Oct. 2026, Volume.3 No.3

Pages 121-194

Oct. 2026 Volume.3 • No.3

igee proceedings

IGEE Center for Global Sustainability Research
Yonsei University, Seoul, Korea

#301 Appenzeller Hall, Yonsei University, Seoul, Republic of Korea

e-igee.org igee.yonsei.ac.kr geef-sd.org

pISSN: 3022-5183 eISSN: 3022-5191
Oct. 2026, Volume.3 No.3

igee proceedings

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IGEE Proceedings is an international, multidisciplinary, scholarly, peer-reviewed, and open-access journal that aims to publish original research, review, and perspective papers across all fields relevant to achieving the 17 United Nations Sustainable Development Goals (SDGs). We aim to foster a holistic and integrated approach to sustainable development research by bringing together various disciplines and fields. *IGEE Proceedings* intends to help researchers, policymakers, practitioners, and the general public understand how to ensure the well-being of current and future generations by addressing complex social, environmental, and technological problems that pose sustainability challenges, which cannot be tackled in isolation.

We welcome submissions from researchers worldwide, with an emphasis on promoting diversity, equity, and inclusion. *IGEE Proceedings* values research that helps develop a better conceptual base for understanding sustainability and the social responsibility of organizations/institutions across borders. We encourage authors to explore innovative approaches and practical solutions that advance sustainable development in various contexts, including local, regional, national, and global levels. Our ultimate goal is to contribute to sustainable development by disseminating high-quality research that informs policymaking, decision-making, and public awareness.

We are open to accepting papers related to the SDGs, and we encourage authors to address issues related to various aspects of the SDG Framework, including, but not limited to, sustainable development, climate change, energy, food systems, water, biodiversity, health, education, poverty, inequality, and peace.

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Publisher IGEE Center for Global Sustainability Research at Yonsei University

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#805, 26 Sangwon 1-gil, Seongdong-gu, Seoul 04779, Korea
Tel: +82-2-6966-4930 Fax: +82-2-6966-4945
E-mail: support@m2-pi.com

Published on October 30, 2026

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This paper meets the requirements of KS X ISO 9706, ISO 9706-1994 and ANSI/NISO Z39. 48-1992 (Permanence of paper).

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Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):121-124
https://doi.org/10.69841/igee.2026.017

Perspective

Will We Shape AI, or Will AI Shape Us? A Call to Action for Sustainable Development

Jenny Shipley

36th Prime Minister of New Zealand; First Woman Prime Minister of New Zealand; Chair, APEC (1999); Senior Advisor, Boao Forum for Asia; Chair, Waitangi National Trust Board, New Zealand

Artificial intelligence is no longer a distant idea. It is our daily companion. We have each consented to have it in our lives, and AI is now taking on a life of its own within each of our personal, lived experiences. In that context, we need to accept that while this is a very exciting time, we also need to look past the hype around AI and think about sustainable development solutions, and indeed human development boundaries, with clarity.

So it is a time for action, and we must call on all nations at this moment to think about what comes next. These are challenging times, and it is very important, in my opinion, that even though there are personalities and events in recent weeks that are challenging our traditional thinking, we must not be overwhelmed by those circumstances or let them deter us from clarity of thought about how we look at a technologically enabled world, and in particular, what opportunities and conditions must exist to bring the Sustainable Development Goals into sharply focused reality for the future.

We must call on all nations and global companies to be participants, not just observers, in these circumstances, as we drive to close the gaps in the Sustainable Development Goals and make progress by 2030, at this very important moment of rapid transition that is imposing unprecedented change already impacting developed and developing economies alike.

But we must remember that in these circumstances, the world is the customer here. We need to think about what that really

Received: September 2, 2026 **Revised:** September 11, 2026
Accepted: September 29, 2026

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The Global Engagement & Empowerment Forum on Sustainable Development (GEEF) 2026, hosted by Yonsei University, was successfully held over two days from March 12 to 13, 2026. Addressing global challenges such as climate change, inequality, and humanitarian crises requires stronger international cooperation and collective action than ever before. GEEF 2026 serves as a global platform that moves beyond dialogue toward real action and measurable impact. As part of this year's program, a keynote address by Jenny Shipley, the 36th Prime Minister of New Zealand, examined how humanity must govern and direct the impact of artificial intelligence in order to accelerate progress on the Sustainable Development Goals. The following is a transcript of the keynote: https://www.youtube.com/watch?v=OBaAvhZgaDI

means. We must boldly indicate to developers of AI and other technological innovations that the world wants solutions for the many, not just novelty for the few. Trillions of dollars are currently being deployed across all manner of new technologies, and power is being concentrated in the hands of a few. I would argue that much of this investment may eventually come to nothing. Only a few of the many will deliver deployable technologies that produce commercially viable solutions and meaningful sustainable change for humanity at large.

So what must our call to action be at this conference, and in our broader conversations? I believe there is an urgent need to champion the concept of AI for good. It may sound naive, or simple in its clarity, but boundaries in this conversation are required. We need to define the space within which AI can move forward, and beyond which there are consequences, and we need to discuss who will bear the responsibility for those consequences in terms of impact, cost, and imposition.

Let us call on sustainable development funders, as the customer on behalf of us all, to make clear what they are willing to fund and scale in terms of solutions directly applicable to the Sustainable Development Goals. Perhaps we should call on all governments, developed and developing alike, to measure their own progress more deeply, framed in SDG language, so that the SDG narrative becomes meaningful across all of our economies. Perhaps we should demand that statisticians globally give equal prominence to SDG progress alongside GDP as a measure of a country's success. Let us consider establishing a global recognition brand for companies that are SDG champions, delivering AI-ready solutions that help achieve specific SDG outcomes. And let us call on investors to be discerning in their investment intentions, contributing specifically to what can be achieved through the SDGs, while remaining mindful of the impact of these innovations on human development as well as sustainable development.

And let us each commit to facing up to the demanding questions that need to be answered. Will we shape AI, or will we allow AI to shape us?

We have a responsibility to confront this question not tomorrow, not in the next political cycle, but now, while we have the time to insist that AI contributes to building a more just, sustainable, and human-centered world. If we do nothing, there are clearly grave risks that technology may deepen inequality, among other substantial risks that are constantly being identified. I hope many potential progressive solutions will be discussed at this conference that can meaningfully advance SDG outcomes.

And of course, there are reasons for hope. AI-assisted technologies and renewable energy, as has already been mentioned, are driving massive global shifts across developing and developed economies alike, optimizing solar and wind generation, managing smart grids, and improving battery storage and efficiency. These innovations are no longer theoretical. They are already reshaping global energy systems and prompting meaningful climate action, reducing emissions in transport and buildings, for example, and assisting us in monitoring our forests, our oceans, and our biodiversity in real time. In food production, AI deployment is directly contributing to improving food access and reducing vulnerability, and hopefully will continue to improve food security and, in the future, even more materially reduce poverty and improve prosperity.

There are many other positive examples we could consider, but two I view as particularly important are the gains in access to healthcare, and the innovation flourishing there even in the most remote corners of the globe, and access to finance now available to millions of people through AI innovation on platforms who would otherwise have had finance out of reach.

And while this is progress, there are of course many risks. What is clear is that if we are to ensure humanity and AI rise together to a point where they can comfortably coexist, we have a lot of work to do. At a global level, at the very least, we need a robust global AI governance framework to guide us, and a renewed commitment to delivering AI solutions in areas like the SDGs, which are not a theoretical framework but a commitment to close an equity gap and improve people's lives.

In a human sense, we must ensure that we share with our children and communities the reality that repetitive work may be replaced by AI-enabled systems and robotics. We must not avoid this conversation. It is already becoming a reality, and it will affect the middle classes more than anywhere else in most of our respective economies. It is a culture shock that has yet to have its full impact, and it will present huge challenges to the public policy environment in how we respond.

The education system, in my opinion, faces a huge challenge in terms of how it will pivot toward the skills that will flourish in the generation ahead of us. In my opinion, these

must include creativity, the ability to think critically and analyze rather than simply accept knowledge as presented, an ethical framework within which to exercise judgment, and deep emotional intelligence that does not allow machines to substitute the heart of who we are. And of course, adaptability and flexibility, but perhaps adaptability above all. What do we do when we are uncertain? Do we let it overwhelm us, or do we provide the skills and framework for people to navigate their way through these new complexities? These are conversations that families, households, communities, universities, societies, and global organizations need to be raising urgently, because it is something that cannot be deferred, given the speed with which AI is being deployed.

These qualities are at the heart of who we are as human beings, not just what we do, and that is the dividing assessment we need to think about. There is no question that AI has an unlimited capacity to change what we do and what it can do for us, and we may then have to deal with the consequences.

Trust has already been mentioned. To make progress, agreement must be achieved on how humanity and AI can coexist together, anchored on the values of trust, responsibility, and accountability. These three values require moral clarity. Political, industrial, and investor leaders must decide, and as they do, it will, in my opinion, be a mirror reflecting our priorities, our ethics, and our vision for the future. How do we close that gap and ensure we get this right, or will we leave these as two separate conversations, only to realize some way down the track that this has gotten beyond our ability to pull back together?

In my opinion, developers must understand that as they create a world of possibilities in this space, they must build trust and expect to be held responsible for the impact of their innovations, and to take accountability for the outcomes, both intended and unintended. Will governments be ahead of the developers, or will developers, as they are now, remain well ahead of governments? These are critical questions that I hope this conference will find the capacity to discuss.

Let us raise our voice at this forum in our call for a new collaboration among players in this AI-enabled human development space, as tools and solutions emerge that are affordable and sustainable, in order to accelerate progress in delivering the elusive Sustainable Development Goals, but that also enhance human development in the years, the centuries, and beyond.

The SDGs represent our collective promise to the world. More than ten years have passed, but the need has not abated. This promise, to end poverty, to protect our planet, and to ensure dignity for all, is as relevant now as it has ever been. But we need to accept that we cannot simply be observers. We have to be participants if these gaps are to be closed. That means something of each of us. We are the first generation, all of us in this room, senior and young alike, to live with AI, and perhaps we are the last generation with the power to shape it in the direction of AI for good.

As people who live in the Asia-Pacific region, at a moment when global institutions are under significant international stress and, whether we like it or not, weakened to some extent in their ability to make contributions, I would argue that the Asia-Pacific has an opportunity to show its natural agility here. Korea is clearly a champion and has already established well-developed systems. But I would encourage us to think about how, across the Asia-Pacific, we can use our connections, our alliances, and our friendships, historic and current, through vehicles such as APEC or RCEP, where local collaboration, cultural knowledge, and confidence in each other offer us an opportunity to move ahead. If we wait until global institutions are ready, it will be too late. There is a capacity for us here in this region to show leadership in this space.

So let 2026 be a year where we build collaborative relationships, set ambitious and achievable targets, and remain inspired in our belief that AI and humanity can rise together, delivering intentional AI-for-good solutions that give us a chance to secure the human development of our species in the future, and close the gaps of the SDGs as soon as we are able.

Acknowledgments

Dame Jenny Shipley served as the 36th Prime Minister of New Zealand from 1997 to 1999 and was the first woman to hold the office. Widely regarded for her leadership in economic and social reform, she has built a career of more than three decades spanning national government, corporate governance, and international engagement with leaders across Asia and the developing world. Before becoming Prime Minister, Shipley held senior Cabinet portfolios including Social Welfare, Women's Affairs, Health, and Transport, where she oversaw major reforms of New Zealand's welfare and health systems. As Prime Minister, she led a coalition and later a mi-

nority government through New Zealand's first parliament under the MMP electoral system, steered the country through the Asian financial crisis and back to growth, and chaired APEC in 1999, the first woman to do so. Since retiring from politics in 2002, Shipley has held board and advisory roles in New Zealand and abroad, including as Chair of Genesis Energy and as a director of China Construction Bank, and has served on the boards of the Boao Forum for Asia and the International Finance Forum. She is a long-standing member of the Club of Madrid, a network of former heads of state and government that promotes democratic governance, in which she has served as Vice President, and is a member of the World Women's Leadership Council. In 2026 she was appointed Chair of the Waitangi National Trust. She is a member of the Privy Council, a Dame Companion of the New Zealand Order of Merit, and trained as a teacher at the Christchurch College of Education before entering Parliament in 1987.

Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):125-128
https://doi.org/10.69841/igee.2026.019

Perspective

Building an AI Universal Basic Society: A Call for Global Intelligence Equity

Jiho Cha

Member of Parliament, The 22nd National Assembly, Korea

This theme, time for action, emerging technology, and global solidarity, reminds me of my own time for action twenty years ago, when I was working in humanitarian crises with Médecins Sans Frontières (MSF) and other humanitarian organizations. I tried to contribute something to the most marginalized communities around the world. But after ten years of humanitarian work and research, I found that the structural problems underlying this situation, including violence, poverty, and lack of healthcare access, were extremely difficult to improve, even where we had the resources and the financial and human commitment to contribute.

At the time, as both a researcher and a practitioner, I tried, as a physician, to make my own diagnosis of the fundamental problem. My conclusion was that the key barrier was the lack of a human intelligence system, or more precisely, extreme inequality in the human intelligence system. This was before artificial intelligence; at that time it was a human-only intelligence system. Developing a human intelligence system in healthcare, for doctors, or in other social sectors, requires a very sustainable education system. But the world's circumstances are not like that. Many countries in the Global South, and fragile states in particular, keep encountering conflict, social instability, and political difficulty, which makes it extremely difficult to build the education and training systems needed to strengthen the human intelligence system around the world. Even with significant energy and financial resources moving from the Global North to the Global South, our current world still suffers from extreme

Received: March 13, 2026 **Revised:** September 21, 2026
Accepted: October 12, 2026

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inequality. As a young physician, I could not understand why children were dying, and why so many patients could not be diagnosed, despite modern technology and available resources.

In that difficulty, I initially identified the problem as one of political structure, and as a professor and practitioner I focused my research on the political determinants of health crises. But I later realized that even if we could change the political system, that alone had already been attempted, and largely resolved, in the last century. At that point I encountered another transformation. About ten years ago, I encountered AlphaGo. For many of us, it was a shocking experience, and at that moment I recognized it clearly as a new kind of intelligence, a game changer with the potential to rebalance our human intelligence system and address the inequality inherited in its current, unequal distribution. I expanded my research entirely into artificial intelligence, held a series of meetings with MSF and other organizations, and came to see this as an area of huge potential for our future. Over the past ten years, I have devoted my effort to this area. I even changed universities, from the University of Manchester in the UK, which focuses on the humanities, to KAIST, and I have since moved into politics to help prepare for this transformation. But this is no longer only my own understanding; everyone in this room clearly understands the potential of artificial intelligence, and I have seen a strong commitment to translating these emerging technologies into globally marginalized countries on the basis of global solidarity.

The task now is to design what kind of global AI governance framework, and what type of official development assistance (ODA), needs to emerge in this context. In our government, and particularly during preparations for last year's presidential election, we developed the concept of an AI Universal Basic Society. It began as a concept for domestic AI transformation, but we came to see it as a strategy that could also contribute globally. The concept is simple: using artificial intelligence as a new intelligence model, and conceptualizing it specifically as a form of public intelligence. Treating artificial intelligence as public infrastructure allows us to scale up existing essential social services, healthcare, finance, education, and social care, and to mitigate environmental risk (Figure 1). There are many ways to apply these technologies to our current disparities in access to healthcare and other services.

In South Korea, for example, and in many other countries, even where the healthcare system is quite mature, there remains significant regional disparity in access to specialty care. If we conceptualize an AI-based universal basic healthcare model, not simply primary care but what might be called a "1.5-tier" healthcare system, integrating primary healthcare physicians and other providers with AI, we believe we can

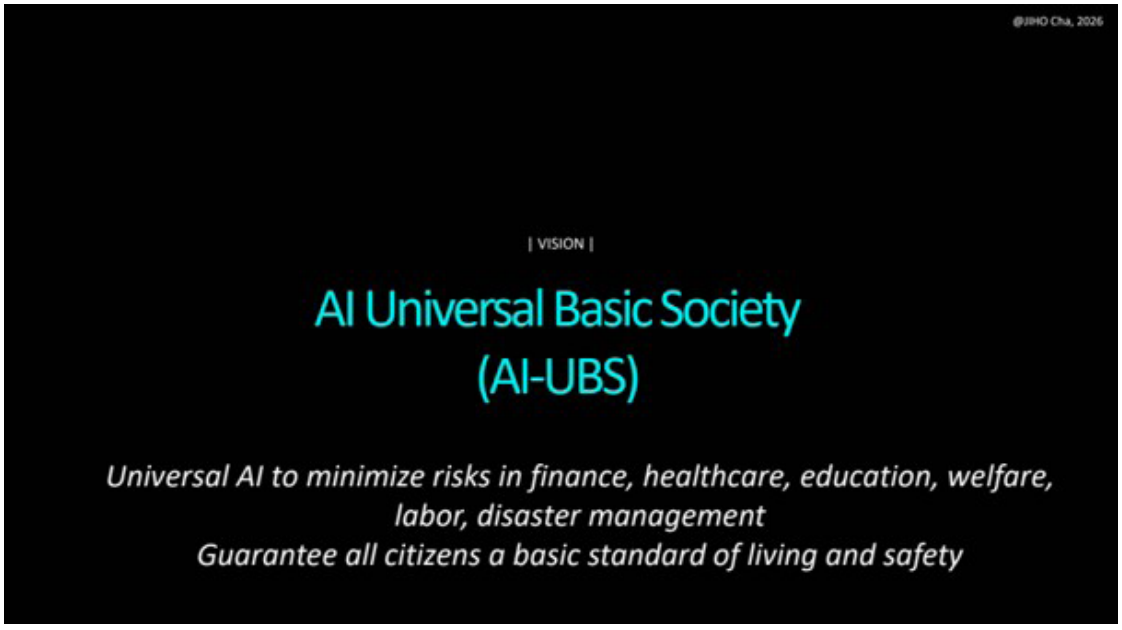

Figure 1. AI Universal Basic Society (AI-UBS): using universal AI to minimize risk across finance, healthcare, education, welfare, labor, and disaster management, and to guarantee all citizens a basic standard of living and safety.

scale this idea into something between primary and secondary healthcare. This concept could also apply in other global crisis contexts or resource-constrained settings, because an AI and digital healthcare platform built around primary healthcare can be readily linked to other contexts.

A similar approach applies to social care. If we integrate multidimensional data related to social welfare, economic conditions, and livelihoods, we can predict which households may be at risk of crisis weeks or even months in advance. This allows us to combine different social care models proactively, before a household reaches crisis, and prevent that kind of suffering. The same logic extends to education, where we can build much better accessibility, and to finance. Currently, financial intelligence is distributed unequally; loan terms and interest rates differ based on market logic and each individual's financial knowledge. But if we combine artificial financial intelligence with each citizen's circumstances, we can close the gap between those with greater financial knowledge and those with less, building better access to loans and other financial resources.

The fundamental fact is that our human intelligence system is unequal, but AI, as a form of public or digital intelligence, can help address this inequality within and between societies (Figure 2). We are working to translate the AI Universal Basic Society concept with other global partners, and we are currently discussing this concept with United Nations partners. Two days ago, we announced an initiative called the Global AI Hub, and we are now building partnerships with seven or eight key UN agencies. The UN system is currently under significant strain, suffering from financial crisis, which leaves it more vulnerable and often without sufficient resources to develop new initiatives in response to challenges like climate adaptation or artificial intelligence. An emerging country like South Korea, with financial resources, strong political commitment to change, a mature AI ecosystem, and standing as a representative democracy, is well positioned to help build this kind of global solidarity in AI application, across healthcare, education, and finance, and to support Global South countries in building the next generation of their social systems. This requires bilateral commitment and partnership with Global South countries, which South Korea is actively pursuing, as well as multilateral engagement through platforms like the United Nations, to support the UN in supporting the Global South.

This combination, our vision of AI Universal Basic Society within the UN framework, our bilateral partnerships with key Global South countries, and our effort to strengthen the UN system's capacity to adapt artificial intelligence to its mandate, forms a strong platform. But this is not the whole picture. While AI transformation may appear to be led by governments or the United Nations, in practice, the financial and technological drivers of AI transformation are led mostly by

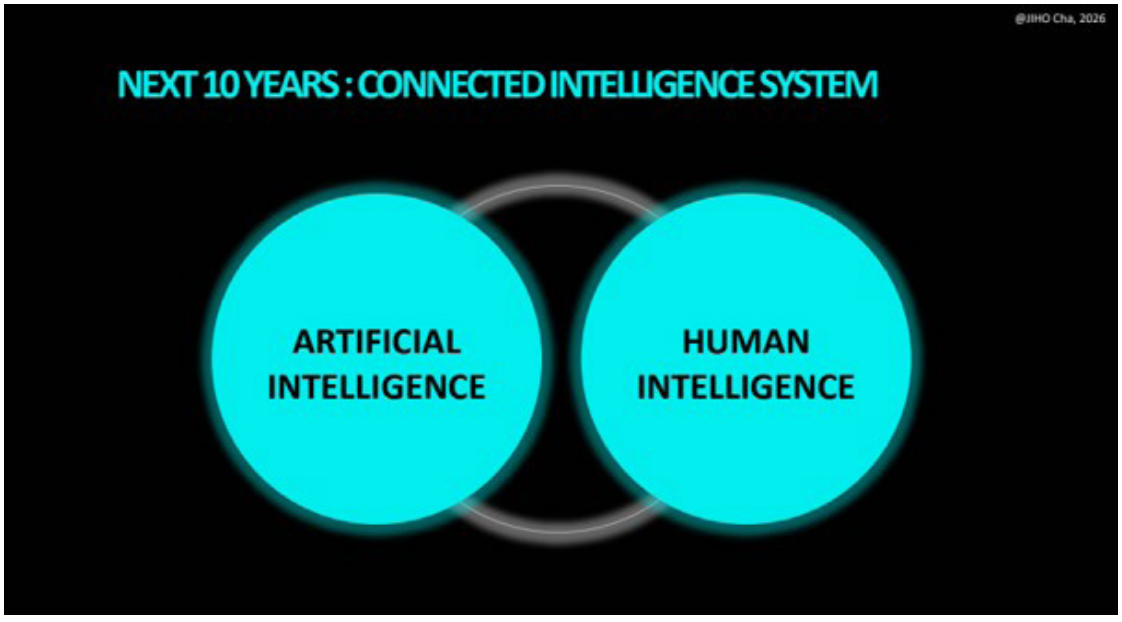

Figure 2. The connected intelligence system: closing the equity gap between artificial and human intelligence.

the private sector. It is therefore extremely important to engage the private sector in this transformation for the global public good, because the next major target of the AI market and industry will likely not be manufacturing or robotics, but the service economy. And the service economy, including healthcare and education, operates under public governance. This means that for AI transformation in these areas, a strong partnership between the public and private sectors is unavoidable if we are to remodel our society. How we engage this new model of innovation within multilateral organizations, and how we build a new AI-governed society that involves not only public authorities like government but also the private sector, is essential.

