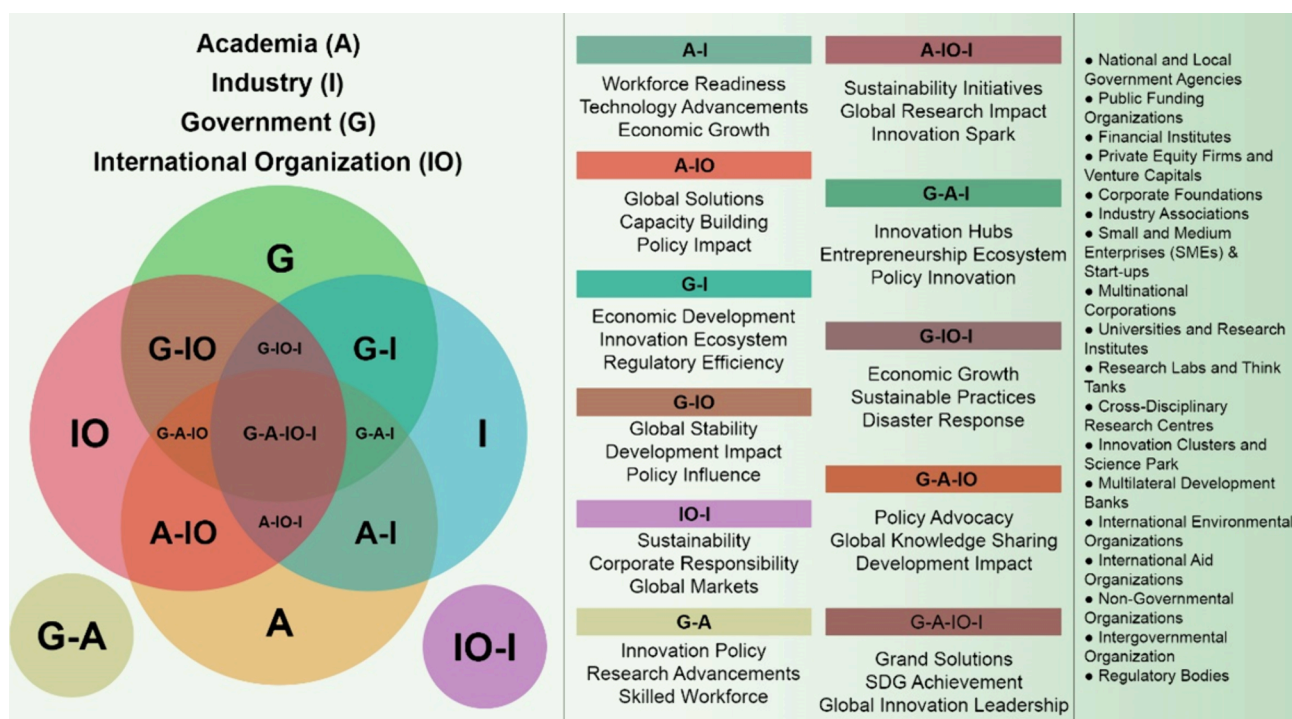


Figure 4. Expansive Quadruple Helix Collaboration Framework and Network for Sustainable Development.

potential funding sources, thereby translating these concepts into actionable, on-ground initiatives.

International sustainability development projects often face challenges such as biased dependency on external agencies, technological constraints, fragmented stakeholder collaboration, knowledge gaps in implementation, and limited access to data and finance resources.^{60–63} Recognizing that traditional quadruple and quintuple helix models, which emphasize collaboration among governments, industries, academic institutions, civil society, or more localized communities,^{64–66} have their limitations, we introduce a technological innovation platform based on quadruple helix collaboration model: the ASEAN-Korean Integrated Green Technology Platform (AKIGTP). This approach makes the collaboration more proactive and broadens the range significantly.

This strategic expansion transcends the conventional model, fostering a more comprehensive and globally-focused collaboration.

Significant research has explored Quadruple Helix collaboration cases across various sectors and regions, underscoring the advantages and obstacles of user-oriented innovation.⁶⁷ Concurrently, studies on earlier quadruple and quintuple helix collaboration models in innovation environment highlights a lack of standardization in representing society in helix models, noting variations in their passive engagement as well as challenges in active implementation.⁶⁸ The AKIGTP introduces a strategic shift by incorporating international organizations. It harnesses entities with proven implementation capabilities, extensive networks, and a pronounced commitment to global objectives. This approach addresses a critical gap in previous models, transforming the passive roles of the fourth and fifth actors into active, impactful participation. This evolution marks a significant enhancement, offering a more dynamic and effective framework for achieving sustainable development goals. It also transforms the quadruple helix framework, positioning it as both a product and an enabler of

effective, committed collaboration among government, industry, academia, and international organizations.