This discussion, this vision, and this policy should be grounded in our citizens' consensus. Two years ago, I tried to persuade political leadership on this dimension, but I came to realize that in a mature democratic society, the key question, what our next society, and our next generation of global society, should look like, belongs to our citizens to decide, because artificial intelligence will change everything. This is common knowledge, even among primary school students, yet we do not yet have this question reflected practically in policy, in our elections, or in our key political agendas. Gatherings like this one, at the leadership or technical level, are important, but it is equally important to bring this question into the minds of our citizens, because it is a profound political decision, one that concerns what kind of next society we need to design.

Returning to our theme, time for action, emerging technology, and global solidarity: my fundamental challenge and question is this. We all know about climate change, conflict, and global stress, but we are not ready for the compounding and cascading impact of these multiple, simultaneous crises. We do not currently have a global crisis resilience system capable of addressing this. Based on my twenty years of humanitarian experience, artificial intelligence is one of the few drivers I have found capable of building such a system. Our next generation, and the generations after it, will need strong resilience built on a more equal distribution of connected intelligence, between artificial and human intelligence, in order to prepare our societies for global crises and move toward a more equitable world.

This needs to be decided within the next fifteen years of AI transformation, and for Korea specifically, within the next five years, because the archetype of AI society our government establishes now will continue to shape the next fifty years. It is truly a time for action, now. We need to design our government and our society this year and next, and that design can be shared with our global partners and neighbors. I hope that all of us in this room, and all of our citizens outside it, can hold a single, shared question in mind: what should our next society be? It is time for action now.

Acknowledgments

Jiho Cha is a Member of the National Assembly of the Republic of Korea, representing Osan in Gyeonggi Province since 2024 as a member of the Democratic Party of Korea. A physician by training, he is widely regarded for his expertise in global health, humanitarian response, and the application of artificial intelligence to public health systems, and has built a career of more than two decades combining frontline medical practice, academic research, international policy work, and legislative leadership. Before entering the National Assembly, Cha served as a professor at KAIST's Moon Soul Graduate School of Future Strategy, where his research focused on AI-based strategic systems for anticipating and responding to future crises, including the design of AI-enabled public health services for regions facing social and humanitarian emergencies. He previously served as a professor at the University of Manchester in the United Kingdom, and has worked with Médecins Sans Frontières, the World Health Organization, and Human Rights Watch on humanitarian and refugee health issues. His interest in humanitarian and refugee studies began early in his career, when he provided medical care to North Korean defectors as a public health doctor at the Hanawon resettlement center. Cha currently serves as co-chair of the Lancet Commission on Sea-Level Rise, Health and Justice. He graduated from medical school in 2005 and holds an M.Sc. in Refugee and Forced Migration Studies from the University of Oxford and a Ph.D. in International Health from Johns Hopkins University.

Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):129-132
https://doi.org/10.69841/igee.2026.022

Letter

Introducing the 2025 'Social Engagement Fund' Cohort

Sarah Soyeon Oh*, Eun Kyoung Rhee

Institute for Global Engagement & Empowerment (IGEE), Yonsei University, Seoul, Korea

We are proud to present the finalists of Yonsei University's 2025 Social Engagement Fund (SEF), hosted by the Institute for Global Engagement & Empowerment (IGEE). As an institution committed to advancing the United Nations' Sustainable Development Goals (SDGs), IGEE designs and implements a variety of social contribution programs to address real-world challenges and generate practical solutions for a better future. The SEF program empowers students to transform their awareness and ideas about global social issues into tangible, positive change. In 2025, 34 teams applied; after a rigorous review by multiple faculty members, 12 teams (10 domestic and 2 international) were selected to receive support (Figure 1).

Following last year's commitment to incorporate more comprehensive IRB guidance and oversight, this year's program placed greater emphasis on research ethics and on preparing results for publication in IGEE Proceedings. Where ethical approval could not be fully secured, all authors were required to report the issues faced transparently in their ethical statements. However, we wish to emphasize that these activities continued to offer invaluable learning experiences for our undergraduate students as they engaged with real-world social challenges. Future initiatives will further strengthen this guidance so that ethical approval precedes recruitment in every project.

Across all four projects, a total of seven different Sustainable Development Goals (SDGs) were mainly addressed: SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 10 (Reduced Inequalities), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The projects demonstrated a broad and integrated approach to sustainable development by targeting multiple goals. For example, the Uganda electric motorcycle project addressed SDGs 3, 7, 8, 11, and 13 through its focus on public health, clean energy, riders' livelihoods, urban mobility, and climate action. The Hyderabad household waste study targeted SDGs 11 and 12 by examining what sustains waste segregation once the rules are already known. The Seoul environmental inequality study was aligned with SDGs 10 and 11, examining whether environmental burdens and housing vulnerability coincide across the city's neighborhoods, while the REGREEN initiative addressed SDGs 7 and 13 by linking renewable energy policy to youth participation and balanced regional development.

Received: October 10, 2026 **Revised:** October 13, 2026
Accepted: October 14, 2026
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SEF 2025 Selected Research Teams

Social Engagement Fund 2025, Yonsei University Institute for Global Engagement & Empowerment

Total teams: 12 | Domestic: 10 | International: 2

Category	Research project title
Domestic	Neuroimaging evidence of the effect of a cognitive behavioral therapy application on reducing short-form video viewing (인지행동치료 어플리케이션을 이용한 숏폼 시청 억제효과의 신경영상기법적 증명 연구)
Domestic	Effects of role-reversal cognitive behavioral therapy and a digital phenotyping-based puzzle video game for alleviating depression and anxiety in young adults (청년의 우울 및 불안 완화를 위한 역할 전환 인지행동치료 및 디지털 피노타이핑 기반 퍼즐 비디오 게임의 효과성 연구)
Domestic	Expanding opportunities for quality education through AI technology: designing a sustainable global citizenship education program for middle and high school students in Songdo (AI 기술을 통한 양질의 교육 기회 확대 방안 (AI 기술을 활용한 지속 가능한 세계시민교육 프로그램 설계–송도지역 중 · 고등학생을 중심으로))
Domestic	REGREEN: activating climate action for balanced regional development (REGREEN: 지역 균형 발전을 위한 기후행동 활성화)
Domestic	Creating sustainable and inclusive cities through GIS and ESG management analysis (GIS와 ESG경영 분석을 통한 불평등 없는 지속가능한 도시 만들기)
Domestic	Eco Step: small steps toward a sustainable future (에코스텝: 지속가능한 미래를 위한 작은 걸음)
Domestic	SafeZone: development of a game-based chatbot to support the social adaptation of patients with schizophrenia (SafeZone: 조현병 환자의 사회 적응을 위한 게임 기반 챗봇 개발)
Domestic	Drawing sustainable maps: a local SDGs mapping project in Sinchon and Yeonhui-dong (지속 가능한 지도를 그리다: 신촌 · 연희동 SDGs 로컬 매핑 프로젝트)
Domestic	Yonsei Eco Service: a clothing rental and upcycling system to address the single-use consumption of festival outfits (연세 에코 서비스 (축제 의상의 일회성 소비문제 해결을 위한 의상 대여 및 업사이클링 시스템))
Domestic	Curiosity-driven ethical consumption: exploring the moderating effect in the relationship between perceptions of people with disabilities and consumer behavior (호기심이 이끄는 윤리적 소비: 장애인 인식과 소비 행동 간 관계의 조절 효과 탐색)
International	Decentralized composting for climate adaptation: a field study of rural villages in Telangana, India (기후 적응을 위한 분산형 퇴비화: 인도 텔랑가나 농촌 마을의 현장 연구를 중심으로)
International	An integrated analysis of the respiratory health effects of the expansion of Uganda's motorcycle taxi industry and the barriers to transitioning to electric motorcycles (우간다 이륜택시 산업 확산의 호흡기질환 영향과 전기 이륜차로의 전환 장벽에 대한 통합적 분석)

Figure 1. Our 2025 SEF Finalists (Project titles translated from Korean for the following publication).

The following four articles showcase the exceptional work and dedication of several of these teams in advancing the Sustainable Development Goals (SDGs):

1. Can Electric Motorcycles Save Lives? Evidence from Uganda and Rider-Level Barriers to Electric Transition

Authors: Hyeongchan Yun, Beomjun Kim, Seoyoon Jung

Departments: Underwood International College; School of Economics, College of Commerce and Economics; Department of Cultural Anthropology, College of Social Sciences

Confronting the intertwined challenges of air pollution, road safety, and precarious livelihoods in Kampala's motorcycle taxi (boda boda) sector, this project asked whether electric motorcycles can save lives, and why riders may find it difficult to switch to electric transition in Uganda. Utilizing a complex, difference-in-differences (DID) design that incorporates data about the 2022 Ebola-induced lockdown in Mubende district as a natural experiment, the team estimated that transportation accounts for approximately 13.9% of ambient PM2.5, implying that full boda boda electrification could reduce PM2.5 by 5% and avert approximately 58 premature deaths annually in Kampala.

2. Where the Effort Disappears: Opacity, Reciprocity, and Household Organic Waste Practice in Hyderabad, India

Authors: Sohye Park, Sara Nuruddin Panjawani

Departments: Underwood International College; Yonsei School of Business

This study examined how urban households in Hyderabad, India handle organic waste, and why segregation mandates so often fail to translate into everyday practice. Through ten household interviews, in-home observation, and the distribution of composting kits followed by a return visit two and a half months later, the team found that neither knowledge nor equipment was missing: households could

state the rules and had received containers twice, yet the only stage of the waste chain they could see was the building gate, where their separated bags were consolidated. As one participant explained, “The government is not doing their part. Why should I do mine?” The authors concluded that “where collection infrastructure functions, the obstacle lies in what households can see of it.”

3. Environmental Inequality and Socioeconomic Vulnerability: A Meta-Analysis and Exploratory GIS-Based Spatial Analysis of Seoul

Authors: Seoyoung Park, Minseo Kim, Dayoung Lee, Seohyun Lee, Sohye Lee

Departments: Department of Chinese Language and Literature; College of Nursing

This research examined the relationship between environmental inequality and socioeconomic vulnerability by combining a PRISMA-guided systematic review and meta-analysis of ten empirical studies with an exploratory GIS analysis of Seoul’s 426 administrative dongs. The meta-analysis yielded a positive pooled association between environmental disadvantage and socioeconomic vulnerability ($r = 0.316$, 95% CI: 0.183–0.438) despite substantial between-study heterogeneity, while the Seoul analysis identified a weak positive association between environmental infrastructure facility proximity and the proportion of publicly supported housing ($r = 0.187$), together with statistically significant spatial clustering of the proximity indicator (Moran’s $I = 0.216$).

The project was commended for its methodological ambition and, equally, for its restraint: the Seoul findings are framed as a first-stage screening tool for identifying candidate areas for closer investigation rather than as definitive evidence of environmental injustice. The study aligned with SDGs 10 and 11.

4. Climate Action for Balanced Regional Development: Exploratory Youth Preferences for Renewable Energy Policy Using Conjoint-Informed Scenario Ratings

Authors: Sujin Kim, Dain Jin, Sihyun Jung

This project, led by the student initiative REGREEN (Regional Equity for GREEN Action), investigated which features of renewable energy policy design make young Koreans willing to participate in climate action initiatives. A field study at the Yeongdeok community wind energy cooperative informed an online pilot study ($N = 50$, ages 18–29) combining an educational video, four gamified learning modules, a simulated cooperative market, and a conjoint-informed rating of six policy scenarios. According to the research data, renewable energy awareness increased from 4.2 to 5.7 on a 7-point scale (Cohen’s $d = 1.18$), and governance structure emerged as the strongest preference signal, with cooperative joint ownership rated on average 1.77 points higher than the expert-managed scenario. In quote of the authors:

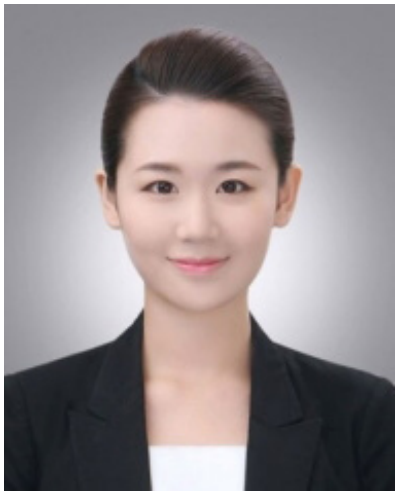
“Governance architecture emerged as the strongest observed preference signal among these young Korean university participants, but the finding should be interpreted as exploratory and post-intervention rather than as a stable national estimate for Korean youth.”

The study was commended for developing a potentially replicable research platform and for the transparency with which it reports the limits of a pilot study. The project contributed especially to SDG 7 (affordable and clean energy) and SDG 13 (climate action), with its emphasis on balanced regional development speaking to SDG 10 as well.

These projects were a testament to the creativity, research expertise, and empathy valued by our student community. SEF 2025 reminded us that the SDGs are not abstract targets but lived commitments shaped by our students’ commitment to foster a more sustainable world.

We extend our deepest congratulations to all SEF 2025 finalists and look forward to the continued impact of their work.

Warm regards,



Sarah Soyeon Oh *is a research professor at the Institute for Global Engagement & Empowerment (IGEE) at Yonsei University, where she helps coordinate the Social Engagement Fund and leads a range of research projects focused on sustainable development and student empowerment. With a background in public health, Oh's primary interests include applying machine learning and statistical analyses techniques to maternal and child epidemiological research to build inclusive support systems for underrepresented communities.*

Eun Kyoung Rhee *is a visiting professor at Yonsei University's Institute for Global Engagement & Empowerment (IGEE), where she supports the Social Engagement Fund and conducts research on sustainable development. With a background in Political Science, her work focuses on balanced regional development as a core strategy for achieving sustainable development, exploring policy approaches and practical solutions to address social challenges such as regional decline.*

Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):133-151
https://doi.org/10.69841/igee.2026.021

Article

Climate Action for Balanced Regional Development: Exploratory Youth Preferences for Renewable Energy Policy Using Conjoint-Informed Scenario Ratings

Sujin Kim*, Dain Jin, Sihyun Jung

Yonsei University, Seoul, Korea

Background: Korea's Renewable Energy 3020 Implementation Plan targeted a 20% share of power generation from new and renewable energy by 2030, yet such sources supplied only 10.6% of electricity in 2024. This implementation gap highlights social acceptance, community governance, and youth civic participation as important barriers alongside technology and finance. Quantitative evidence on which specific policy design attributes shape young Koreans' willingness to participate in renewable energy initiatives remains limited, and the mechanism by which educational engagement translates into pro-environmental behavioral choice has not been directly examined in this population.

Methods: The study employed a two-phase sequential design. Phase 1 consisted of an on-site preliminary field study at the Yeongdeok Renewable Energy Exhibition Hall (November 2025), involving direct observation of operational infrastructure and structured engagement with local cooperative stakeholders to ground subsequent instrument development in real-world context. Phase 2 was a one-group pre-post quasi-experimental online pilot study (N = 50, ages 18-29) in which participants completed a five-stage integrated protocol: a baseline awareness survey, a 15-minute educational video, four gamified learning modules linked to an Energy Coin (E.C.) reward system, a simulated cooperative online market transaction under experimentally induced point-budget constraints, and a post-survey incorporating an exploratory conjoint-informed scenario-rating task across six policy scenarios defined by four attributes (installation location, economic benefit type, participation mechanism, and governance structure). The six profiles are reported explicitly and treated as a burden-reduced profile set for main-effect exploration rather than a fully orthogonal conjoint design. Sample size was determined via G*Power 3.1 analysis of the paired awareness comparison (93% power at n = 50 for a medium within-person effect); the same n is not sufficient for regression-based attribute modelling, so the attribute results are reported as exploratory.

Results: Renewable energy awareness increased significantly from M = 4.2 to M = 5.7 on a 7-point scale ($t(49) = 8.34$, $p < 0.001$, Cohen's $d = 1.18$). Because the six-profile set cannot identify a full dummy-coded specification, attribute effects are report-

Received: February 4, 2026 **Revised:** September 29, 2026
Accepted: October 12, 2026
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ed as marginal means. Governance structure showed the widest spread (design-dependent relative importance 47.8%; cooperative joint ownership M = 5.69 vs. expert-managed M = 3.92, Δ = +1.77, 95% CI [1.27, 2.26]), followed by economic benefit (26.0%) and installation location (22.2%, Δ = +0.82 for farmland/idle land, 95% CI [0.37, 1.27]); the six scenario profiles accounted for 24.9% of the total variance in ratings ($\eta^2 = 0.25$). Participation mechanism accounted for 4.1% and was not significant; inferential claims are treated cautiously because ratings were repeated within participants, the profile set was small and nonorthogonal, and preferences were measured immediately after the educational intervention. In the only pair of scenarios that differed on governance structure alone (S6 vs. S4), the cooperative joint-ownership profile was rated 1.59 points higher than the expert-managed profile (95% CI [1.08, 2.10]). Energy Coin accumulation was associated with ecofriendly product selection (r = 0.42, 95% CI [0.16, 0.63], p = 0.002), although this association is descriptive because the same E.C. score also determined participants' simulated purchasing budget.

Conclusion: Governance architecture emerged as the strongest observed preference signal among these young Korean university participants, but the finding should be interpreted as exploratory and post-intervention rather than as a stable national estimate for Korean youth. A two-phase design combining field exposure with gamified online simulation was associated with large immediate awareness gains and simulated pro-environmental choice under explicit point-budget tradeoffs, offering a scalable evidence-generating approach for youth-centered climate policy research while requiring replication with more diverse regional and socioeconomic samples.

Keywords Renewable energy policy, Conjoint-informed scenario ratings, Youth preferences, Cooperative governance, Balanced regional development

1. Introduction

Korea's energy transition confronts a structurally revealing paradox. The country has pledged carbon neutrality by 2050 and, under the Renewable Energy 3020 Implementation Plan, targeted a 20% renewable share by 2030; however, new and renewable energy sources supplied only 10.6% of electricity in 2024, up from 4.99% in 2018 and crossing the 10% threshold for the first time (International Energy Agency, 2020; Korea Energy Agency, 2024). The trajectory is positive, but the gap between policy ambition and implementation reality remains substantial, and it cannot be closed by technology deployment and capital investment alone. A convergent body of interdisciplinary research points to a more intractable constraint: the absence of structured, community-level social acceptance for the infrastructure that energy transition demands.

This distinction is consequential. Renewable energy projects-particularly wind installations and distributed solar-are uniquely vulnerable to forms of community resistance that differ in character from opposition to conventional energy infrastructure. Rather than objecting only on environmental grounds, communities often contest renewable projects on procedural and distributional grounds: concerns about who governs the project, who benefits from its revenues, and whether the terms of community engagement are genuine or performative. Wüstenhagen, Wolsink, and Bürer (2007) conceptualize renewable-energy acceptance across sociopolitical, community, and market dimensions, while Walker and Devine-Wright (2008) and Warren and McFadyen (2010) show that community ownership and local participation can shape public attitudes toward wind energy. From a behavioral perspective, Thaler and Sunstein (2008) further demonstrate that choice architecture-the way options are framed, structured, and presented-can shape engagement independently of objective policy content.

Young people aged 18–29 occupy a theoretically central but empirically underexamined position in this landscape. As the cohort that will bear the preponderance of long-term climate consequences, constitute the future labor force of the green economy, and be called upon to sustain political legitimacy of the energy transition across multiple decades, their preferences are not merely demographically interesting—they are a policy-critical input whose absence from the evidence base represents a genuine gap in governance quality. Yet despite the proliferation of youth-oriented climate communication campaigns, Korean research on which specific dimensions of renewable energy policy design resonate most strongly with young people—and how educational interventions translate into behavioral choice rather than mere attitude change—remains thin.

In this study, balanced regional development is used in a specific operational sense: renewable energy policy designs are considered regionally balanced when they distribute eco-

nomic, participatory, and symbolic benefits to non-metropolitan communities that host or support energy infrastructure. This concept is operationalized through the installation-location attribute (where infrastructure is placed), the economic-benefit attribute (how material benefits are distributed), the governance-structure attribute (who holds decision authority), and the cooperative market's regional products and Development Fund surcharge (how value circulates back to local communities).

This study addresses that gap through REGREEN (Regional Equity for GREEN Action), a student-led research initiative at Yonsei University. The project employed a two-phase design: Phase 1 was a preliminary field study at the Yeongdeok community energy cooperative, designed to ground the research team's understanding of real-world cooperative governance before instrument construction; Phase 2 was an online simulation study incorporating educational video content, four game-based learning modules, a cooperative market with simulated cost constraints, and a conjoint-informed scenario-rating survey. The study pursues four research objectives:

(1) to describe the design-dependent relative importance of four policy attributes-installation location, economic benefit type, participation mechanism, and governance structure-in shaping willingness to support renewable energy initiatives among the recruited pilot sample;

(2) to assess whether a structured, gamified educational intervention produces measurable pre-post change in renewable energy awareness;

(3) to examine whether educational engagement, operationalized through game performance and E.C. accumulation, is associated with pro-environmental behavioral choice in a simulated cooperative market; and

(4) to derive evidence-informed hypotheses for youth-oriented renewable energy policy in the Korean context rather than definitive national policy prescriptions.

Consistent with the pilot character of the project, the empirical claims are framed as exploratory and hypothesis-generating. The study estimates post-intervention preference patterns among a small, digitally recruited university sample rather than making definitive claims about all Korean youth. This framing is important because the Phase 2 sample is geographically concentrated in the Seoul metropolitan area, the ratings were collected after-not before-the educational intervention, and the Yeongdeok cooperative case may have made cooperative governance especially salient.

The theoretical contribution of this study is threefold. First, it adapts conjoint logic-well established in consumer choice, stated-preference, and political survey research-to a youth-focused energy policy context in Korea while explicitly acknowledging that the six-profile design cannot support full conjoint inference (Green & Srinivasan, 1990; Hainmueller, Hopkins, & Yamamoto, 2014; Louviere, Hensher, & Swait, 2000). Second, it operationalizes the attitude-behavior gap not through self-report intention scales alone but through a simulated point-budget market transaction, offering a behaviorally richer proxy than conventional survey items while not equating the task with real market behavior. Third, it tests whether gamified climate education is associated with immediate awareness change and simulated downstream choice within a single integrated session, moving beyond awareness measurement to capture explicit trade-offs under simulated cost premiums.

2. Materials and Methods

Materials

The REGREEN research infrastructure consisted of four integrated components. The primary digital interface was a custom browser-based web application (https://fullhqkb.gensparkspace.com) developed by the REGREEN team, hosting game modules, the cooperative market, and the participant progress dashboard. Survey instruments were administered via Google Forms (baseline and post-survey), chosen for compatibility across device types used by participants accessing the protocol remotely. The central educational component was a narrated, slide-based video of approximately 15 minutes, developed from publicly available sources and the REGREEN team's Phase 1 field documentation from Yeongdeok. External data sources included the IEA policy description of Korea's Renewable Energy 3020 Plan, 2024 Korean power-generation statistics reported by the Korea Energy Agency from Ministry of Trade, Industry and Energy data, the Global Carbon Budget 2024, United Nations SDG documentation, and Korea's 2050 Carbon Neutral Strategy (Friedlingstein et al., 2025; Government of the Republic of Korea, 2020; International Energy Agency, 2020; Korea Energy Agency, 2024; United Nations, 2015). Video content covered: the definition and typology of renewable energy sources; Korea's current energy mix and policy trajectory toward the 2030 renewable target; global fossil CO2 emissions

projected at approximately 37.4 GtCO2 in 2024 and total anthropogenic CO2 emissions projected at approximately 41.6 GtCO2; SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action); and a 5-minute documentary case study of the Yeongdeok community wind energy cooperative, drawing directly on field observations and stakeholder interviews conducted in Phase 1. Phase 1 fieldwork materials included structured observation protocols, semi-structured interview guides used with cooperative managers and local school partners, and participant briefing materials for the workshop. These Phase 1 materials informed both the Yeongdeok case study content in the educational video and the formulation of the governance attribute levels in the scenario-rating design, ensuring that the cooperative and resident co-management levels reflected institutional arrangements encountered in the field rather than purely abstract constructs.

Methods

1) Participants

The study was organized into two sequential participant groups corresponding to the two phases. *Phase 1 — Yeongdeok Field Study (29 November 2025)*: A convenience sample of 17 university-affiliated participants (four REGREEN team members and 13 affiliated university students; n = 17) attended the on-site workshop at the Renewable Energy Exhibition Hall in Yeongdeok, North Gyeongsang Province. All 17 Phase 1 participants were university-affiliated members of the project network; cooperative managers, local school representatives, and a local social-enterprise partner took part as stakeholder informants in structured conversations with the research team, not as study participants. The workshop served a dual function:

(a) as an experiential pre-study for the research team to calibrate the policy attribute levels against real-world cooperative governance structures encountered at the site, and

(b) as a pilot run of the educational materials in a face-to-face setting. No scenario-rating data were collected in Phase 1, and no Phase 1 data enter the Phase 2 analyses. Phase 1 data consisted of (i) a pilot administration of the five pre- and post-awareness items to the 17 participants, (ii) pilot runs of the four game modules and an in-person version of the market task in which participants allocated E.C. to physically labelled products, and (iii) qualitative field notes and stakeholder interview records. The pilot survey and market data are reported descriptively in the Results; the field notes and interview records produced a refined understanding of how community energy cooperatives operate in practice that directly informed Phase 2 instrument development. Field notes were reviewed by the research team and organized by consensus into four practical themes: governance transparency, benefit-sharing, educational accessibility, and regional circulation of value. Because formal independent coding and inter-coder reliability checks were not conducted, Phase 1 is reported as a structured qualitative pilot rather than as a stand-alone qualitative study.

Phase 2 - Online Platform Study (N = 50): Fifty participants (Table 1) were enrolled via a two-stage recruitment and screening process; recruitment and data collection took place between 13 and 31 December 2025. Stage one involved public posting through the Yonsei University Everytime application, departmental mailing lists, Instagram, and Facebook via the REGREEN team's official accounts. Stage two applied a structured screening form to verify:

(a) age between 18 and 29 years;

(b) Korean language proficiency sufficient for survey and game instructions;

(c) absence of academic or professional specialization in renewable energy or energy policy, to minimize systematic prior knowledge bias;

Table 1. Participant Demographic Characteristics, Phase 2 (*N* = 50)

Characteristic	Category	n (%)
Age	18-22	31 (62%)
	23-26	14 (28%)
	27-29	5 (10%)
Gender	Female	28 (56%)
	Male	19 (38%)
	Non-binary / Prefer not to say	3 (6%)
University Region	Seoul Metropolitan Area	45 (90%)
	Outside Seoul	5 (10%)
Academic Year	1st-2nd year	26 (52%)
	3rd-4th year	20 (40%)
	Graduate	4 (8%)
Academic Major	Business / Economics / Social Sciences	24 (48%)
	Humanities/Arts	11 (22%)
	STEM (non-energy)	10 (20%)
	Other	5 (10%)
Pre-intervention Awareness	M (SD)	4.2 (1.3)

(d) no participation in an energy policy study within the previous six months; and

(e) absence of physical or cognitive barriers to computer-based game participation. Instructor-affiliated classes were excluded from recruitment to minimize researcher-participant power imbalances. All participants provided informed consent via an online checkbox acknowledgment after reading a standardized digital participant information sheet; participation was voluntary; data were stored anonymized and separately from identifying information.

The resulting sample should be understood as a purposive pilot sample of digitally active university-age participants, not as a probability sample of Korean youth. This distinction is carried through the analysis and discussion: effect sizes and preference rankings are reported as internally informative patterns requiring external validation rather than as nationally representative estimates.

Sample size justification: The target of 50 participants was set with reference to a power analysis conducted in G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) for the study's confirmatory outcome, the paired pre-post awareness comparison. In the initial submission the sample-size justification was anchored to the regression-based attribute model; because the six-profile design does not identify that model and the attribute analysis is reported as exploratory marginal means, the justification has been re-anchored to the paired awareness comparison, the only inferential test the design was powered to support, and the regression-based calculation is retained below for transparency. For a two-tailed paired-samples t-test with $\alpha = 0.05$ and a medium within-person effect ($d = 0.50$), $n = 34$ is required for 80% power and $n = 50$ provides 93% power. The same n is not sufficient for a regression-based attribute model: with four predictors, $\alpha = 0.05$ and $f^2 = 0.15$, 80% power would require $n = 85$, and power at $n = 50$ is 0.52. This asymmetry is stated explicitly rather than smoothed over, and it is the reason the attribute-level results are framed as exploratory throughout. The calculation likewise does not establish that six policy profiles are sufficient for fully orthogonal conjoint estimation, interaction testing, or subgroup analysis. Rather, $N = 50$ should be understood as adequate for an initial exploratory platform test and immediate pre-post awareness analysis, while the scenario-rating coefficients remain design-dependent. A maximum recruitment ceiling of 60 was set to buffer against an anticipated 15-20% attrition rate typical of online behavioral research. The achieved 100% completion rate rendered attrition analysis moot, though the protocol included pre-specified criteria for identifying and excluding inattentive respondents based on response-time flags and game abandonment rates.

2) Measures

Four categories of measures were employed across the protocol.

(1) *Renewable energy awareness* was assessed at baseline and post-intervention using a five-item composite scale administered on a 7-point Likert scale. Items included: "How important do you consider renewable energy for Korean society?"; "How much do you currently know about renewable energy?"; "How interested are you in eco-friendly products and services?"; "Do you believe renewable energy can realistically address climate change?"; and "How willing would you be to support a renewable energy project in your local area?" The composite score was the mean across items (Cronbach's $\alpha = 0.81$ at baseline, indicating good internal consistency).

(2) *Game performance* was operationalized as total Energy Coins (E.C.) accumulated across the four modules (theoretical range: 200–800 E.C.), with performance-linked E.C. tiers calibrated per game as specified below. E.C. served dual analytical functions: it indexed educational engagement as a continuous variable for correlation analysis, and it constituted the point-budget constraint in the Stage 4 cooperative market, creating experimentally induced scarcity that approximated real purchasing tradeoffs.

(3) *Cooperative market behavior* was automatically logged by the platform, capturing: product category selected (eco-friendly, general, or regionally-produced); proportion of total E.C. allocated to each category; and binary acceptance of the Green Tax surcharge (eco-friendly items) and Development Fund surcharge (regional items). The primary behavioral outcome was a binary variable: eco-purchase = 1 if at least one eco-friendly product was selected, 0 otherwise. Because E.C. were in-platform points, the outcome is interpreted as simulated cost-bearing choice rather than verified real-world purchase behavior.

(4) *Policy scenario preference* was the dependent variable in the conjoint-informed scenario rating analysis: a 1–7

willingness-to-participate rating (1 = "Would not participate at all"; 7 = "Would participate very actively") for each of six policy scenarios. Because each respondent rated all six scenarios, these observations were analyzed as repeated measures rather than as independent observations.

3) Study Model

The study was organized as a sequential two-phase design in which Phase 1 qualitative field observations informed Phase 2 instrument construction, and Phase 2 employed a one-group pre-post quasi-experimental design within a five-stage integrated protocol. The logic model framing the overall inquiry is: *Input* (Phase 1 field knowledge + Phase 2 educational video + four game modules + cooperative market) → *Process* (sequential engagement with escalating cognitive and behavioral demands, building from awareness through knowledge to consequential choice) → *Output* (conjoint preference structure + pre-post awareness gain + behavioral market choice data) → *Outcome/Impact* (evidence base for youth-centered renewable energy policy redesign in Korea).

Phase 1 - Yeongdeok Field Study: On 29 November 2025, the research team conducted a structured site visit and workshop at the Renewable Energy Exhibition Hall in Yeongdeok, North Gyeongsang Province. The visit included: guided observation of operational wind turbine infrastructure and photovoltaic installations; semi-structured conversations with cooperative managers regarding benefit-sharing mechanisms, governance structures, and community engagement history; and structured meetings with representatives from Yeongdeok middle and high schools and from Cafe BOUM, a local social enterprise that collaborates with the cooperative. The field observations served two functions for Phase 2. First, they grounded the "cooperative joint ownership with transparent management" governance attribute level in observed institutional practice-the Yeongdeok cooperative's resident board, transparent revenue accounts, and annual community meetings provided the practical template. Second, the Yeongdeok case study embedded in the Phase 2 educational video was documented during this visit, ensuring the educational content reflected verifiable, on-the-ground conditions rather than idealized descriptions.

Phase 2 — Online Platform Protocol: The five-stage online protocol was designed as a sequential engagement funnel (Table 2), where each stage deepened participants' cognitive and affective engagement with renewable energy while generating distinct categories of analytical data.

Stage 3 — Gamified Learning Modules: Four sequential browser-based games were administered, each designed to operationalize a distinct educational or behavioral construct:

- *Game 1 (Knowledge Quiz)*: A 20-item multiple-choice quiz modeled on the Kahoot platform format (20-second time limit per item; four answer options), assessing comprehension of the educational video content across domains: renewable energy definitions, Korea's energy statistics, the SDG framework, global carbon emissions, and the Yeongdeok cooperative model. Reward tiers: 18–20 correct → 200 E.C.; 15–17 → 150 E.C.; 12–14 → 100 E.C.; ≤11 → 50 E.C. Construct measured: *knowledge acquisition and video comprehension*.
- *Game 2 (Precision Timer)*: A browser-based timer task requiring participants to stop a running clock at precisely 60.00 seconds (maximum 90 seconds before auto-termination). This game carried no content-specific renewable energy dimension; its inclusion was motivated by the need to measure *executive attention and temporal self-regulation*—cognitive constructs associated with the quality of sustained learning engagement—while maintaining participant arousal during what might otherwise be a monotonic survey session. Reward tiers: deviation ≤ 0.05s → 200 E.C.; ≤ 0.15s → 150 E.C.; ≤ 0.30s →

Table 2. Two-Phase Study Design: Sequential Structure and Analytical Outputs

Phase	Stage	Activity	Duration	Analytical Output
Phase 1	0	Yeongdeok field study (observation, interviews, workshop)	Full day	Qualitative field notes; instrument calibration; educational video content
Phase 2	1	Baseline survey	5 min	Pre-awareness composite (1–7); demographics
	2	Educational video	~15 min	Standardized knowledge exposure; no direct measurement
	3	Gamified learning modules (×4)	10-15 min	E.C. score (200–800); per-game performance data
	4	Cooperative market transaction	5 min	Product choice (eco/general/regional); E.C. allocation per category
	5	Post-survey: conjoint + experience	10-15 min	6 Scenario ratings (1-7); post-awareness composite; satisfaction scores

Table 3. Policy Attributes and Levels Used in the Scenario-Rating Task

Attribute	Level 1 (Reference)	Level 2	Level 3
Installation Location	Residential / campus vicinity	Public land / campus area	Farmland / idle land
Economic Benefit	10% Electricity bill discount	Local vouchers (100,000 KRW/month)	Free educational / experiential programs
Participation Mechanism	Information sessions only	Voluntary / applicants-based	Open, Continuous participation
Governance Structure	Expert-managed	Resident youth representative co-management	Cooperative joint ownership with transparent management

Table 4. Six Policy Scenarios: Exploratory Burden-Reduced Profile Set

Scenario	Location	Benefit	Participation	Governance
S1	Public land	Local vouchers	Open, Continuous	Resident youth co-management
S2	Farmland/idle land	Educational programs	Open, Continuous	Resident youth co-management
S3	Residential/campus	Electricity discount	Open, Continuous	Resident youth co-management
S4	Public land	Educational programs	Voluntary	Expert managed
S5	Farmland/idle land	Local vouchers	Voluntary	Cooperative joint ownership
S6	Public land	Educational programs	Voluntary	Cooperative joint ownership

100 E.C.; otherwise → 50 E.C.

- *Game 3 (Turbine Matching Puzzle)*: A 30-second visual matching task pairing six wind turbine image types (blade-type, paddle-type, cross-flow, Dutch, Darrieus, and propeller) with their correct labels. Construct measured: *technical domain recognition and visual knowledge consolidation*. Reward tiers: 6 correct → 200 E.C.; 5 → 150 E.C.; 4 → 100 E.C.; ≤3 → 50 E.C.
- *Game 4 (Solar Car Racing)*: A 3D mouse-tracking racing game in which a solar-powered vehicle follows the participant's cursor around an obstacle course; completion time was automatically recorded. Construct measured: *hand-eye coordination, sustained attention, and hedonic engagement*—included explicitly to maintain motivational state and assess subjective enjoyment as a secondary construct relevant to platform replicability. Reward tiers: ≤10s → 200 E.C.; ≤12s → 150 E.C.; ≤15s → 100 E.C.; ≤18s → 50 E.C.

Stage 4 — Cooperative Market Transaction: Participants accessed a simulated cooperative market interface populated with three product categories, each priced in E.C.:

(a) eco-friendly products, carrying a "Green Tax" surcharge—a deliberate simulation of the price premium associated with sustainably produced goods and a proxy for carbon pricing tradeoffs;

(b) regionally-produced goods from Yeongdeok and North Gyeongsang, carrying a "Development Fund" surcharge simulating the localized revenue-sharing premium of cooperative market structures; and

(c) general products without surcharge. The E.C. budget was bounded by Stage 3 performance, creating a simulated scarcity constraint. All transactions were server-logged automatically.

Stage 5 — Post-Survey: Survey A presented six policy scenarios constructed from the attribute levels in Table 3 (Table 4) and asked participants to rate each on the 1–7 willingness-to-participate scale. The scenario set was a burden-reduced profile set selected from the full 3^4 profile universe to preserve respondent attention in a 45–55-minute online protocol; it was not intended to estimate interaction effects or stable population-level part-worth utilities. Survey B measured: game learning effectiveness (1–7); game engagement (1–7); cooperative market satisfaction (five items, 1–7); and future research participation intent (binary Yes/No).

Design generation and constraints: The profile design began with the 3^4 = 81 possible combinations of location, economic benefit, participation mechanism, and governance structure (Table 3). Six profiles were retained for the online pilot to minimize fatigue after the video and game modules and to retain ecological plausibility based on Phase 1 field observations. The exact retained profiles are reported in Table 4 to make the design transparent and replicable. However, a six-profile design cannot achieve full orthogonality for four three-level attributes, cannot support interaction estimates, and cannot identify causal average marginal component effects in the sense of fully randomized conjoint experi-

ments (Hainmueller et al., 2014). Several features of the retained set should be borne in mind when reading the attribute-level results, because the effects of some attributes cannot be separated from one another within this design: the reference level of participation mechanism (information sessions only) does not appear in any retained profile; open, continuous participation occurs in exactly the profiles in which resident youth co-management occurs (S1–S3), so those two levels cannot be separated; expert management appears only in S4; and the reference levels of installation location (residential/campus vicinity) and economic benefit (electricity bill discount) both appear only in S3, so those two reference levels are confounded with each other. S6 and S4 are the only pair of profiles that differ on a single attribute (governance structure), and that contrast is therefore reported separately in the Results. Consequently, the estimates below are reported as exploratory, design-dependent rating contrasts rather than conclusive part-worth utilities, and the participation coefficients in particular should be read as descriptive of the profile set rather than as isolated attribute effects.

4) Analysis

Five analytical procedures were employed, organized from descriptive to inferential.

Descriptive statistics: Frequency distributions and percentages were computed for demographic variables; means, standard deviations, and ranges were computed for game performance and scenario preference scores.

Conjoint-informed scenario-rating analysis (primary exploratory analysis): Attribute effects were estimated as marginal means rather than as dummy-coded regression part-worths. For each attribute level, the marginal mean is the mean willingness-to-participate rating across the scenarios that contain that level, averaged over participants, and is computed from the same pooled dataset (50 participants x 6 scenarios = 300 observations). This estimator was chosen because a full main-effects specification for four three-level attributes requires nine parameters (an intercept plus eight level indicators), whereas the six retained profiles span only six independent design points; a dummy-coded regression is therefore not identified, and marginal means are the recommended quantity when reference-category-dependent estimates would be unstable or undefined (Leeper, Hobolt, & Tilley, 2020). Standard errors follow a deliberately conservative convention: the standard deviation used for a level spanning k scenarios is the mean of those scenarios' standard deviations, an upper bound on the standard deviation of the participant-level average whenever the within-person correlation is non-negative. Contrasts between levels use the corresponding independent-samples standard error, which likewise overstates the paired standard error under non-negative within-person correlation (the pre-post data imply r = 0.45), so the reported confidence intervals and p-values are conservative bounds. The resulting quantities are descriptive of the observed profile set; they are not stable population-level part-worth utilities or causal average marginal component effects. The design-dependent relative importance (RI) for attribute k was calculated as:

$$RI_k = \frac{max\left(\widehat{M}_{kj}\right) - min\left(\widehat{M}_{kj}\right)}{\sum_{k=1}^{K}\left[max\left(\widehat{M}_{kj}\right) - min\left(\widehat{M}_{kj}\right)\right]} \times 100$$

where $\widehat{M}_{kj}$ denotes the estimated marginal mean rating for level *j* of attribute *k* and *K* = 4 attributes. Because every quantity in this expression is an average of the scenario means reported in the Results, the attribute analysis can be recomputed by hand from the published tables.

Repeated-measures adjustment: Because each participant rated all six profiles, the ratings are repeated measures. The conservative standard-error convention described above is applied throughout, and the omnibus test of between-profile differences treats observations as independent, which is a lower bound on the corresponding within-subjects test when ratings are positively correlated within person. This adjustment addresses within-person correlation but does not overcome the limited number of unique profiles or the absence of a fully randomized orthogonal profile design.

Pre-post awareness comparison: A paired-samples t-test (two-tailed, α = 0.05) was used to assess statistical significance of composite awareness change from pre- to post-intervention.

Correlation analysis: The point-biserial Pearson correlation coefficient (r) between total E.C. score (continuous) and the binary eco-purchase variable was computed. A partial correlation was additionally computed controlling for age and gender to assess robustness of the association to demographic confounds. Because E.C. score also determined the simulated purchasing budget, this association is treated as descriptive rather than causal evidence that learning independently produced eco-purchase.