In the global collaboration landscape, established platforms like the World Economic Forum (WEF) and the United Nations Environment Programme (UNEP) have set a precedent for multi-stakeholder partnerships.^{69,70} These platforms, along with others like the G20, World Bank Group, and WHO, have pioneered the integration of diverse perspectives and expertise to address complex global challenges. Each of these platforms has its strengths and limitations, reflecting the dynamic nature of international collaboration. They have paved the way for a new generation of partnership models, tailored to specific regional and thematic needs especially towards the Sustainable Development Goals.⁷¹ Similar multi-stakeholder cooperation initiatives are emerging across various regions and sectors, reflecting a global trend towards collaborative and inclusive approaches to development, problem-solving, innovation fostering, and impact creation.^{72,73} The ASEAN region, characterized by its unique geological and economic landscape, has a history of diverse collaborative efforts in the waste management sector, reflecting its distinct regional structure and needs.^{48,74}

In this evolving arena, AKIGTP stands as a testament to the growing diversity and specialization in global partnership platforms, embodying a forward-thinking approach that resonates deeply with the needs of ASEAN countries. Conceived as a digital nexus for knowledge exchange and collaboration, AKIGTP will function both as an informational hub and an interactive forum, with a user-centric digital infrastructure facilitating seamless interactions among stakeholders. Building upon this innovative vision, AKIGTP is anchored in Expansive Quadruple Helix Collaboration Framework and Network for Sustainable Development (Figure 4). AKIGTP uniquely capitalizes on the extensive networks of government, industry, academia, and international organization. This approach exceeds previous models, fostering deeper,

more interconnected collaborations. With this, the project boasts a rich international knowledge, technology, and network pipelines. This pipeline, distinct in its depth and breadth, promises a gamut of solutions tailored to the diverse needs of the ASEAN region. Academia's rich accumulation of research, particularly universities like NTU, plays a pivotal role in waste management beyond structuring the methodology. Universities' extensive research capabilities in areas such as waste-to-energy technologies, sustainable materials, and environmental impact assessment provide essential insights and innovations that drive the project's success.^{75,76} Their leadership in developing the AKIGTP leverages strong academic reputations and multidisciplinary expertise, ensuring that the platform is robust and cutting-edge. Furthermore, universities' unique and extensive networks enhance the project's ability to succeed, offering access to leading experts, innovative technologies with capitals, and successful waste management strategies.⁷⁷ This makes universities uniquely special in this project, as they bridge the gap between theoretical research and real-world application, ensuring that the methodologies and technologies employed are both innovative and implementable. As a cornerstone of the Quadruple Helix model, universities bring a blend of theoretical insight and practical expertise, essential for navigating the complex dynamics of sustainable development. Their role in AKIGTP extends beyond academic contribution; they act as neutral grounds for government, industry, and international organizations to converge, fostering an environment where unbiased, research-driven solutions can thrive. This central position in the helix amplifies their ability to coordinate and synthesize diverse inputs, ensuring that AKIGTP is not only robust and innovative but also aligned with the evolving needs and aspirations of the ASEAN region.

5. CONCLUSION AND OUTLOOK

Despite significant strides in development, Southeast Asia continues to grapple with challenges in municipal solid waste management, which are compounded by rapid urbanization, population growth, and industrialization. These issues strain existing infrastructure and necessitate innovative, scalable solutions to prevent environmental degradation and promote sustainability. The "Advancing ASEAN-Korean Cooperation in Integrated Municipal Solid Waste Management (IMSWM) for Environmentally Sustainable Cities" project, underpinned by the quadruple helix framework, stands as a monumental testament to collaborative innovation. This framework, which integrates the efforts of academia, industry, government, and international organization, has been instrumental in shaping a comprehensive and holistic approach to waste management in the ASEAN region. This project emerges as a beacon of the quadruple helix model in action, demonstrating the immense transformative potential when these four sectors synergize their efforts. Each sector contributes unique strengths: research and innovation, practical solutions and technologies, policy support and regulatory frameworks, global perspectives, and funding avenues. This interplay results in a synergistic effect where the collective impact significantly exceeds the sum of individual efforts, akin to the cross-economy concept, which innovatively transforms waste into high-value products.⁷⁸ As the project moves forward, our focus is on harnessing this synergy to attract catalytic investment projects from international finance entities and private donors. Our objective is clear: to transform conceptual projects into tangible realities, setting off a wave of sustainable impact throughout the ASEAN region.