All analyses were conducted in R (version 4.3.2), including the marginal-mean estimates and the variance decomposi-

tion; supplementary descriptive checks were performed in SPSS 25.0. Statistical significance was set at α = 0.05 throughout.

This study was conducted in two phases. Phase 1 (the Yeongdeok field study) consisted of preliminary fieldwork and a face-to-face pilot run of the study materials with 17 university-affiliated participants (four REGREEN team members and 13 affiliated university students), carried out on 29 November 2025 as a precursor to the online pilot protocol. Phase 2 (the online platform study) involved human participants. Phase 2 recruitment and data collection took place from 13 December 2025 to 31 December 2025. An application for ethical review (No. 202601-HR-5140-01), comprising a research protocol, recruitment materials, informed-consent language, and risk-management procedures, was submitted to the Yonsei University Institutional Review Board in December 2025, during the Phase 2 data-collection period, but approval had not been obtained when data collection began. The Board requested successive revisions to the application, and after those revisions it was ultimately returned without approval because the Phase 2 data had already been collected. The Phase 2 data reported here therefore have no IRB approval, and none is claimed; this procedural limitation should be considered when interpreting the findings as student-led, minimal-risk pilot evidence. Participants received a digital information sheet, provided online checkbox consent before any survey or platform activity, participated voluntarily, could withdraw without penalty, and had their responses anonymized and stored separately from identifying information. Future confirmatory replications should secure IRB approval before recruitment and should report the approval number, approval date, and data-collection window.

3. Results

Demographic Characteristics

The Phase 2 analytical sample of 50 participants was consistent with the recruited population of digitally active Korean university students aged 18–29, but not representative of Korean youth as a whole (Table 1). The sample was majority female (56%), predominantly in the 18–22 age range (62%), and drawn overwhelmingly from the Seoul metropolitan area (90%). Business, economics, and social sciences constituted the most common disciplinary background (48%). The deliberate exclusion of energy-related majors produced a sample with a mean pre-intervention awareness score of 4.2 (*SD* = 1.3)—consistent with general-public familiarity rather than domain expertise, validating the screening procedure's effectiveness. The 100% five-stage protocol completion rate is substantively noteworthy given the 45–55 minute total time commitment and the voluntary, uncompensated nature of participation, and suggests the sequential engagement design was effective in sustaining motivation across all stages within this recruited sample.

The Phase 1 Yeongdeok pilot cohort (*n* = 17) was by design a convenience sample of four REGREEN team members and 13 affiliated university students who travelled to the site, as described in the Methods; it skewed older (mean age 23.4 vs. 21.8 in Phase 2), had a higher proportion of participants with prior community-level renewable energy exposure, and produced ceiling effects on several awareness items (pre-intervention mean = 4.9 on the composite; Table 5). These characteristics confirm that Phase 1 served its intended purpose as an ecologically rich experiential pilot rather than as a representative sampling frame, and justify the decision to analyze Phase 1 data separately from the primary conjoint and behavioral analyses.

Table 5. Phase 1 Yeongdeok Pilot: Descriptive Summary (n = 17)

Measure	Phase 1 (*n* = 17)	Phase 2 (*n* = 50)
Pre-awareness composite (1-7)	4.9 (0.9)	4.2 (1.3)
Post-awareness composite (1-7)	6.1 (0.7)	5.7 (1.1)
Awareness gain (change)	+1.2	+1.5
Eco-purchase rate (%)	71%	76%
Governance model identified as most resonant (structured discussion; qualitative)	Cooperative joint ownership	Cooperative joint ownership
Protocol completion rate	100%	100%

Phase 1 data are descriptive only; no inferential statistics were computed for the pilot sample. Phase 1 values come from the pilot administration of the awareness items and the in-person market task to the 17 university-affiliated participants; the governance row summarizes structured discussion and does not reflect a scenario-rating task, which was not administered in Phase 1

Phase 1: Yeongdeok Field Study — Qualitative and Pilot Findings

The Yeongdeok session yielded three categories of findings that directly informed the design refinements implemented before Phase 2. First, participants consistently identified the cooperative governance model of the Yeongdeok facility as its most distinctive and resonant feature, spontaneously contrasting it with hypothetical expert-managed alternatives during structured discussion. This qualitative signal—that governance architecture may generate a stronger affective response than economic benefit structure—was subsequently operationalized as a distinct attribute in Phase 2, where governance structure showed the widest spread of marginal means in the exploratory scenario-rating analysis; the correspondence offers informal, post-hoc triangulation between the field-grounded impression and the quantitative pattern rather than independent confirmation.

Second, pilot testing of the Knowledge Quiz (Game 1) identified three items with ambiguous phrasing that produced response distributions inconsistent with expected difficulty gradients; these items were revised before Phase 2 deployment. Similarly, pilot participants in the Turbine Matching Puzzle (Game 3) consistently reported confusion between the Darrieus and cross-flow turbine images at the resolution used; image quality was upgraded before Phase 2.

Third, the in-person market transaction component piloted in Yeongdeok—where participants physically handled product labels before making E.C. allocation decisions—produced qualitatively richer verbal explanations of product choice than the online interface. While the online format necessarily sacrifices tactile engagement, the Green Tax and Development Fund pricing mechanisms were calibrated based on the price sensitivity patterns observed in the Yeongdeok pilot to ensure that the surcharges were large enough to constitute a real cost signal without being so prohibitive as to eliminate variation in eco-purchase rates.

Phase 2: Online Platform Study

1) Pre-Post Awareness Change

The paired-samples t-test revealed a statistically significant increase in composite renewable energy awareness from M = 4.2 (SD = 1.3) at baseline to M = 5.7 (SD = 1.1) post-intervention ($t(49) = 8.34$, $p < 0.001$, Cohen's d = 1.18). A Cohen's d of 1.18 constitutes a large within-person change by conventional benchmarks (Cohen, 1988) and is consistent with literature suggesting that gamification can support cognitive and motivational learning outcomes, although effects vary by design and outcome type (Douglas & Brauer, 2021; Sailer & Homner, 2020). The 1.5-point absolute gain represents a 21.4% improvement relative to the 7-point scale maximum and is consistent in magnitude with the 1.2-point gain observed in the smaller Phase 1 Yeongdeok cohort. Because no randomized control group or delayed follow-up was included, this result should be interpreted as an immediate post-intervention awareness gain rather than evidence of durable attitude change.

Item-level analysis revealed meaningful variation in the distribution of gains (Table 6, Figure 1). Self-assessed knowledge ("How much do you currently know about renewable energy?") showed the largest absolute gain (Δ = +1.8), consistent with the content-specific nature of the educational video targeting factual knowledge gaps. The behavioral intention item ("How willing would you be to support a local RE project?") showed the second largest gain (Δ = +1.7), consistent with, though not demonstrating, a translation of knowledge acquisition into motivational change within the same session. The smallest gain was observed for the broad societal importance item (Δ = +1.0), consistent with ceiling effects on a value that participants already rated relatively high at baseline (*M* = 5.1 pre-intervention).

2) Game Performance Distribution

The four game modules produced distinct performance distributions reflecting their different cognitive demands (Table 7). The Knowledge Quiz (Game 1) showed the widest variance in E.C. outcomes, with a bimodal distribution concentrated at the 150 E.C. (15–17 correct, 34%) and 200 E.C. (18–20 correct, 28%) tiers, indicating that most participants demonstrated substantive video comprehension. The Precision Timer (Game 2) showed a more uniform distribution across tiers, reflecting the task's dependence on individual temporal self-regulation capacity rather than learned content. The Turbine Matching Puzzle (Game 3) produced the highest ceiling performance, with 42% of participants achieving the maximum 200 E.C. tier (6/6 correct), likely reflecting the visual distinctiveness of turbine types following the educational video. The Solar Car Racing Game (Game 4) produced the most right-skewed distribution, with 24% of participants achieving the top tier (≤10 seconds), reflecting heterogeneity in fine motor coordination. The composite E.C.

Table 6. Pre-Post Awareness Change by Survey Item, Phase 2 (*N* = 50)

Survey Item	Pre-*M* (SD)	Post-M (SD)	Change	*p*
Importance of renewable energy for society	5.1 (1.1)	6.1 (0.9)	+1.0	< 0.01
Self-assessed knowledge of renewable energy	3.4 (1.4)	5.2 (1.2)	+1.8	< 0.001
Interest in eco-friendly products/services	4.3 (1.3)	5.8 (1.0)	+1.5	< 0.001
Belief that RE can realistically address climate change	4.5 (1.2)	6.0 (0.9)	+1.5	< 0.001
Willingness to support a local RE project	3.7 (1.5)	5.4 (1.1)	+1.7	< 0.001
Composite Score	**4.2 (1.3)**	**5.7 (1.1)**	**+1.5**	**< 0.001**

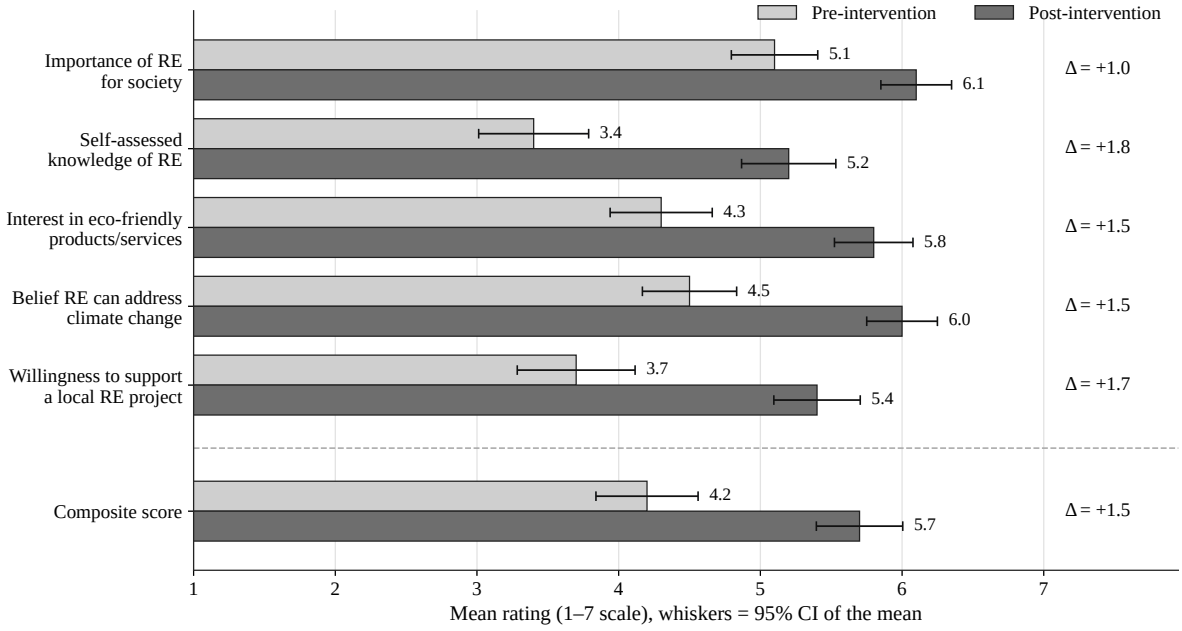

Figure 1. Pre- and Post-intervention Mean Ratings for the Five Awareness Items and the Composite Score, Phase 2 (N = 50). Whiskers Show 95% Confidence Intervals of the Mean, Computed from the Standard Deviations in Table 6. Δ Values are Post-minus-pre Differences.

score across all four games ranged from 200 to 800, with a sample mean of 554 E.C. (*SD* = 112), the sum of the four tier-weighted per-game means (139, 126, 154, and 135 E.C.).

3) Cooperative Market Behavior

Of the 50 participants, 38 (76%) voluntarily selected at least one eco-friendly product in the simulated cooperative market despite the Green Tax surcharge (Table 8). An additional 18 participants (36%) selected at least one regionally-produced product carrying a Development Fund surcharge, and 12 participants (24%) - the complement of the eco-purchasing group - chose general products exclusively. Mean expenditure was 435 E.C. per participant, or 78.5% of the 554 E.C. earned on average, indicating that the point budget operated as a binding but not exhaustive constraint. The result is substantively interesting because research on renewable-energy adoption documents that supportive attitudes do not always translate into cost-bearing behavior when barriers and reasons against adoption are introduced (Claudy, Peterson, & O'Driscoll, 2013). However, the current market used in-platform E.C. rather than externally verified monetary transactions; therefore, the outcome should be interpreted as a simulated trade-off under point-budget scarcity, not as evidence of actual consumer purchasing behavior.

The point-biserial correlation between total E.C. score (game performance composite) and eco-purchase was r = 0.42 (95% CI [0.16, 0.63], p = 0.002). This relationship remained significant after controlling for age and gender in partial correlation analysis (r_partial = 0.39, p = 0.006), indicating that the association is not explained by these two demographic variables. At the same time, higher E.C. performance mechanically increased the participant's simulated

Table 7. Game Performance Distribution, Phase 2 (*N* = 50)

Game	E.C. Tier	Threshold	n (%)
G1: Knowledge quiz	200 E.C.	18-20 correct	14 (28%)
	150 E.C.	15-17 correct	17 (34%)
	100 E.C.	12-14 correct	13 (26%)
	50 E.C.	≤11 correct	6 (12%)
G2: Precision Timer	200 E.C.	≤0.05s deviation	11 (22%)
	150 E.C.	≤0.15s deviation	14 (28%)
	100 E.C.	≤0.30s deviation	15 (30%)
	50 E.C.	>0.30s deviation	10 (20%)
G3: Turbine Matching	200 E.C.	6/6 correct	21 (42%)
	150 E.C.	5/6 correct	16 (32%)
	100 E.C.	4/6 correct	9 (18%)
	50 E.C.	≤3/6 correct	4 (8%)
G4: Solar Car Racing	200 E.C.	≤10s	12 (24%)
	150 E.C.	≤12s	18 (36%)
	100 E.C.	≤15s	13 (26%)
	50 E.C.	>15s	7 (14%)
Composite E.C.	**Mean (SD)**	**Range**	**554 (112), 200-800**

Table 8. Cooperative Market Product Selection, Phase 2 (*N* = 50)

Product Category	Surcharge	n Selecting	%	Mean E.C. Allocated	% of Total E.C. Budget
Eco-friendly	Green Tax	38	76%	183 E.C.	42.1%
Regionally-produced	Development Fund	18	36%	94 E.C.	21.6%
General products	None	41	82%	158 E.C.	36.3%

Participants could select products from multiple categories, so the n selecting column does not sum to 50; 12 participants (24%) selected general products only. Mean E.C. allocated is averaged across all 50 participants (zero for non-selectors) and therefore sums to mean total expenditure (435 E.C.); the final column expresses each category as a share of that total. E.C. allocations reflect choices in a simulated point-budget market, not verified external purchases.

purchasing capacity, so the correlation cannot be interpreted as an independent causal effect of learning on eco-purchase. Notably, the correlation was stronger for Game 1 (Knowledge Quiz) performance alone ($r = 0.38$, $p = 0.006$) than for the precision and motor coordination games (Game 2, $r = 0.19$, $p = 0.186$; Game 4, $r = 0.21$, $p = 0.143$), which is consistent with-but does not prove-a content-learning pathway.

4) Conjoint-Informed Scenario-Rating Results

The exploratory scenario-rating analysis (300 observations: 50 participants x 6 scenarios) shows that the six-profile structure accounts for 24.9% of the total variance in ratings ($\eta^2 = 0.25$; $F(5, 294) = 19.45$, $p < 0.001$), computed from the scenario-level means and standard deviations. Conservative standard errors were used because each participant rated all six profiles. Within this exploratory specification, governance structure produced the widest spread of marginal means and the largest design-dependent relative importance (Table 9, Table 10, Figure 2), and installation location and economic benefit produced intermediate spreads, whereas the participation-mechanism contrast that the design supports did not reach conventional significance.

Figure 2 summarizes this pattern. In panel (A), the intervals for cooperative joint ownership, local vouchers, and farmland/idle land lie entirely above the grand mean of 5.17, the interval for the expert-managed reference level lies far below it, and the two participation-mechanism levels straddle it; panel (B) shows that governance structure accounts for nearly half of the summed attribute ranges, whereas participation mechanism contributes almost nothing. Three aspects of these results warrant specific, cautious interpretive attention because the six-profile design is exploratory. First, the governance structure attribute generates the widest spread of marginal means: within the observed profile set, scenarios featuring transparent cooperative governance averaged 1.77 scale points higher than the expert-managed reference level. That estimate rests on a single expert-managed scenario

Table 9. Attribute-Level Marginal Means and Design-Dependent Contrasts, Phase 2 (*N* = 50, 300 pooled ratings)

Attribute	Level	Scenarios	Marginal Mean	SE	Δ vs. Ref.	95% CI	t (49) / p
Governance Structure	Cooperative joint ownership (transparent)	S5, S6	5.69	0.14	1.77	[1.27, 2.26]	7.18 / < 0.001
(Ref: Expert managed)	Resident youth co-management	S1–S3	5.25	0.16	1.33	[0.82, 1.84]	5.22 / < 0.001
	Expert managed (reference)	S4	3.92	0.20	—	—	—
Installation Location	Farmland/idle land	S2, S5	5.60	0.14	0.82	[0.37, 1.27]	3.66 / 0.001
(Ref: Residential/ campus vicinity)	Public land	S1, S4, S6	5.02	0.17	0.24	[−0.25, 0.72]	0.98 / 0.332
	Residential/campus vicinity (reference)	S3	4.78	0.17	—	—	—
Economic Benefit	Local vouchers	S1, S5	5.74	0.14	0.96	[0.51, 1.41]	4.32 / < 0.001
(Ref: Electricity bill discount)	Educational / experiential programs	S2, S4, S6	4.92	0.17	0.14	[−0.35, 0.63]	0.59 / 0.558
	Electricity bill discount (reference)	S3	4.78	0.17	—	—	—
Participation Mechanism	Open, continuous participation	S1–S3	5.25	0.16	0.15	[−0.30, 0.60]	0.66 / 0.511
(Ref: Voluntary/ applicants-based)	Voluntary/applicants-based (reference)	S4–S6	5.10	0.16	—	—	—
	Information sessions only	not in profile set	—	—	—	—	not estimable

The marginal mean is the unweighted mean of the scenario means listed in the Scenarios column (Table 11). SE is a conservative upper bound (mean of the component scenario SDs divided by the square root of 50); contrast standard errors assume independence and therefore overstate the paired standard error whenever the within-person correlation is non-negative, making the reported intervals and p-values conservative. The six profiles account for 24.9% of the total variance in ratings (η^2 = 0.25; F(5, 294) = 19.45, p < 0.001, under the same conservative convention). Because the profile set is non-orthogonal and partially aliased, these are design-dependent descriptive quantities, not part-worth utilities or causal average marginal component effects; open, continuous participation is not separable from resident youth co-management in this profile set, so those two rows rest on the same scenarios.

Table 10. Scenario-Rating Analysis: Design-Dependent Relative Importance of Policy Attributes, Phase 2 (*N* = 50)

Attribute	Range of Marginal Means (max – min)	Design-Dependent Relative Importance(%)
Governance Structure	5.685 – 3.920 = 1.765	47.8%
Installation Location	5.600 – 4.780 = 0.820	22.2%
Economic Benefit	5.740 – 4.780 = 0.960	26.0%
Participation Mechanism	5.247 – 5.097 = 0.150	4.1%
Total	**3.695**	**100%**

(S4), so it is more exposed to scenario-specific idiosyncrasy than the other attributes. The cleanest evidence available within the design is the comparison of S6 with S4, the only two profiles that differ on a single attribute: both place the installation on public land with educational/experiential benefits and voluntary participation, and they differ only in governance structure. S6 (cooperative joint ownership) was rated M = 5.51 (SD = 1.11) versus M = 3.92 (SD = 1.41) for S4 (expert management; Table 11), a difference of 1.59 scale points (95% CI [1.08, 2.10]; t(49) = 6.27, p < 0.001 under the same conservative convention). Because this contrast holds the other three attributes constant, it is not affected by the aliasing described in the Methods, although it still rests on a single pair of profiles rated after the educational intervention. This magnitude is substantively large in the pilot sample, but it should not be read as a nationally generalizable effect size or as a fully isolated counterfactual effect from changing a single attribute. Second, the participation-mechanism contrast that the design permits - open, continuous versus voluntary/applicants-based - is small and does not reach conventional statistical significance, and the third level of that attribute was never presented; its 4.1% relative importance should therefore be read as no evidence of an effect within the two levels tested rather than as evidence that participation format does not matter. Third, the design-dependent relative importance of economic benefit

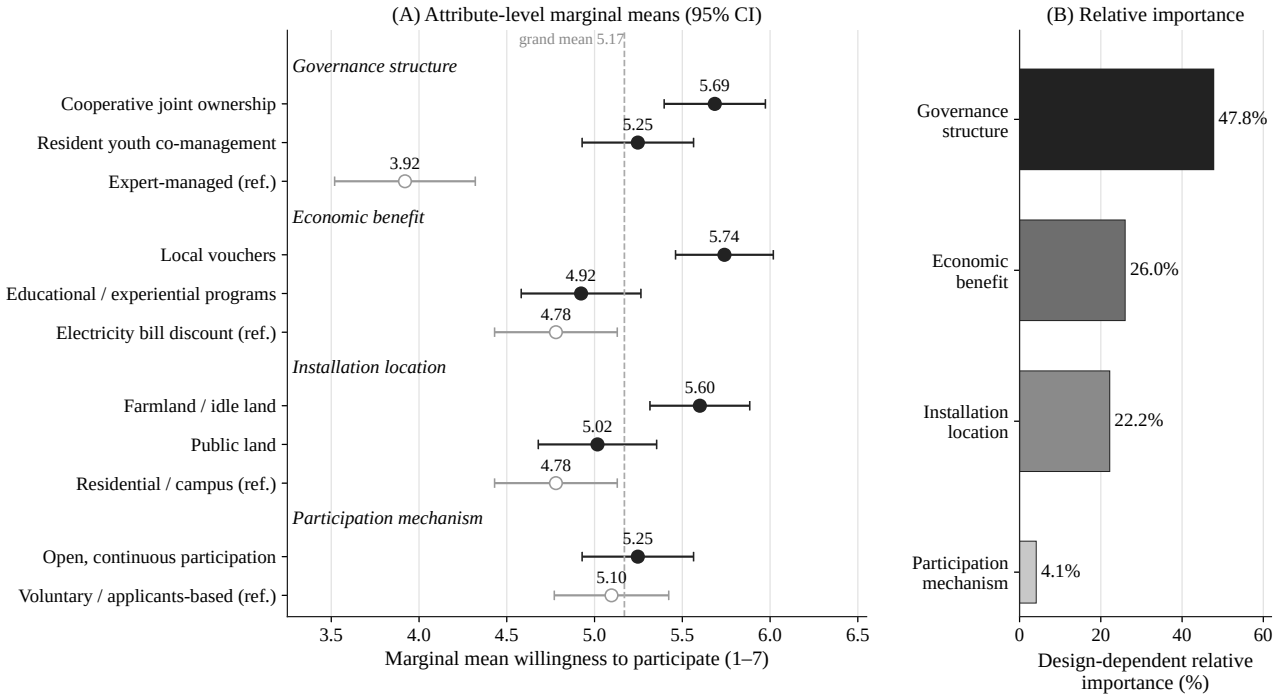

Figure 2. (A) Attribute-level Marginal Mean Willingness to Participate with 95% Confidence Intervals (conservative bounds; open markers denote reference levels, dashed line the grand mean of 5.17). (B) Design-dependent Relative Importance of Each Attribute (Table 10). All Values Derive from the Scenario means in Table 11; Estimates are Exploratory and Specific to the Six-profile Set.

Table 11. Mean Willingness-to-Participate by Policy Scenario, Phase 2 (*N* = 50, 1–7 scale)

Scenario	Governance	Location	Benefit	Participation	*M*	*SD*	Rank
S5	Cooperative joint ownership	Farmland/idle land	Local vouchers	Voluntary	5.86	0.92	1
S1	Resident youth co-management	Public land	Local vouchers	Open, Continuous	5.62	1.04	2
S6	Cooperative joint ownership	Public land	Educational programs	Voluntary	5.51	1.11	3
S2	Resident youth co-management	Farmland/idle land	Educational programs	Open, Continuous	5.34	1.08	4
S3	Resident youth co-management	Residential/campus	Electricity discount	Open, Continuous	4.78	1.23	5
S4	Expert managed	Public land	Educational programs	Voluntary	3.92	1.41	6

(26.0%) is meaningful but much smaller than governance (47.8%) and close to installation location (22.2%); the economic benefit and location spreads have overlapping confidence intervals and should be treated as comparable in this sample rather than rank-ordered. Within this pilot design, governance and spatial embedding warrant further testing as possible drivers of youth support rather than treating financial incentives as the sole policy lever.

5) Mean Willingness-to-Participate by Scenario

The 1.94-point gap between the highest-rated scenario (S5, M = 5.86) and the lowest (S4, M = 3.92) is descriptively instructive: S4 and S5 differ on governance structure, installation location, and economic benefit (both use voluntary participation), making the contrast suggestive of the importance of institutional design but not a controlled causal estimate. The large magnitude of this contrast—spanning the difference between a "moderate-to-strong" willingness level and a "neutral-to-reluctant" one—is consistent with the governance pattern in the rating-contrast model. The two cooperative joint-ownership scenarios occupy the first and third ranks (S5, S6), interleaved with the highest-rated resident-youth co-management scenario (S1); averaged over scenarios, cooperative joint ownership (M = 5.69) is rated above resident-youth co-management (M = 5.25), which in turn is rated above the expert-managed scenario (M = 3.92), consistent with a preference ordering within the observed profile set: full cooperative ownership > resident-youth

co-management > expert management.

6) Post-Survey Platform Experience

Post-survey satisfaction data indicated a strongly positive reception to the gamified protocol. Participants rated game learning effectiveness at M = 5.4 (SD = 0.9) and game engagement at M = 5.7 (SD = 1.0) on the 7-point scale. Cooperative market satisfaction averaged 5.2 (SD = 1.1) across the five satisfaction items. Eighty-two percent of participants (41 of 50) indicated willingness to participate in a future similar research study—an uncommonly high re-participation intent rate that supports the platform's potential for longitudinal follow-up studies.

Open-ended qualitative responses converged on three themes:

(a) the Energy Coin mechanism was perceived as creating stake-like trade-offs, transforming the learning experience from purely performative to more consequential within the simulation;

(b) the Yeongdeok cooperative case study embedded in the educational video was spontaneously identified by the largest number of respondents as influential in shaping governance preferences, which also means it may have primed cooperative governance before the rating task; and

(c) several participants described the cooperative market transaction as "the first time I thought about what eco-friendly products actually cost," indicating that the Green Tax operationalization communicated the simulated price-premium dimension of sustainable consumption in a way that abstract survey items about willingness-to-pay typically do not.

4. Discussion and Conclusions

A Two-Phase Design as a Methodological Contribution

Before turning to the substantive findings, the REGREEN project's two-phase sequential design warrants discussion as a methodological contribution in its own right. The integration of a real-world field study (Phase 1, Yeongdeok) with a scalable online platform deployment (Phase 2) addresses a persistent tension in policy preference research between ecological validity and statistical power. Field-based methods generate rich, contextually grounded data but are resource-intensive and difficult to scale; online survey experiments are scalable and cost-efficient but risk producing preferences that are abstract, hypothetical, and disconnected from the real-world conditions that would actually govern participant behavior. The REGREEN design attempts to resolve this tension by using Phase 1 as a credibility bridge: by grounding the educational content (the Yeongdeok cooperative case study), the governance scenario wording, and the market product categories in observed reality, the online protocol's stimuli become anchored to something participants can evaluate not just as policy abstractions but as recognizable institutional forms.

The convergence of findings across phases supports this design logic while remaining exploratory. The governance preference hierarchy observed qualitatively in Phase 1 (cooperative ownership > resident-youth co-management > expert management) reappeared directionally in Phase 2. The eco-purchase rates (71% in Phase 1 vs. 76% in Phase 2) are also similar across phases despite the very different delivery formats. These convergences provide informal cross-phase triangulation, but they should not be treated as independent validation because both phases were non-randomized and relied on convenience samples exposed to the Yeongdeok cooperative frame.

A Possible Governance Premium: Institutional Architecture as a Candidate Driver of Youth Support

The finding that governance structure has the largest design-dependent relative importance score (47.8%) and that cooperative joint ownership carries the largest positive rating contrast (+1.77 relative to expert management) constitutes the central hypothesis-generating result of this study. Standard political economy accounts of infrastructure acceptance often emphasize economic benefit as a primary determinant of public support, with governance treated as secondary or procedural. The REGREEN scenario-rating results suggest a different possible hierarchy in this recruited sample: young Korean university participants responded especially positively to cooperative and transparent governance designs, even when economic benefit was not the most generous attribute in the profile.

This pattern is interpretable through at least two theoretical lenses. From a procedural-justice perspective (Lind & Tyler, 1988; Tyler, 2006), individuals evaluate policies and the insti-

tutions that deliver them not only by their distributional outcomes but also by the fairness, transparency, and participatory structure of the process through which outcomes are determined, and perceived procedural fairness has been shown to shape community acceptance of wind-energy projects independently of the outcomes themselves (Gross, 2007). This procedural dimension complements the choice-architecture account (Thaler & Sunstein, 2008), in which the framing and structure of options shape engagement independently of policy content. A cooperative governance model—by conferring co-ownership rights, transparency obligations, and participatory decision-making—may signal procedural fairness in ways that expert-managed models do not. From an energy-citizenship perspective (Schlindwein & Montalvo, 2023), cooperative governance can reconstitute participants as active civic stakeholders rather than passive beneficiaries, activating civic identity as a motivational driver of participation. These interpretations remain theoretical mechanisms for future testing rather than mechanisms directly identified by the current data.

The policy implications are suggestive rather than definitive. Many utility-scale renewable projects are planned and governed through expert-led institutional arrangements, while community energy cooperatives remain comparatively marginal in installed capacity and policy investment relative to corporate-scale projects. The REGREEN results do not prove that cooperative governance would produce higher national acceptance, but they suggest that expert-managed models may underuse participatory institutional designs that could matter for youth legitimacy. Cooperative and community-managed structures therefore warrant further testing in larger, regionally diverse, and IRB-approved policy pilots.

Game-Based Simulation and the Attitude-Behavior Gap

The 76% eco-purchase rate under simulated budget constraints and explicit price premiums, combined with the significant association between E.C. accumulation and behavioral choice ($r = 0.42$), is consistent with the value of game-based simulation as an engagement methodology in the energy domain, while not proving behavior change. The critical design element is not gamification per se but the integration of the gamified education component with the downstream behavioral task: participants earned E.C. through platform engagement and then spent that E.C. in a market where eco-friendly choices were more expensive. This sequence created motivational continuity from learning to choice, but it also created a methodological confound because the same performance measure used as the predictor also determined the available budget.

The specificity of the game performance-behavior association-strongest for the Knowledge Quiz ($r = 0.38$) and weaker for the motor coordination game ($r = 0.21$)-is consistent with the content-learning dimension of engagement being relevant to simulated eco-purchase. However, the current design cannot establish that factual knowledge was the proximate cause of the purchasing decision. Future experimental work should separate knowledge scores from the purchasing budget, estimate eco-friendly spending share as E.C. spent on eco-friendly products divided by total E.C. earned, and test whether the Knowledge Quiz component alone drives behavioral choice or whether the cumulative engagement architecture of all four games is necessary.

Regional Embeddedness and the Spatial Politics of Energy Justice

The 22.2% design-dependent relative importance of installation location, with farmland/idle-land scenarios rated 0.82 scale points higher than campus-adjacent ones (95% CI [0.37, 1.27]), suggests a spatial pattern among young urban participants that resists simplistic NIMBY framing. The classic NIMBY model predicts opposition to proximate installations and support for distant ones. The REGREEN pattern is more nuanced: participants appeared to make land-use appropriateness judgments—they preferred installations on land where the renewable energy function reinforces rather than displaces existing use patterns (agricultural, idle). Notably, public land was not rated significantly above residential/campus siting (+0.24, $p = 0.332$), so the pattern is specifically about agricultural and idle land rather than about distance from the respondent as such. Residential and campus-adjacent sites generated lower willingness, possibly because they were perceived as locations where the trade-offs were more personal and insufficiently justified by the governance or benefit structures on offer.

More substantively, the preference for regional installation-understood in the context of the Yeongdeok case study-may reflect an emerging understanding of renewable energy infrastructure as a vehicle for balanced regional development rather than solely a climate mitigation instrument.

Young participants who learned about a real community cooperative in a rural industrial region responded to that spatial story: the frame is not only "where to put turbines to minimize disruption" but also "where to put turbines to distribute economic and social benefits more equitably." This dual-purpose frame-energy transition and regional revitalization-is consistent with the study's operational definition of balanced regional development, but the durability and external validity of this interpretation require confirmation in broader samples and in designs where regional development framing is experimentally varied.

Limitations and Future Directions

Eight limitations require explicit acknowledgment. First, the Phase 2 sample's geographic and institutional concentration (90% Seoul metropolitan area, predominantly university students and largely Yonsei-affiliated recruitment channels) limits its generalizability to rural youth, working-age adults, non-university youth, and regional populations who may hold systematically different preferences about installation location and community benefit design (Bidwell, 2016). Future work should deploy the platform through stratified sampling across Korean regions, particularly North and South Gyeongsang provinces where renewable energy development is actively proceeding, and should include socioeconomic background measures. Second, the one-group pre-post design cannot isolate the specific contribution of the video, games, and cooperative market to observed awareness gains; factorial or randomized controlled designs with active comparison conditions would be required to estimate component-specific effects. Third, the scenario-rating task used only six profiles for four three-level attributes. This reduced burden and improved completion, but it prevents full orthogonality, interaction estimation, and stable subgroup analysis; within the retained set the reference level of participation mechanism was never presented, open, continuous participation is not separable from resident youth co-management, expert management appears in a single profile (S4), and the reference levels of installation location and economic benefit are both carried by a single profile (S3), so these levels cannot be separated from one another. Because a dummy-coded main-effects model is not identified on six design points, attribute effects are reported as marginal means, which are defined for every observed level but remain partly confounded with the attributes that co-occur with them. The reported quantities should therefore be interpreted as exploratory, design-dependent descriptive contrasts rather than definitive population part-worths, and a replication should use at least a nine-run orthogonal main-effects array for a 3^4 design. Fourth, preference ratings were collected at the end of a 45–55-minute protocol, immediately after an educational intervention (a 15-minute video followed by four gamified learning modules) designed to increase renewable energy awareness. Because the Yeongdeok cooperative case was presented before the rating task, cooperative governance may have been made especially salient; the observed governance preference should therefore be interpreted as a post-intervention preference pattern under cooperative-case exposure, not as an unprimed baseline attitude. Fifth, E.C. performance was both a measure of game engagement and the determinant of the simulated purchasing budget, so the association between E.C. accumulation and eco-purchase is partly confounded by purchasing capacity. Sixth, the cooperative market relied on simulated point-budget behavior rather than longitudinal tracking of actual energy behavior, product purchasing, or political participation. Seventh, Phase 2 data were collected while the IRB application was still under review, and the application was ultimately returned without approval because data collection had already been completed, as described in the ethical statement; this limits the evidentiary status of the study for formal publication, and future replications should complete IRB approval before data collection and report the approval number. Eighth, the sample is powered for the paired awareness comparison but not for attribute-level hypothesis testing, so the scenario-rating estimates are best treated as effect-size inputs for future power planning rather than as tests. The field is now sufficiently mature to warrant 6-month and 12-month follow-up studies examining whether attitudes and behavioral intentions observed post-intervention translate into actual energy-related civic behavior.

Conclusions

This study provides an exploratory, conjoint-informed scenario-rating analysis of renewable energy policy preferences among young Korean university participants, grounded in a two-phase methodology that combines community-level field immersion in Yeongdeok with a scaled online gamified simulation platform. Three findings carry policy relevance, but they should be read as hypothesis-generating rather than conclu-

sive. First, cooperative governance emerged as the strongest observed attribute in the pilot scenario set, generating a design-dependent contrast of +1.77 scale points over expert-managed alternatives. This pattern suggests that participatory institutional design may matter for youth acceptance and should be tested more rigorously in future Korean energy-policy research. Second, a 45–55-minute gamified protocol was associated with a large immediate awareness gain (Cohen's d = 1.18) and 76% simulated pro-environmental choice under explicit point-budget trade-offs. Because the design lacks a control group, delayed measurement, and budget-independent behavioral outcome, this finding supports further experimentation rather than definitive claims about durable behavior change. Third, preference for regionally embedded installations appears consistent with interest in the energy transition as a vehicle for regional economic revitalization and spatial equity. Taken together, the findings support future research and policy pilots that test cooperative governance, regional development framing, and game-based civic education using larger, more geographically diverse, longitudinal, and ethically pre-approved samples.

The REGREEN platform itself, having now been developed, tested in the field, and deployed online, represents a potentially replicable protocol rather than a fully validated policy instrument. Its main value is methodological: it offers a modular infrastructure that future researchers, government agencies, and NGOs can adapt to measure youth energy preferences across diverse regional and national contexts, provided that future deployments use stronger sampling, a more complete conjoint or discrete-choice design, pre/post or delayed preference measurement, and clearer separation between learning scores and purchasing budgets.

To support replication, the manuscript reports the core reproducibility elements required to reconstruct the pilot: the five awareness items, E.C. scoring tiers for all four games, market categories and surcharges, the six-profile design matrix, the repeated-measures structure, the conservative standard-error convention, and the interpretation limits of the profile set. A complete supplementary package for future submission should include the Korean and English survey wording, the educational-video script or slides, screenshots or source code for each game module, the product list and E.C. prices used in the cooperative market, any scenario or product-order randomization protocol, the de-identified scenario-level dataset, and R syntax for the marginal-mean, variance-decomposition, and pre-post analyses.

Because the sample is small and drawn from a concentrated university population, participant-level data should be shared only in de-identified form and only after review for re-identification risk. Analysis code and the scenario-level data structure can be made available as supplementary material or from the corresponding author, subject to ethical and institutional requirements.

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Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):152-166
https://doi.org/10.69841/igee.2026.023

Article

Environmental Inequality and Socioeconomic Vulnerability: A Meta-Analysis and Exploratory GIS-Based Spatial Analysis of Seoul

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Background: Environmental inequality refers to the unequal distribution of environmental risks and benefits across social groups and geographic areas. Previous studies have reported associations between various environmental indicators and socioeconomic factors; however, substantial heterogeneity across studies has limited the ability to draw generalized conclusions. Therefore, this study aimed to synthesize the overall pattern of association between environmental disadvantage and socioeconomic vulnerability reported in previous empirical studies, explore how related spatial patterns are manifested within Seoul, and consider their implications for environmental justice screening and ESG-informed urban environmental governance.

Methods: Following the PRISMA guidelines, a systematic review of domestic and international literature was conducted, and a random-effects meta-analysis was performed on ten empirical studies. Effect sizes were based on reported correlation coefficients (r), which were transformed using Fisher's z transformation, pooled, and subsequently converted back to correlation coefficients. In addition, an exploratory area-level GIS analysis was conducted across 426 administrative dongs (neighborhood-level administrative units) in Seoul, South Korea. Potential environmental burden was represented by the proportion of land area located within a 300-m proximity zone surrounding environmental infrastructure facilities, while housing vulnerability was represented by the proportion of publicly supported housing. The association between these proxy indicators was examined using correlation analysis, and spatial clustering of the environmental facility proximity indicator was assessed using Global Moran's I and Local Indicators of Spatial Association (LISA).

Results: The meta-analysis yielded a positive pooled association between environmental disadvantage and socioeconomic vulnerability (r = 0.316, 95% CI: 0.183–0.438), although substantial between-study heterogeneity indicated considerable variation across research contexts. The GIS analysis of Seoul identified a weak positive area-level association between the 300-m environmental facility proximity indicator and the publicly supported housing ratio (r = 0.187, R^2 = 0.035). Furthermore, the Global Moran's I analysis showed statistically significant positive spatial autocorrelation in the environmental facility proximity indicator (I = 0.216,

Received: February 4, 2026 **Revised:** June 12, 2026
Accepted: October 14, 2026
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z = 7.790, pseudo p = 0.001; 999 permutations). A 500-m sensitivity analysis produced similar directional results.

Conclusions: This study quantitatively synthesized evidence suggesting an overall positive relationship between environmental inequality and socioeconomic vulnerability. The Seoul case study further provided exploratory evidence of a weak positive association between environmental facility proximity and the proportion of publicly supported housing, as well as the presence of localized spatial clustering patterns. However, given the limited number of included studies, the substantial heterogeneity among them, and the use of proxy measures for both environmental burden and housing vulnerability in the GIS analysis, the findings should be interpreted as preliminary evidence rather than definitive causal conclusions. Accordingly, the Seoul analysis should be interpreted as a screening-oriented exploratory assessment that may help identify candidate areas for more detailed environmental and socioeconomic investigation, rather than as a stand-alone basis for designating environmentally unjust areas or determining direct policy intervention.

Keywords Environmental inequality, Socioeconomic vulnerability, Meta-analysis, GIS, Environmental justice screening, ESG-informed urban environmental governance

1. Introduction

Environmental inequality refers to the uneven distribution of environmental risks and benefits across social groups and geographic areas. In urban environments, living conditions such as air pollution, noise exposure, flood risk, access to green spaces, and proximity to environmental infrastructure often vary substantially between neighborhoods. These disparities carry important policy implications when combined with socioeconomic vulnerability. Populations with limited residential mobility, restricted access to environmental information, lower capacity to file complaints, or fewer resources to mitigate environmental burdens may face greater difficulty avoiding or reducing the impacts of environmental hazards.

Research on environmental justice has consistently highlighted the close relationship between environmental risks and socioeconomic conditions. Mohai et al. (2009) identified the disproportionate concentration of environmental hazards among specific social groups and regions as a central issue in environmental justice research. Hajat et al. (2015) reviewed socioeconomic disparities in air pollution exposure and reported that low-income and socially vulnerable populations are often exposed to higher levels of environmental risk. Similarly, Wolch et al. (2014) emphasized that access to urban green spaces and parks is strongly associated with health outcomes, quality of life, and environmental justice, while also noting that the distribution of green infrastructure may vary according to socioeconomic conditions. Together, these studies suggest that environmental inequality is not limited to a single environmental factor but rather reflects a complex interaction between urban environmental conditions and socioeconomic vulnerability.

Environmental justice is a multidimensional concept that encompasses not only the distribution of environmental burdens and benefits but also issues of recognition and participation (Schlosberg, 2007). The present study is primarily situated within the distributive dimension of environmental justice, which concerns how environmental burdens and benefits are distributed across social groups and geographic areas. Accordingly, this study does not attempt to evaluate environmental justice in its entirety. Rather, it examines whether indicators of potential environmental disadvantage tend to coincide with indicators of socioeconomic vulnerability across previous empirical studies and within urban space.