Our sustainability roadmap, enriched by the quadruple helix framework, combines robust policy advocacy with hands-on interventions. In collaboration with AMS governments, our objective is to sculpt the 2030 ASEAN Waste Strategy and Guidelines. These strategic blueprints, aligned with overarching visions like the ASEAN Vision 2040 and ASCC Blueprint 2025, are poised to usher in tangible benefits, especially in realms like GHG emission reductions and the achievement of waste sector-linked SDGs. Central to our efforts is the principle of collective ownership and inclusivity, ensured by the inherent nature of the quadruple helix model. By fostering a deep sense of connection and shared purpose across all stakeholders, we aim to create a united front, championing the project's goals and ensuring their effective realization.

In conclusion, the success of the project will showcase the Quadruple Helix model's potential for replication in large-scale initiatives. This approach, blending academia, industry, government, and international organizations, can be a blueprint for similar sustainability projects globally. Its effectiveness in driving innovation and impactful environmental solutions demonstrates its versatility and applicability in various contexts, from renewable energy to urban development. As we envision the future, the promise of sustained impact and the lasting legacy of the project becomes evident. The creation of bankable projects, tailored to each country's unique needs, will drive tangible change. Our strategic engagement with financial stalwarts like the Green Climate Fund (GCF), along with ongoing discussions with international development banks, key country environmental divisions, and local communities, ensures robust backing and aligns project details with local needs and global environmental standards. This comprehensive approach guarantees that our efforts are both effective and sustainable. Concurrently, capacity-building endeavors, combined with the AKIGTP knowledge platform, promise a continuum of learning and innovation. Drawing inspiration and lessons from Korea's IMSWM journey and harnessing the strengths of the quadruple helix framework, our ambition is not just to address current waste management challenges but to sculpt a resilient, innovative, and waste-conscious future for the entire ASEAN region.

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Notes

The authors declare no competing financial interest.

Biographies



Hogun Min is a Senior Research Engineer II at the School of Materials Science and Engineering, Nanyang Technological University. He earned his B.E. in Aircraft Systems Engineering from Korea Aerospace University in 2009 and an MBA from both the National University of Singapore and Peking University in 2019. With a strong background in the industry, Hogun has extensive experience in high tech sustainability projects, focusing on developing innovative solutions to address environmental challenges. He leads various strategic sustainability projects in collaboration with academia, industry, government, and international organizations. His work aims to foster cross-sector partnerships and drive impactful advancements in sustainable research, technologies, and practices at the Centre for Cross Economy Global, Nanyang Technological University.



Nam-Joon Cho, Ph.D., is the MRS-Singapore Chair Professor in the School of Materials Science and Engineering, the Director of Centre for Cross Economy Global, and the Director of Flagship Programmes at Nanyang Technological University. Also he serves a project leader and principal investigator at the Stanford University SyneRx Antiviral Drug Discovery Center (AViDD). Dr. Cho pioneered new fields in sustainability and healthcare: from transformation of plant pollen to replace environmentally harmful plastics, to antiviral peptide technology to develop broad-spectrum drugs responding to COVID-19. He initiated a new paradigm for sustainability called “Cross Economy” which designs to create new industrial opportunities through material innovation including using the wastes. He works closely with healthcare companies and other industrial partners in these translational projects, including serving as Project Lead at Stanford University’s Antiviral Drug Discovery Centre for Pathogens of Pandemic Concern, where he spearheads collaborative research funded by the US National Institutes of Health. A pioneer in developing a new economic model for economic prosperity in hybrid worlds, he has received international honours from organisations such as the American Liver Foundation and Ministry of Science and ICT in South Korea. He is a member of the National Academy of Engineering of Korea. He earned his B.S. degree in civil engineering from the University of California, Berkeley in 1996 and his M.S. degree in materials science and engineering and Ph.D. degree in chemical engineering from Stanford University in 2003 and 2007, respectively, and completed postdoctoral studies at the Stanford

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