Despite growing evidence, previous studies differ considerably in terms of environmental indicators, study regions, spatial units, and socioeconomic measures, making it difficult to identify a general pattern across findings. Associations between socioeconomic vulnerability and environmentally disadvantaged conditions have been reported in diverse domains, including air pollution, green-space accessibility, flood risk, hazardous substance exposure, and transportation accessibility(Park & Song, 2014; Chakraborty & Basu, 2021; Myeong, 2017; Padilla et al., 2014; Tyrrell et al., 2013; Verbeek, 2019; Han et al., 2014; Seo & Jun, 2011; Seo & Han, 2019; Næss et al., 2007). However, the magnitude and consistency of these relationships vary substantially across studies. Therefore, there is a need to quantitatively synthesize existing evidence to examine the overall direction and magnitude of association between environmental disadvantage and socioeconomic vulnerability across heterogeneous research contexts. Meta-analysis provides a useful approach

for integrating effect sizes reported in different studies and identifying common patterns observed across diverse research contexts.

However, while meta-analysis can reveal average associations reported in previous studies, it cannot directly illustrate how environmental burdens and social vulnerability are spatially distributed within a specific city. Urban policy requires not only an understanding of overall average relationships but also an examination of how environmental facility proximity and social vulnerability indicators are spatially distributed and associated within urban space. Geographic Information System (GIS)-based spatial analysis can complement meta-analysis by examining the relationships, distributions, and spatial clustering of environmental and social vulnerability indicators at detailed spatial scales such as administrative neighborhoods.

In the Seoul GIS analysis, environmental facility proximity and the proportion of publicly supported housing were employed as proxy indicators of potential environmental burden and housing vulnerability, respectively, based on data availability and comparability at the neighborhood level. Accordingly, the purpose of this analysis is not to make definitive judgments regarding environmental inequality, but rather to explore how environmental facility proximity and housing vulnerability indicators are spatially distributed and associated within the urban environment.

The two analytical components therefore serve complementary rather than confirmatory purposes. The meta-analysis summarizes the average direction of associations reported across heterogeneous environmental domains, geographic contexts, and measurement approaches, whereas the Seoul GIS analysis examines how a potentially related pattern is manifested within a specific urban context. The Seoul analysis is not intended to validate or replicate the pooled meta-analytic effect. Instead, integrating the two approaches allows general cross-study tendencies to be considered alongside place-specific spatial patterns. Convergence as well as divergence between these levels of analysis may be informative because environmental inequality may vary according to environmental domain, geographic context, indicator selection, and spatial scale.

Based on these considerations, this study addresses the following research questions. First, what overall pattern of association between environmentally disadvantaged conditions and socioeconomic vulnerability is observed across the eligible empirical studies? Second, at the administrative-dong level in Seoul, what pattern of association is observed between environmental facility proximity, a proxy for potential environmental burden, and the proportion of publicly supported housing, a proxy for housing vulnerability? Third, does the environmental facility proximity indicator exhibit spatial clustering within Seoul?

By integrating evidence from previous empirical studies with the Seoul case, this study examines environmental inequality at two complementary analytical levels: cross-study evidence synthesis and within-city area-level spatial analysis. This complementary design contributes by placing cross-study evidence and place-specific spatial patterns within the same interpretive framework, thereby highlighting both broadly observed tendencies and local variation that may be obscured by citywide averages or individual studies alone. Furthermore, the findings are intended not as definitive evaluations of particular areas but as foundational evidence for future field investigations, indicator development, and the identification of priorities for environmental management and urban policy. In addition, the study considers how such area-level screening may inform ESG-relevant urban environmental governance, while recognizing that it does not constitute an ESG assessment.

2. Materials and Methods

Study Design

This study adopted an exploratory quantitative multi-method design that combined a systematic literature review and meta-analysis with an area-level GIS-based case analysis. The meta-analysis was used to synthesize patterns of association reported across previous empirical studies, whereas the Seoul component was used to explore the spatial distribution and area-level association of environmental facility proximity and housing vulnerability within a specific urban context. The two components were intended to provide complementary levels of evidence rather than mutual validation.

The Seoul component was designed as an exploratory, area-level ecological spatial analysis rather than a confirmatory spatial modeling exercise. Consistent with exploratory spatial data analysis (ESDA), the analysis focused on geographic distributions, bivariate associations, and global and local spatial clustering (Anselin et al., 2006). Accordingly, its primary purpose was descriptive and hypothesis-generating rather than causal or predictive.

The study consisted of three stages.

First, domestic and international empirical studies that quantitatively examined the relationship between environmental inequality and socioeconomic vulnerability were systematically identified and reviewed. Effect sizes reported in these studies were extracted and synthesized. Because the included studies differed in environmental indicators, socioeconomic measures, study regions, and spatial units, the meta-analysis was intended to estimate an overall average association while explicitly recognizing substantial contextual variation across studies.

Second, GIS-based spatial analysis was conducted for 426 administrative neighborhoods (dong) in Seoul, South Korea. In this stage, proximity to environmental facilities was used as a proxy indicator for potential environmental burden, while the proportion of publicly supported housing was employed as a proxy indicator for housing vulnerability. The relationships and spatial distributions of these indicators were examined, and the spatial clustering of environmental facility proximity was analyzed. The objective of this analysis was to explore the spatial relationship between potential environmental burdens and housing vulnerability using comparable neighborhood-level indicators.

Third, the combined findings were interpreted in relation to their potential relevance for environmental justice screening and urban environmental governance. Given the exploratory design, policy implications were framed as directions for subsequent assessment and prioritization rather than as direct prescriptions for intervention.

Systematic Review and Meta-Analysis

A systematic literature search was conducted using RISS, DBpia, Google Scholar, and KCI databases. English search terms included combinations of “environmental inequality,” “environmental injustice,” “unequal environmental exposure,” “socioeconomic status,” “income,” “low-income,” “social vulnerability,” and “economic deprivation.” Korean search terms included “환경불평등” (environmental inequality), “환경부정의” (environmental injustice), “소득” (income), “소득격차” (income ine-quality), “저소득” (low income), and “취약계층” (vulnerable populations).

The literature search and study-selection process was organized and reported with reference to the PRISMA 2020 framework (Page et al., 2021). Studies were included if they examined both environmental and socioeconomic indicators and reported a quantitative relationship between the two variables in the form of a correlation coefficient (r) or equivalent statistical information. Studies that addressed only environmental or socioeconomic factors, lacked quantitative analyses, or did not provide sufficient information to calculate effect sizes were excluded.

To ensure consistency, the direction of effect sizes was standardized. Positive effect sizes were defined as indicating that higher levels of socioeconomic vulnerability were associated with more environmentally disadvantaged conditions. Therefore, indicators such as income level, where higher values represent greater socioeconomic advantage, were reverse-coded for interpretation.

Correlation coefficients (r) were transformed into Fisher’s z values prior to analysis. After synthesis, pooled effect sizes were converted back to correlation coefficients for interpretation. Variances were calculated using sample sizes reported in the original studies. Given the differences among studies in geographic regions, datasets, and measurement approaches, a random-effects model was applied. Between-study variance was estimated using the DerSimonian–Laird method (DerSimonian & Laird, 1986).

Heterogeneity was assessed using Cochran’s Q statistic and the I^2 statistic. Forest plots were generated to visualize the overall and domain-specific pooled effect-size estimates. Publication bias was evaluated using funnel plots, Egger’s regression test (Egger et al., 1997), and the trim-and-fill method (Duval & Tweedie, 2000).

All meta-analyses were conducted using R statistical software.

GIS-Based Spatial Analysis

An exploratory GIS-based spatial analysis was conducted using 426 administrative dongs in Seoul as the area-level units of analysis. The datasets included administrative boundary shapefiles, environmental facility location data, publicly supported housing records, and neighborhood-level household statistics. Potential environmental burden was operationalized using an environmental facility proximity indicator. A 300-meter buffer was generated around each environmental facility, and the proportion of buffer area within each administrative neighborhood was calculated. The 300-meter threshold was selected to ensure consistency and comparability across neighborhoods. The 300-m buffer was not intended to represent a universal physical boundary

of environmental exposure or health risk. Rather, it was adopted as an operational proximity threshold for standardized neighborhood-level screening. Proximity-based indicators have been used in environmental justice screening approaches as proxies for potential environmental burden when direct exposure measurements are unavailable (Sadd et al., 2011). Accordingly, the indicator used here represents environmental facility proximity rather than measured environmental exposure. This indicator was designed to capture the proportion of each administrative dong located within the designated proximity zones surrounding environmental infrastructure facilities, rather than merely counting the number of facilities present. To avoid double counting, overlapping buffers were merged before spatial analysis. Buffer polygons were then intersected with neighborhood boundaries, and the total buffer area within each neighborhood was calculated. The environmental facility proximity indicator was subsequently derived by dividing the buffer area by the total area of the neighborhood. As a sensitivity check, the same procedure was repeated using a 500-m proximity threshold to examine whether the direction of the association and the spatial autocorrelation pattern were robust to an alternative buffer specification. Socioeconomic vulnerability was operationalized using the proportion of publicly supported housing. This measure was defined as the percentage of households residing in national housing and permanent rental housing relative to the total number of households within each neighborhood. The indicator was selected because it provides a comparable measure of housing vulnerability and residential constraints at the neighborhood level. Public housing records were geocoded and converted into spatial point data before being joined with neighborhood polygons. The number of national housing and permanent rental housing units was aggregated for each neighborhood and divided by the total number of households to calculate the publicly supported housing ratio. The association between the two indicators was explored using descriptive statistics, Pearson correlation analysis, and a simple bivariate regression. The regression was used only as a descriptive summary of the linear association and was not intended as a causal or spatially adjusted explanatory model.

Zero values were treated as valid observations rather than missing data because neighborhoods without environmental facility buffers or publicly supported housing units remain important components of Seoul's urban structure. Spatial clustering of environmental facility proximity was assessed using Global Moran's I and Local Indicators of Spatial Association (LISA), which are commonly used to examine global and local patterns of spatial autocorrelation (Anselin, 1995). Spatial weights were constructed using a first-order Queen contiguity matrix, and statistical significance was evaluated through 999 permutations. LISA analysis was used to identify High–High, Low–Low, High–Low, and Low–High clusters. These analyses allowed the spatial distribution and clustering patterns of environmental facility proximity to be examined across Seoul. Spatial data processing and analysis were conducted using QGIS and GeoDa. GeoDa was used to support exploratory spatial data analysis and the assessment of global and local spatial autocorrelation (Anselin et al., 2006).

3. Results

Study Selection and Characteristics

Using the study-selection process organized with reference to the PRISMA framework, 584 records were initially identified through database searches and title screening.

After reviewing abstracts and introductions, 146 studies addressing both environmental and socioeconomic factors were retained. Among these, 43 studies employed quantitative approaches to examine the relationship between the two variables. Ultimately, 10 studies reporting correlation coefficients or sufficient statistical information for effect-size calculation were included in the meta-analysis (Figure 1).

The selected studies consisted of empirical investigations examining the relationship between environmental inequality and socioeconomic vulnerability. Although the studies differed in geographic context, spatial scale, environmental indicators, and socioeconomic measures, they shared the common objective of statistically assessing associations between environmental conditions and socioeconomic characteristics.

The included studies covered multiple environmental domains: flood vulnerability (Park & Song, 2014; Seo & Han, 2019), air pollution and social deprivation (Chakraborty & Basu, 2021; Padilla et al., 2014; Verbeek, 2019; Næss et al., 2007), green-space accessibility (Myeong, 2017; Seo & Jun, 2011), toxicant exposure (Tyrrell et al., 2013), and transportation accessibility (Han et al., 2014). Socioeconomic indicators included income level, poverty measures, deprivation indices, and regional inequality indicators. Among the included

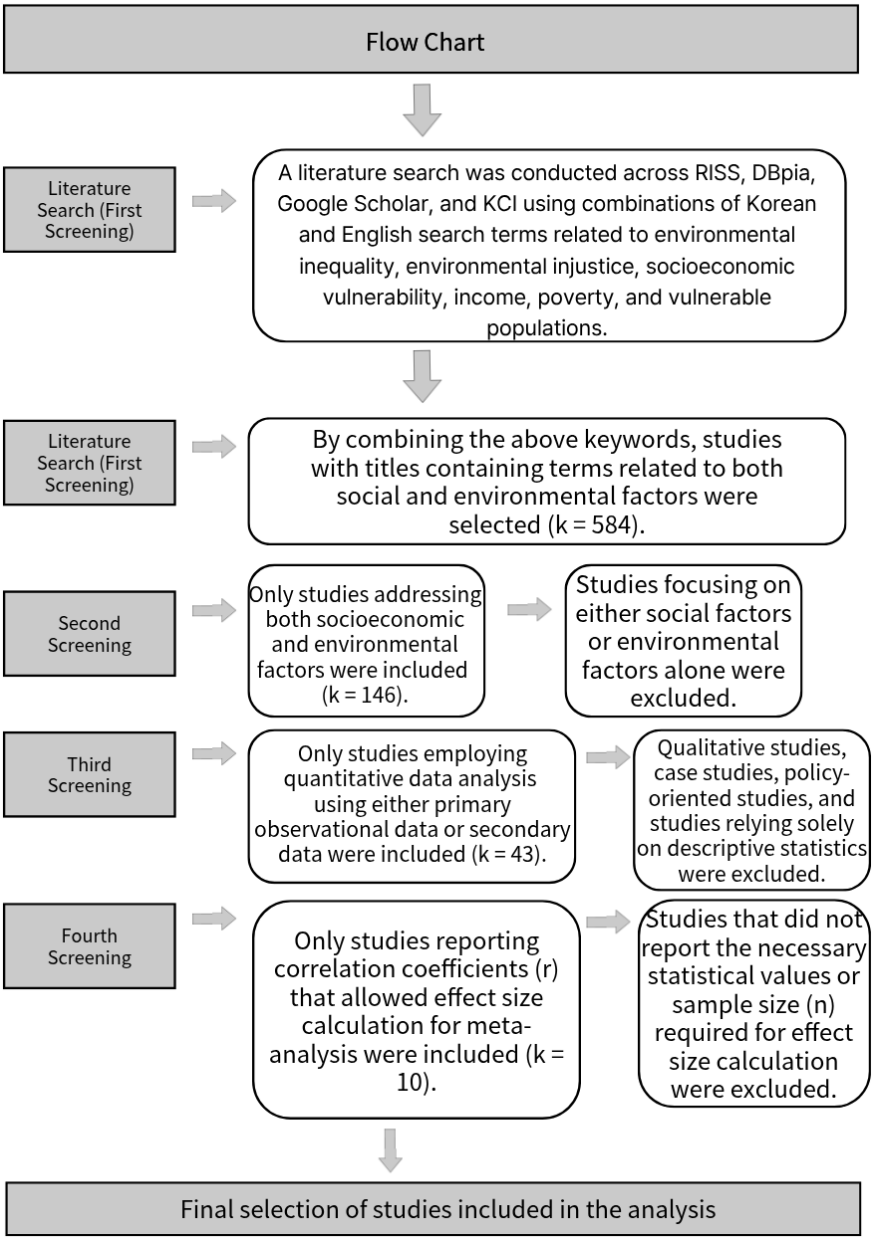

Figure 1. PRISMA Flow Chart.

studies, four focused on air pollution, two on green-space accessibility, two on flood risk, one on hazardous substance accumulation, and one on transportation accessibility (Table 1).

Meta-Analysis Findings

A random-effects meta-analysis of the 10 included effect sizes yielded a pooled correlation coefficient of r = 0.316 (95% CI: 0.183–0.438) (Table 2, Figure 2). The pooled estimate indicates that, on average, higher socioeconomic vulnerability was associated with more environmentally disadvantaged conditions across the included studies. However, this estimate represents an average association across heterogeneous research contexts and should not be interpreted as a universal magnitude of environmental inequality.

Substantial heterogeneity was observed among the studies. Cochran's Q statistic was 206.36 (df = 9, $p < 0.001$), and the I^2 value reached 95.64%, indicating that the variability among effect sizes could not be explained solely by sam-

Table 1. Characteristics of Included Studies

Authors (Year)	Study	Analytical Sample(n)	Socioeconomic Indicator	Environmental Indicator	Effect Size(r)
(Park & Song, 2014)	Empirical Study on Environmental Justice through Correlation Analysis of the Flood Vulnerability Indicator and the Ratio of the Poor Population.	n = 50	Poverty Vulnerability Index (PVI)	Flood Vulnerability Indicator (FVI)	r = 0.41441
(Chakraborty & Basu, 2021)	Air Quality and Environmental Injustice in India: Connecting Particulate Pollution to Social Disadvantages.	n = 640	Scheduled Caste population	PM2.5 mean concentration (2010)	r = 0.407
(Myeong, 2017)	Green Space Accessibility Analysis in Terms of Environmental Justice.	n = 229	Percentage of single mother households	Lack of park and green space (reverse-coded)	r = 0.51
(Padilla et al., 2014)	Air quality and social deprivation in four French metropolitan areas – A localized spatiotemporal environmental inequality analysis.	n = 545	Deprivation index	NO2 concentration (annual mean)	r = -0.042
(Tyrrell et al., 2013)	Associations between socioeconomic status and environmental toxicant concentrations in adults in the USA: NHANES 2001–2010.	n = 4196	Poverty income ratio (PIR)	Blood lead concentration	r = 0.04
(Verbeek, 2019)	Unequal residential exposure to air pollution and noise: A geospatial environmental justice analysis for Ghent, Belgium	n = 164	income	Annual mean NO_2 concentration	r = 0.451
(Han et al., 2014)	Correlation Analysis between Median Household Income and LEED-Certified Public Transportation Access	n = 150	income	Public transportation access (light rail stations, LEED-qualified)	r = 0.263
(Seo & Jun, 2011)	Environmental Equity Analysis of the Accessibility of Urban Neighborhood Parks in Daegu City	n = 16	Basic Pension Recipient Rate	Lack of park and green space development area (reverse-coded)	r = 0.526
(Seo & Han, 2019)	Exploring the Relationship Between Floods and Socially Vulnerable Groups: The Case of Jeju	n = 1230	The elderly	Urban flooding	r = 0.242
(Næss et al., 2007)	Air Pollution, Social Deprivation, and Mortality: A Multilevel Cohort Study.	n = 66	Living in flat	PM2.5	r = 0.48

Effect-size directions were harmonized so that positive values indicate greater socioeconomic vulnerability associated with greater environmental disadvantage. Reverse coding was applied where necessary.

Table 2. Pooled Correlation Coefficients by Study Group

Study group	k	ES r	95% CI
Total	10	0.316	0.183–0.438
Air pollution studies	4	0.329	0.041–0.567
Studies examining green-space accessibility	2	0.511	0.411–0.598
Flood-related studies	2	0.283	0.131–0.423

pling error (Table 3). Differences in environmental indicators, geographic settings, socioeconomic measures, and spatial units may have contributed to this heterogeneity. Therefore, the pooled effect size should be interpreted as an average association observed across diverse research contexts rather than a universal effect. The high heterogeneity is substantively informative as well as methodologically limiting, suggesting that the strength of environmental inequality is context-dependent rather than uniform across environmental domains and geographic settings.

Subgroup analyses revealed variation across environmental domains. The two studies examining green-space accessibility yielded a pooled correlation coefficient of r = 0.511 (95% CI: 0.411–0.598), with no observed heterogeneity (I^2 = 0.00%). However, because this subgroup contained only two studies, the apparent absence of heterogeneity should be interpreted cautiously. Air pollution studies yielded a pooled correlation of r = 0.329 (95% CI: 0.041–0.567), although

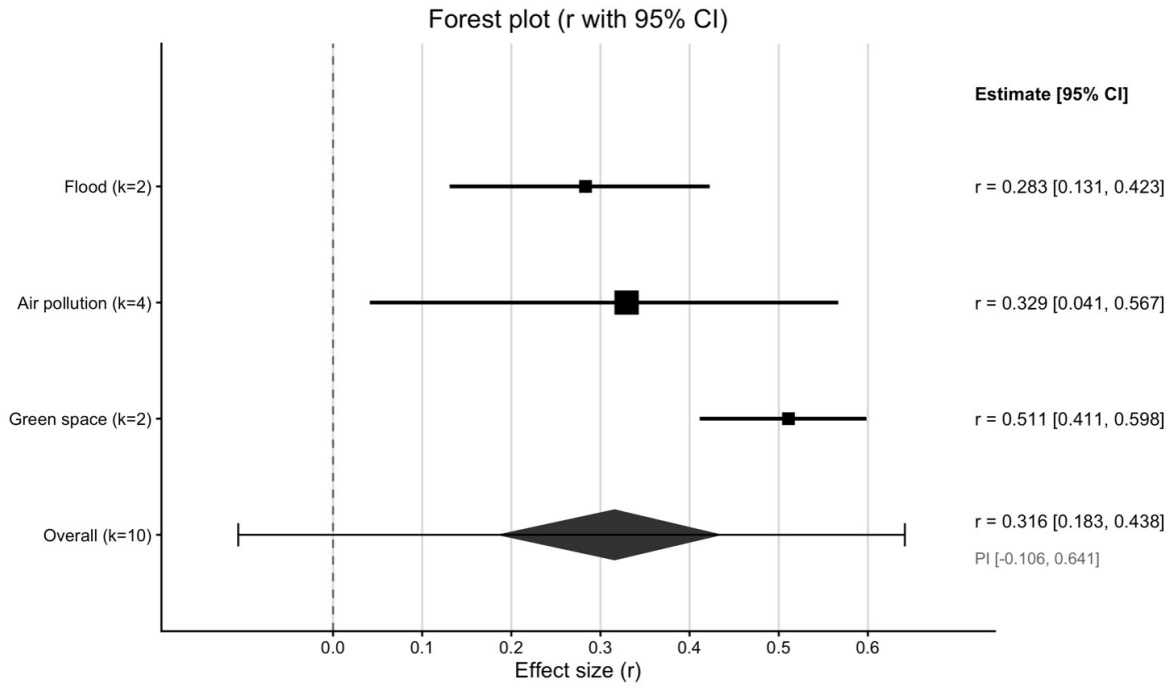

Figure 2. Forest Plot.

Table 3. Heterogeneity Statistics

Study group	k	Q	I²(%)
Total	10	206.36	95.64
Air pollution studies	4	80.86	96.29
Studies examining green-space accessibility	2	0.006	0.00
Flood-related studies	2	1.70	41.32

heterogeneity remained high (I^2 = 96.29%). Flood-related studies reported a pooled correlation of r = 0.283 (95% CI: 0.131–0.423) with moderate heterogeneity (I^2 = 41.32%) (Table 2, Table 3, Figure 2).

Overall, the subgroup results suggest that the association between socioeconomic vulnerability and environmental disadvantage may vary across environmental domains. However, the small number of studies in several subgroups limits the precision of these estimates and the strength of comparisons between domains. These findings should therefore be interpreted as exploratory rather than as definitive evidence that any particular environmental domain exhibits a stronger or more stable association.

Publication Bias Assessment

To assess potential funnel plot asymmetry and small-study effects, a funnel plot was examined and Egger's regression test was conducted (Figure 3). Egger's test indicated statistically significant funnel plot asymmetry (t = 2.437, df = 8, p = 0.041), suggesting the possibility of small-study effects or publication bias. However, this finding should be interpreted cautiously given the small number of included studies and the substantial between-study heterogeneity.

A trim-and-fill analysis was subsequently conducted as a sensitivity analysis to examine the robustness of the pooled effect estimate (Figure 3, Figure 4). After adjustment, the pooled correlation coefficient was r = 0.305 (95% CI: 0.175–0.425), slightly lower than the original estimate of r = 0.316 (95% CI: 0.183–0.438). The adjusted confidence interval remained above zero, indicating that the positive average association persisted after adjustment. However, the adjusted 95% prediction interval ranged from −0.115 to 0.633, crossing zero and suggesting that the direction and magnitude of the association may vary across research settings.

Overall, the trim-and-fill analysis yielded an adjusted pooled estimate that was broadly consistent with the original result. Nevertheless, the significant Egger's test and the limited number of included studies warrant caution in interpreting the possibility of publication bias. These diagnostics should therefore be regarded as exploratory evidence of potential small-study effects rather than definitive evidence of

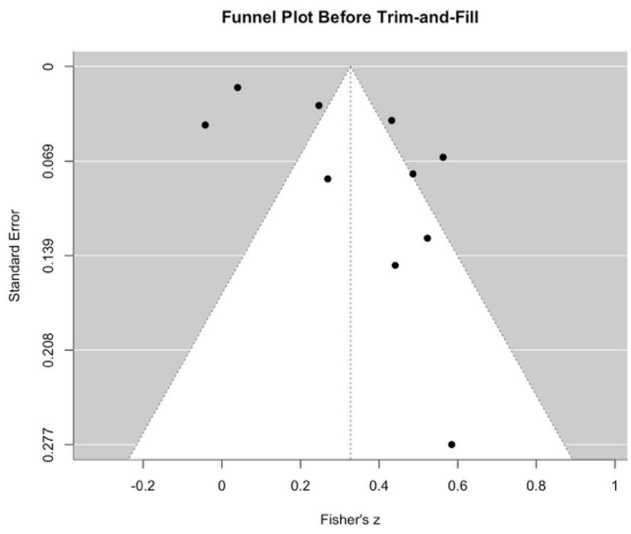

Figure 3. Funnel Plot before adjustment.

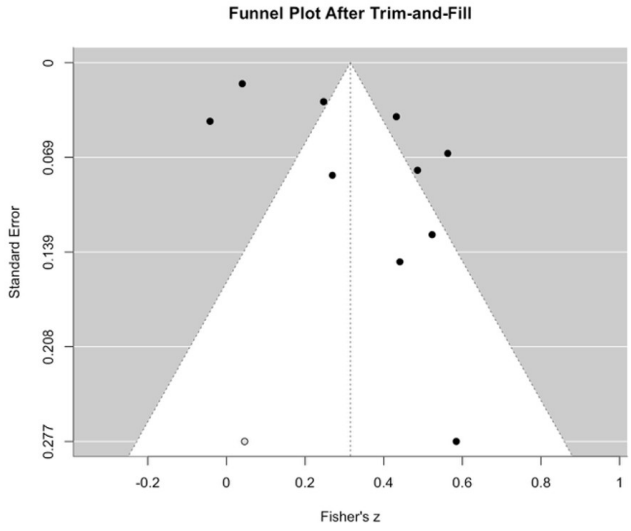

Figure 4. Funnel Plot after adjustment.

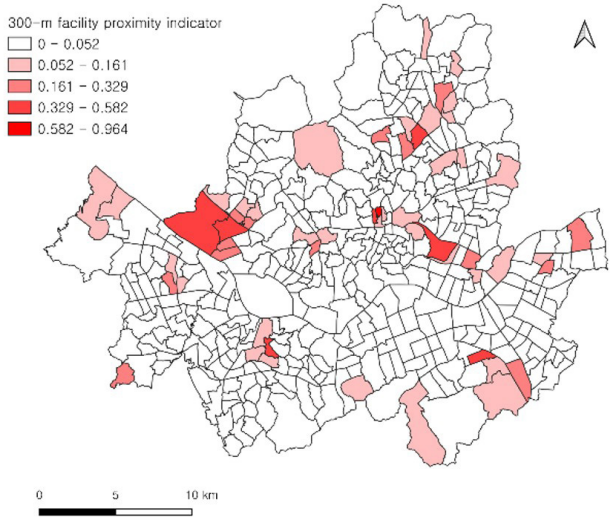

Figure 5. Environmental Facility Proximity Indicator by Administrative Dong in Seoul.

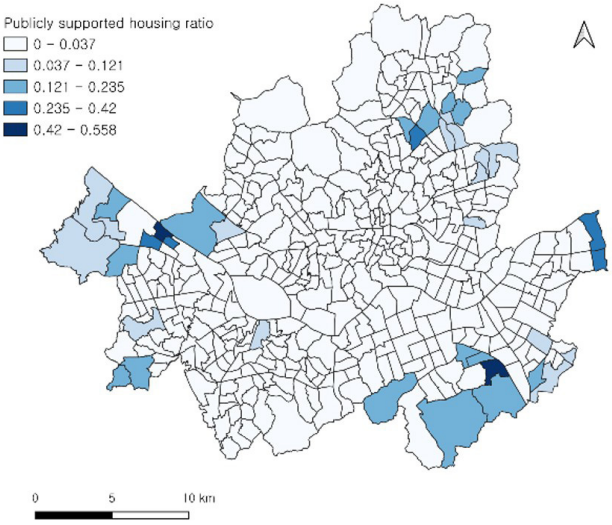

Figure 6. Publicly Supported Housing Ratio by Administrative Dong in Seoul.

publication bias.

GIS-Based Spatial Analysis

An exploratory GIS-based spatial analysis was conducted across 426 administrative dongs in Seoul. The distributions of both the 300-m environmental facility proximity indicator and the publicly supported housing ratio exhibited a strong concentration around zero or relatively low values. The median values of both indicators were close to zero, while relatively high values were observed in a limited number of administrative dongs for each indicator. These distributional patterns indicate that the two indicators were spatially uneven, but they do not by themselves demonstrate direct overlap between high environmental facility proximity and high housing vulnerability (Figure 5, Figure 6).

Pearson correlation analysis between the 300-m environmental facility proximity indicator and the publicly supported housing ratio yielded a weak positive association ($r = 0.187$). A descriptive bivariate regression produced an R^2 value of

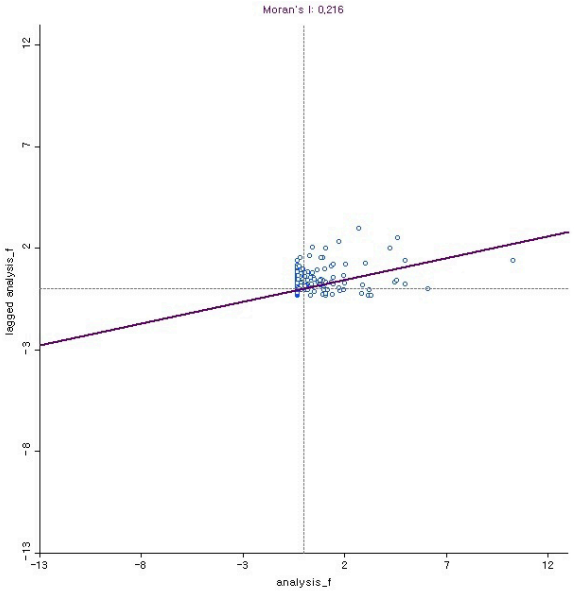

Figure 7. Global Moran's I Result for the 300-m Environmental Facility Proximity Indicator.

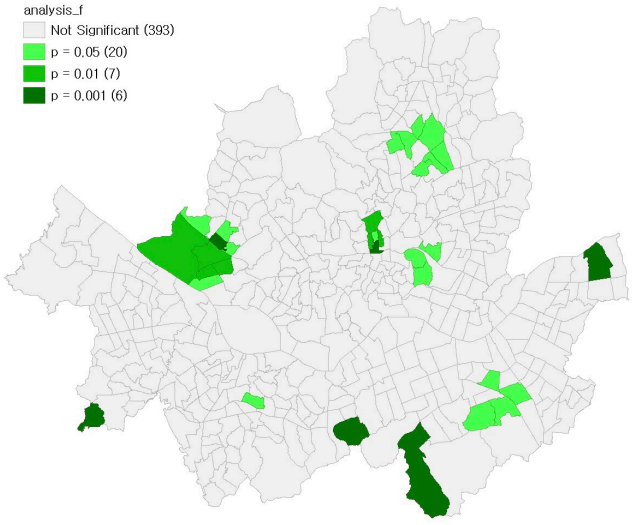

Figure 8. LISA Significance Map for the 300-m Environmental Facility Proximity Indicator.

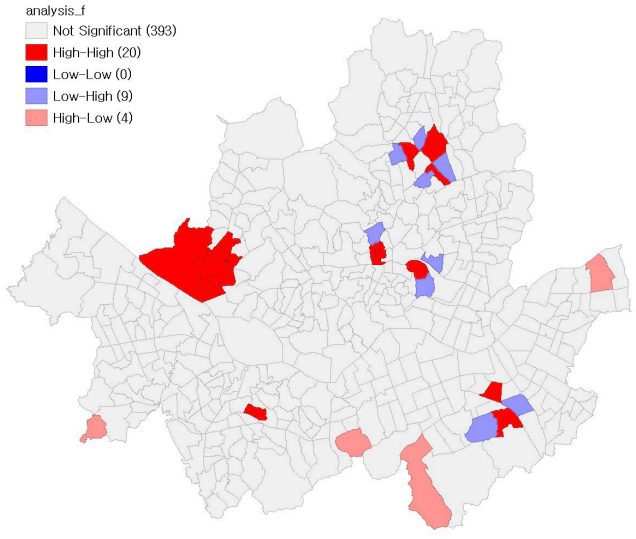

Figure 9. LISA Cluster Map for the 300-m Environmental Facility Proximity Indicator.

0.035, indicating that publicly supported housing alone explained only a limited portion of the spatial variation in environmental facility proximity. This regression is interpreted descriptively rather than as a spatially adjusted explanatory model.

As a sensitivity check, the 500-m proximity indicator showed a similar weak positive association with the publicly supported housing ratio ($r = 0.195$, $R^2 = 0.038$), suggesting that the direction of the association was not solely dependent on the 300-m threshold. Nevertheless, the explanatory power remained limited under both buffer specifications. Therefore, a more comprehensive understanding of the spatial distribution of environmental facility proximity requires consideration of additional socioeconomic and urbanspatial factors, including land use, urban planning, facility siting, demographic composition, income, aging populations, green space accessibility, flood risk, and air quality.

Spatial Clustering of Environmental Facility Proximity

To examine the spatial clustering of the environmental facility proximity indicator, measured as the proportion of land area within a 300-m proximity zone surrounding environmental infrastructure facilities, a Global Moran's I analysis was conducted. The Global Moran's I analysis produced statistically significant positive spatial autocorrelation for the 300-m environmental facility proximity indicator ($I = 0.216$, $z = 7.790$, pseudo $p = 0.001$; 999 permutations) (Figure 7). This finding suggests that the environmental facility proximity indicator was spatially clustered rather than randomly distributed across Seoul, with neighboring administrative dongs tending to exhibit similar levels of facility proximity. The 500-m sensitivity analysis also showed statistically significant

positive spatial autocorrelation (I = 0.309, z = 11.195, pseudo p = 0.001), indicating that the spatial clustering pattern was robust to the alternative proximity threshold. Local Indicators of Spatial Association (LISA) analysis further identified statistically significant local spatial association in 33 of the 426 administrative dongs: 20 at $p \leq 0.05$, 7 at $p \leq 0.01$, and 6 at $p \leq 0.001$ (Figure 8). Figure 8 indicates where the local spatial association was statistically significant, whereas Figure 9 classifies the significant local patterns into cluster and spatial-outlier categories. The LISA cluster map showed 20 High–High clusters, 9 Low–High outliers, and 4 High–Low outliers, with no Low–Low clusters (Figure 9). In Figure 9, High–High indicates administrative dongs with high environmental facility proximity values surrounded by neighboring dongs with similarly high values, whereas Low–Low indicates low-value dongs surrounded by low-value neighboring dongs. Low–High and High–Low represent spatial outliers: Low–High indicates low-value dongs surrounded by high-value neighboring dongs, while High–Low indicates high-value dongs surrounded by low-value neighboring dongs (Figure 9). These results indicate localized concentrations of high environmental facility proximity and local spatial outliers, rather than direct evidence of spatial overlap between environmental burden and housing vulnerability.

4. Discussion and Conclusions

Interpretation of Main Findings

This study examined environmental inequality through two complementary analytical components: a systematic review and meta-analysis of previous empirical evidence and an exploratory area-level GIS analysis of Seoul. The meta-analysis identified a positive pooled association on average (Table 2, Figure 2), whereas the Seoul analysis showed a weaker positive area-level association between environmental facility proximity and publicly supported housing, together with localized spatial clustering of the proximity indicator (Figure 7, Figure 8, Figure 9). These findings should not be interpreted as direct replication across analytical levels; rather, they provide complementary evidence regarding general cross-study tendencies and place-specific spatial patterns.

The pooled effect size suggests an average tendency for environmentally disadvantaged conditions to be positively associated with socioeconomic vulnerability across the included studies.

These findings are consistent with the environmental justice perspective, which argues that environmental risks and environmental benefits may be distributed unevenly according to socioeconomic conditions. As the present meta-analysis represents a quantitative synthesis based on correlation coefficients, its primary objective is to determine whether the relationship between environmental inequality and socioeconomic vulnerability is repeatedly observed across diverse research contexts.

Overall heterogeneity across the meta-analysis was very high ($I^2 = 95.64\%$), indicating that differences in effect sizes among the included studies cannot be explained solely by sampling error (Table 3). Variations in environmental indicators, geographical contexts, socioeconomic measures, and spatial units are likely to contribute to this variability. Importantly, the heterogeneity is not only a methodological limitation but also substantively informative, because it suggests that the magnitude of environmental inequality may be strongly context-, indicator-, and scale-dependent. The two green-space studies yielded relatively large and similar correlation estimates, but the very small subgroup size precludes strong conclusions regarding consistency. Likewise, positive pooled estimates in the air-pollution and flood subgroups should be interpreted cautiously because of the limited number of studies and remaining heterogeneity. The subgroup findings therefore serve primarily as exploratory indications of possible domain-specific variation.

In the environmental-domain subgroup analysis, the pooled correlation for green-space accessibility was numerically larger than those for air pollution and flood risk (Table 2, Figure 2). However, the small number of studies in each subgroup prevents firm conclusions about differences in effect sizes across environmental domains. Moreover, whereas the meta-analysis encompassed both environmental burdens and environmental benefits, the Seoul GIS analysis relied on a narrower set of proxy indicators: proximity to environmental infrastructure facilities and the proportion of publicly supported housing. This difference in measurement scope may help explain why the strengths of the observed associations differed between the two analyses, but its contribution was not directly tested in this study. In addition, the meta-analysis synthesized studies conducted across different geographic settings and spatial units, using varied socioeconomic indicators, whereas the Seoul GIS analysis focused on a single city at the administrative-dong level and used publicly supported housing as a proxy for housing vul-

nerability. These differences in geographic context, spatial scale, and indicator selection further limit direct comparisons of the correlation magnitudes. Their individual contributions to the observed difference were not separately assessed. Accordingly, the Seoul GIS findings should be interpreted as complementary, place-specific evidence of associations and spatial patterns rather than as confirmation or strengthening of the meta-analytic findings.

The GIS analysis of Seoul revealed a weak positive area-level association between the 300-m environmental facility proximity indicator and the publicly supported housing ratio. This result should not be interpreted as direct evidence that high environmental burden and high housing vulnerability spatially overlap in specific neighborhoods. Rather, it indicates that, at the administrative-dong level, areas with higher environmental facility proximity tended to show somewhat higher publicly supported housing ratios. The coefficient of determination ($R^2 = 0.035$) indicates that publicly supported housing alone explains only a limited portion of the spatial variation in environmental facility proximity. The 500-m sensitivity analysis produced a similar weak positive association and statistically significant spatial autocorrelation, suggesting that the observed direction and clustering pattern were not solely artifacts of the 300-m buffer specification. However, the explanatory power remained limited, and the results should not be interpreted as evidence of direct spatial overlap between high environmental burden and high housing vulnerability. Therefore, a more comprehensive understanding of the spatial distribution of environmental facility proximity requires consideration of additional social and environmental indicators, including income, aging populations, recipients of basic livelihood security benefits, single-person households, flood risk, green space accessibility, and air quality.

The spatial autocorrelation analysis demonstrated that the environmental facility proximity indicator was not randomly distributed across Seoul but tended to cluster among neighboring administrative dongs with similar levels of facility proximity (Figure 7). The LISA analysis identified 20 High–High clusters, indicating localized concentrations where high values of the proximity indicator were surrounded by neighboring administrative dongs with similarly high values (Figure 9). The analysis also identified 9 Low–High outliers and 4 High–Low outliers, suggesting local deviations from surrounding spatial patterns (Figure 9). These findings indicate localized spatial clustering of facility proximity and may help identify candidate areas for further environmental and socioeconomic investigation. However, because the LISA analysis was conducted on the environmental facility proximity indicator, the results should not be interpreted as direct evidence that environmental burden and housing vulnerability are spatially clustered together.

Policy Relevance and Screening Implications for Urban Environmental Governance

Given the exploratory nature of the Seoul analysis and the weak bivariate association observed between the two proxy indicators, the GIS findings should not be used as a standalone basis for designating environmentally unjust neighborhoods or determining direct policy intervention. Rather, the framework is more appropriately interpreted as a first-stage spatial screening approach for identifying candidate areas that may warrant more detailed environmental and socioeconomic assessment. Environmental justice screening approaches similarly emphasize the use of environmental and social vulnerability indicators to identify areas for subsequent investigation rather than to establish definitive causal conclusions (Sadd et al., 2011). In this sense, the policy relevance of the present framework lies in a staged process of screening, validation, and intervention.

Although this study does not directly evaluate ESG performance, its screening framework is relevant to ESG-informed urban environmental governance in a limited sense. The environmental facility proximity indicator corresponds to the environmental dimension of ESG, as it reflects the spatial distribution of potential environmental burdens, while the publicly supported housing ratio captures one aspect of the social dimension, namely the residential constraints of potentially vulnerable households. The staged process of screening, validation, and intervention proposed above relates to the governance dimension, in that it offers a transparent and reproducible basis for prioritizing areas for further assessment and for documenting how such priorities are set. For instance, public agencies responsible for environmental infrastructure or public housing could use such screening results as one input when reviewing environmental and social risks around vulnerable residential areas. Nevertheless, these connections are conceptual rather than empirical: the present study does not construct ESG indicators, assess the ESG performance of any organization, or evaluate governance outcomes.

Areas identified through initial screening should undergo further validation before specific policy measures are considered. Such validation may incorporate direct environmental measurements, additional socioeconomic indicators, field investigation, resident consultation, and other locally relevant information. Depending on the environmental conditions subsequently confirmed, measures such as environmental monitoring, information provision, resident participation, or locally appropriate environmental improvements may be considered. However, the present analysis does not provide sufficient evidence to determine which specific interventions would be appropriate for individual neighborhoods.

The numerical findings observed in Seoul are not intended to be statistically generalized to other cities. Rather, the potentially transferable contribution lies in the analytical framework, which may be adapted and tested in other urban contexts using locally appropriate environmental and socioeconomic indicators.

For policy applications, spatial analysis results should be combined with field investigations, resident consultations, additional environmental datasets, and social vulnerability indicators. Such an approach can reveal inequalities concealed by district- or city-level averages and provide foundational evidence for the development of Korean environmental justice indicators and urban environmental governance indicators in the future.

Limitations

This study combined meta-analysis and GIS spatial analysis to examine the relationship between environmental inequality and socioeconomic vulnerability. Nevertheless, several limitations should be acknowledged.

First, the number of studies included in the meta-analysis was limited to ten. This was primarily due to the insufficient accumulation of prior studies that quantitatively examined the relationship between environmental inequality and socioeconomic vulnerability and reported the statistical information necessary for effect size estimation. Consequently, the pooled effect size should be regarded as an exploratory summary estimate derived from a limited body of evidence rather than as a definitive population-level effect, and it should be reevaluated as additional eligible studies become available.

Second, substantial heterogeneity was observed across the meta-analysis. To account for between-study variation, this study employed a random-effects model and conducted subgroup analyses by environmental category. However, the included studies differed considerably in terms of environmental indicators, socioeconomic indicators, spatial units, and geographical contexts, limiting the ability to disentangle the specific sources of effect size variation. The high heterogeneity also limits the extent to which the pooled estimate can be generalized to any specific environmental domain, city, or population.

Third, the possibility of publication bias or small-study effects was identified. The funnel plot showed asymmetry (Figure 3), Egger's regression test indicated statistically significant asymmetry, and the trim-and-fill analysis imputed one potentially missing study (Figure 4). Although the direction and statistical significance of the overall effect remained stable after adjustment, the relatively small number of included studies limits the robustness of publication bias assessments. To address this concern, both adjusted and unadjusted effect sizes were reported in the present study.

Fourth, although spatial autocorrelation was identified in the environmental facility proximity indicator, the present study did not estimate spatial regression models such as spatial lag or spatial error models. The simple regression was used as a descriptive extension of the bivariate analysis rather than as a causal or spatially adjusted explanatory model. Consequently, the regression estimates may be affected by unmodeled spatial dependence and should be interpreted cautiously. Future confirmatory research should employ spatial regression models to determine whether the observed association persists after spatial dependence is explicitly accounted for.

Fifth, the scope of environmental and social vulnerability indicators included in the GIS analysis was limited. This study used the proportion of land area within a 300-meter buffer of environmental infrastructure facilities as a proxy measure of potential environmental burden and the proportion of publicly supported housing as a proxy measure of housing vulnerability. Although proximity to environmental infrastructure facilities is useful for assessing spatial overlap between facilities and residential areas at the administrative-dong level, it does not fully capture the diverse environmental burdens present in urban settings, including air pollution, odor, noise, traffic exposure, thermal stress, green space accessibility, and flood risk. Likewise, the proportion of publicly supported housing reflects only one aspect of housing vulnerability and does not encompass broader dimen-

sions of socioeconomic vulnerability, such as income, poverty, assets, employment status, and health conditions.

Sixth, the 300-m proximity measure should be regarded as one operational representation of local facility proximity rather than as a definitive spatial extent of environmental exposure or health risk. Although this study conducted a 500-m sensitivity analysis, additional thresholds such as 100 m and 1 km were not examined. Therefore, the robustness of the observed patterns across a wider range of distance specifications should be further assessed in future research.

Seventh, the use of administrative dongs as the primary unit of analysis may not adequately capture micro-level spatial variations within neighborhoods. Even within the same administrative dong, residents' levels of environmental exposure may differ depending on residential location, actual distance from facilities, population density, land-use characteristics, and neighborhood boundaries. Future research could utilize grid-based datasets, building-level data, and population-weighted exposure indicators to investigate intra-neighborhood spatial disparities in greater detail.

Conclusion

This study examined the relationship between environmental inequality and socioeconomic vulnerability by integrating a systematic literature review, meta-analysis, and GIS spatial analysis at the administrative-dong level in Seoul. The significance of this study lies in its simultaneous examination of quantitative patterns reported in previous studies and the detailed spatial distributions observed in an actual urban environment. In doing so, the study extended the discussion of environmental inequality beyond individual cases or single indicators by linking synthesized evidence from the literature with spatial disparities within the city.

The meta-analysis revealed an overall positive association between environmental inequality and socioeconomic vulnerability. Although substantial heterogeneity was observed across the included studies, this finding suggests that the manifestation of environmental inequality may vary according to environmental characteristics, regional contexts, socioeconomic indicators, and spatial scales. Therefore, the pooled effect size reported in this study should be interpreted as a summary estimate representing the average association repeatedly observed across diverse research settings.

The GIS analysis of Seoul identified a weak positive area-level association between the 300-m environmental facility proximity indicator and the publicly supported housing ratio. In addition, the environmental facility proximity indicator exhibited localized spatial clustering in certain areas. The 500-m sensitivity analysis produced similar directional results, suggesting that the weak positive association and spatial clustering pattern were not solely dependent on the 300-m proximity threshold. These findings suggest that administrative-dong-level spatial screening can help identify candidate areas for further environmental and socioeconomic investigation. However, because this study did not directly analyze the spatial overlap of high environmental burden and high housing vulnerability, the results should not be interpreted as definitive evidence of environmental injustice or as a direct basis for policy intervention.

These findings may also be considered in relation to broader urban and community development agendas, including SDG 10 and SDG 11, as well as ESG-informed governance practices that incorporate environmental and social vulnerability considerations. However, this study does not evaluate progress toward these goals or assess the outcomes of specific policy interventions. Rather, by showing how environmental facility proximity and a proxy indicator of housing vulnerability can be examined at the administrative-dong level, the study illustrates how spatial screening may provide preliminary evidence for identifying intra-urban disparities. Accordingly, the SDG and ESG relevance of this study should be understood as indirect and screening-oriented, rather than as evidence that specific SDG targets have been achieved or that particular areas require immediate policy intervention.

Future research should incorporate a broader range of environmental indicators, including air pollution, noise, odor, thermal environments, green space accessibility, and flood risk, together with direct socioeconomic measures such as income, poverty, aging populations, health conditions, and housing instability. Moreover, integrating longitudinal datasets, resident complaint records, and health-related data would enable a more comprehensive examination of how spatial relationships between environmental burdens and social vulnerability evolve over time and whether policy interventions contribute to reducing regional disparities. As data continue to accumulate, administrative-dong-level spatial analysis can be repeatedly applied and refined, serving as a foundational tool for the development of Korean environmental justice indicators and urban environmental governance frameworks.

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Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):167-179
https://doi.org/10.69841/igee.2026.020

Article

Where the Effort Disappears: Opacity, Reciprocity, and Household Organic Waste Practice in Hyderabad, India†

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Indian waste policy has largely framed the gap between segregation mandates and household practice as a behavioural problem, to be addressed through messaging and outreach. Where residents already know the rules and still do not follow them, the question becomes under what conditions the practice is sustained. This study examines how urban households in Hyderabad, Telangana, handle organic waste and what judgements about the waste system those practices rest on. Ten household-level semi-structured interviews and in-home observation were conducted, with 35 participants recruited through community networks. Standard composting kits were distributed, followed by a return visit after two and a half months. A contrast observation was conducted in Yavatmal, Maharashtra, where municipal collection is irregular. Data were analysed through reflexive thematic analysis. In Hyderabad, verification of sorted waste stopped at the building gate, where the only visible stage was the watchman consolidating separated bags. Participants explained their departure from official segregation by citing the state's own record, suspending their obligation without denying it. The kits were unused at revisit, yet five of the ten households were diverting peels, eggshells, and used tea to their own plants, one for fifteen years. Set against Yavatmal, where infrequent collection left waste to accumulate and be burned in an open field, the Hyderabad case indicates that where collection infrastructure functions, the obstacle lies in what households can see of it. In the households studied, neither knowledge nor equipment was absent. The findings suggest that intervention should target the visibility of the chain rather than household attitudes, and that performance measurement should record where separation breaks down and whether organic material is diverted at home.

Keywords Household waste segregation, Infrastructural opacity, Conditional cooperation, Organic waste diversion, India

Received: February 4, 2026 **Revised:** September 29, 2026
Accepted: October 12, 2026
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†This research is supported by the Social Engagement Fund (SEF) 2025.

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1. Introduction

India's Solid Waste Management Rules, 2016 made source segregation a legal obligation rather than a voluntary practice (Ministry of Environment, Forest and Climate Change [MoEFCC], 2016), and the Solid Waste Management Rules, 2026 have since extended this to four mandatory streams (Press Information Bureau, 2026). Under Swachh Bharat Mission–Urban, the persistent shortfall between mandate and practice has been treated primarily as a behavioural problem, addressed through intensified messaging and household outreach (Press Information Bureau, 2022). Implementation nonetheless remains uneven, and the diagnosis that households do not segregate because they do not know they should is increasingly difficult to sustain. Recent qualitative work reports that residents can articulate the rules and still not follow them, and that segregation functions less as a stable household attribute than as a situational accomplishment negotiated against collection timing, vehicle design, and the perceived credibility of downstream service (Sahoo et al., 2022; Sahoo et al., 2024; Trushna et al., 2026). Where awareness is already present, the question is not what households fail to understand but under what conditions they sustain the practice.

This study pursues that question in Hyderabad, Telangana. Organic material is often the largest component of Indian household waste, and a recent seven-day pick analysis in Ujjain recorded it at 69% of the household stream, with almost half of what households placed in dry bins turning out to be mis-sorted, most of it organic (Kalyanasundaram et al., 2026). Household-level diversion of organic material is therefore a significant means of reducing landfill dependence. Existing qualitative accounts of Indian household segregation have been generated largely through focus groups and interviews conducted away from the home (Trushna et al., 2026), documenting what residents say rather than what occurs in the kitchen. This study enters ten households, combining semi-structured interviews with in-home observation of where organic material is actually placed and sorted, and distributing standard composting kits as a material intervention before revisiting the same households. What the visits made visible allows the study to ask the following questions.

Main question: How do urban households in Hyderabad handle (organic) waste, and on what understandings of and judgements about the waste management system do these practices rest?

Sub-question 1: How do households understand what happens to waste after it is collected, and where does that understanding come from?

Sub-question 2: On what grounds do participants account for their own departure from official segregation?

Sub-question 3: While the distributed standard composting kits went unused, how were households handling organic material?

The visits found households that could state the rules and had received containers twice without using either, while five of the ten were directing part of their food waste into their own plants. Participants located the last point at which they could check their own sorting at the building gate, where they watched it being merged, and they explained their departure from official segregation by citing what the state had failed to do.

The policy–practice gap in urban Indian waste management

The regulatory architecture for household segregation in India is well established. The SWM Rules, 2016 assigned segregation duties directly to waste generators (MoEFCC, 2016). SBM-U treats behaviour change as a central component of its strategy, funding IEC campaigns and door-to-door outreach accordingly (Sahoo et al., 2022; Press Information Bureau, 2022). And Swachh Survekshan tied municipal reputation to measured performance. Yet unprocessed waste continues to accumulate at dumpsites nationally, and household segregation is not consistently maintained. Qualitative research has identified several common constraints: the temporal squeeze of morning routines, spatial limits on storing separated waste in small households, doubt about whether separation survives collection, and the gendered allocation of waste handling to women (Sahoo et al., 2022; Sahoo et al., 2024; Trushna et al., 2026). These studies suggest that non-segregation is reasoned rather than ignorant. They were, however, generated through focus groups and interviews conducted in community halls, Anganwadi centres, and municipal offices. Conducted away from the sites where waste is actually handled, these studies could not reach the moment of sorting itself.

The visibility of infrastructure

Infrastructure characteristically goes unnoticed when it

works, becoming visible only through breakdown (Star, 1999). The underexamined implication for waste from this observation is that users of a functioning collection system have little opportunity to see what happens to what they hand over. Where J. C. Scott's (1998) account of legibility describes the state's capacity to see its subjects, the waste chain poses the reverse problem of how far citizens can see the state's operations. In India, this opacity is compounded by the fact that much of the sorting labour that does occur is performed informally and off the record, by workers whose contribution is structurally unacknowledged (Doron & Jeffrey, 2018; Gidwani & Reddy, 2011). Reframing the segregation problem as a question of visibility rather than of knowledge shifts attention from what households are told to what they can verify.

Conditional cooperation and the conditions of compliance

Experimental work has established that contributions to public goods are conditional on the expectation that others are contributing (Fischbacher et al., 2001). Levi's (1988) concept of quasi-voluntary compliance extends this logic to the state, holding that citizens comply willingly but conditionally, contingent on the state performing its own side of the bargain. Tax compliance research provides the clearest empirical demonstration that perceived fairness and institutional trustworthiness, rather than enforcement alone, sustain voluntary contribution (Frey & Torgler, 2007). On this reading, withdrawal of cooperation is a defensible response to a perceived breach.

Theoretical position: how practices are explained

This study treats participants' explanations for their conduct as accounts rather than as reports of underlying causes (Mills, 1940; M. B. Scott & Lyman, 1968). Accounts are socially available justifications that people use to make their conduct understandable to others. When a participant says that the government fails to do its part, the analysis therefore asks not whether the statement is accurate, but what obligation it releases the speaker from and what it leaves unexplained.

Social Practice Theory describes practices as configurations of materials, meanings, and competences, and its vocabulary fits parts of this material well (Shove, 2010; Shove et al., 2012). Some of that vocabulary is used descriptively in what follows. It is not adopted as the analytical framework, however. SPT deliberately shifts attention away from individuals and toward practices as the unit of analysis. This study is concerned with what that shift makes hard to see, the judgements households make about the state and the relationship those judgements assume.

Contributions

Observational data generated inside the household. Much of the qualitative research on segregation in India has relied on focus groups and interviews conducted outside the home. This study visited ten households directly and observed where organic material is placed and how it is sorted, documenting the relation between what people report doing and what occurs in the kitchen.

Tracing the rejection of a distributed technology. Interventions are more often reported when they succeed than when they fail. This study distributed composting kits and revisited the same households, finding the kits unused while organic material continued to be handled through the households' own arrangements. Treating that failure as an object of analysis makes visible the specific points at which a standardised technology conflicts with the spatial and temporal conditions of the home.

Contrast between two sites with different infrastructural conditions. The study observed a setting where collection functions but its interior is not visible (Hyderabad) alongside one where collection is irregular or absent (Yavatmal), where the progression from open dumping to open burning was directly observed. The contrast permits shifts in waste practice to be attributed to differences in system conditions rather than in levels of awareness.

2. Methods

Study Design

This study used a multi-method qualitative case study design, combining semi-structured interviews, in-home participant observation, and the distribution of standard composting kits followed by a return visit to the same households (Table 1). The kits served two purposes at once, generating data about how households responded to a standardised technology while their non-use became an object of analysis

Table 1. Study Design and Methods

Domain	Element	Description
Design	Overall design	Multi-method qualitative case study
	Semi-structured interviews	10 household-level interviews, 30–40 minutes, audio-recorded with consent, conducted in English, Hindi, Telugu, or a regional language spoken within the community
	In-home participant observation	Where organic material is placed and how it is sorted
	Material intervention	Standard composting kits distributed, same households revisited
	Supplementary contrast observation	Yavatmal, approximately 2 days
Sites	Main study site	Hyderabad, Telangana
	Contrast site	Yavatmal, Maharashtra
Sample	Size	10 households, 35 participants
	Recruitment	Snowball sampling through community networks and personal connections
	Justification	Information power (Malterud et al., 2016)
Fieldwork schedule	First visit	2 weeks, interviews and observation, kit distribution
	Interval	Approximately 2.5 months
	Second visit	1 week, revisit
Analysis	Procedure	Reflexive thematic analysis (Braun & Clarke, 2022)
	Analytical stance	Participants' explanations treated as accounts
Research conditions	Reflexivity	Researcher composition, reactivity arising from the kit-provider relationship
	Ethics	Yonsei University IRB, anonymisation

in its own right.

Site, sample, and fieldwork

Fieldwork was conducted in Hyderabad, Telangana, with ten households and 35 participants recruited by snowball sampling through community networks and personal connections. Participants were therefore linked to one another and to the research team before the study began. Households are identified by a code (HH01 to HH10) and are not otherwise described, so that individual households cannot be traced. Hyderabad served as the main study site, where all interviews, household observation, and kit distribution took place. Yavatmal, Maharashtra, was observed for approximately two days as a contrast site, chosen because municipal collection was irregular, so that household practice could be set against a setting with different infrastructural conditions.

The first visit lasted two weeks and included interviews, observation of where organic material was placed and sorted, and distribution of the kits. Ten household-level interviews were conducted, each lasting 30 to 40 minutes. All were audio-recorded with consent and conducted in English, Hindi, Telugu, or a regional language spoken within the community according to participant preference. Interviews followed a semi-structured guide covering four areas. These were household waste routines and segregation practice, perceived challenges and responsibility for waste, knowledge of collection and post-collection processing, and awareness of and attitudes toward composting. Field notes were written during and immediately after each visit. The team returned approximately two and a half months later for one week to assess kit use and the reasons for non-use, and to observe the handling of organic material at home. Sample size was assessed using information power (Malterud et al., 2016), given the study's narrow aim, a sample specific to the practices in question, and an analytic strategy based on close reading of individual cases.

Analysis and ethics

Data were analysed through reflexive thematic analysis (Braun & Clarke, 2022). Coding was carried out and then discussed within the team, with codes grouped into subcategories and themes through repeated readings. The research team included a Korean researcher and a local researcher, who conducted interviews together. Asking about kit use created an obvious pressure toward socially desirable answers, since the question came from the people who had given the kits. That participants nonetheless reported not using them is treated here as data rather than as a problem to be discounted. The study was approved by the Institutional Review

Board of Yonsei University (IRB No. 7001988-202512-HR-3030-02), and informed consent was obtained from all participants. All participants are anonymised, and identifying details about the community have been removed or generalised to reduce the risk that the group can be located.

3. Results

Three themes were developed from the Hyderabad material, together with a fourth drawn from the contrast site (Table 2). The source of each code is marked as interview, observation, or both. The first two themes concern why cooperation with the municipal system was not sustained, the third concerns what households were doing with organic material instead, and the fourth sets these against a site where collection is largely absent.

Where the effort disappears I: opacity in the post-handover chain

Figure 1 traces the chain that carries household waste to the landfill and marks the points at which households lose sight of it. The chain is visible to households at only one point, and what becomes visible there is the undoing of their own sorting.

Participants who separated paper or recyclables described watching the building watchman consolidate those bags with everything else before handing them to the collection vehicle. This is the last stage at which verification is possible, and several participants reverted to a single bag once they had seen it.

> *"I recycle paper, so I keep paper separately. But the watchman still gives it to the truck along with everything else." (HH01)*

Beyond the building gate, verification stops. Participants consistently reported that collection vehicles mix whatever they receive, and a number of them named this as the reason they had abandoned separation at home. The research team's own observation, together with accounts from the few participants who had looked inside or asked the crew, indicates that compartmentalised collection does in fact occur. The vehicles are simply too tall and too enclosed to be seen into from the street. This divergence is offered here as an observation rather than a settled finding, since the data on vehicle operation are limited.

> *"I was given the two bins earlier, but I am not using them now. The bins became old over time, and the trash collectors still mixed all the waste together, so it felt pointless." (HH06)*

At the final stage the gap widens further. Almost no participant could describe what happens at the landfill, and the only sensory contact anyone reported was the smell. Into that gap participants placed competing assumptions, most commonly that the waste is burned, occasionally that it is sorted again.

Where the effort disappears II: reciprocity and withdrawn cooperation

Participants did not explain their non-participation by saying that segregation was pointless in principle, nor that they did not know how. They explained it by pointing to what the state had failed to do. The record they cited was cumulative rather than episodic. Colour-coded bins had been distributed once, after the pandemic, and never replaced when they wore out; some households reported receiving none at all. Collection vehicles arrived late or not at all, and in one building the residents had to pool money so that a neighbour could lodge a formal complaint, which succeeded only after that expense. Running through these accounts was the judgement that the shortfall was not accidental. Participants named corruption and indifference among municipal staff, and described the state as an actor that had already decided not to hold up its end.

> *"I didn't receive the two coloured bins." (HH09)*
>
> *"My neighbour protested against the garbage collection and succeeded, and now the people in the building support her financially." (HH04)*

Participants expressed this judgement as a matter of exchange, framing their own effort as owed only in return for the state's. One participant put it as a question with an obvious answer.

> *"The government is not doing their part. Why should I do mine?" (HH05)*

Others described themselves as angry at the government, and named that anger as the reason for disposing of waste in the street rather than carrying it to a bin. Read as accounts in M. B. Scott and Lyman's (1968) sense, these are justifications rather than excuses. The speakers do not deny responsibility for what they do. They reject the claim that doing it is wrong. It is a vocabulary of motive available to anyone in this setting, and it goes unchallenged because it draws on a standard of fairness that others recognise (Mills, 1940). The claim is not that the obligation does not exist, but that it has

Table 2. Coding Tree with Themes, Categories, Codes, and Data Source

Theme	Category	Code	Source
1. Opacity in the post-handover chain	1.1 The last point at which households can verify	Sorted paper merged by the watchman at building level	Interview
		Discontinuing separation after observing merging	Interview
		Building-level merging described as unavoidable	Interview
	1.2 The collection vehicle	Belief that trucks combine all fractions during collection	Interview
		Home separation discontinued on account of truck mixing	Interview
		Accounts of compartmentalised collection from participants who had looked inside	Interview
		Sorting within the truck recorded by the research team	Observation
		Vehicle size cited as barrier to seeing the interior	Both
		Truck workers extracting cardboard and steel for private sale	Interview
	1.3 The landfill	No knowledge of processing hubs or post-collection treatment	Interview
		Odour as the only encounter with the landfill	Both
		Assumption that collected waste is incinerated	Interview
		Competing assumption that waste is resorted at the landfill	Interview
2. Reciprocity and withdrawn cooperation	2.1 Accumulated experience of unfulfilled service commitments	One-off bin distribution with no replacement or follow-up	Interview
		Non-receipt of bins reported in some areas	Interview
		Irregular and delayed collection times	Both
		Financial cost of lodging a complaint borne by residents	Interview
		Service failure attributed to corruption	Interview
	2.2 The language of reciprocity	Non-cooperation stated as a response to government non-performance	Interview
		Anger toward government cited as reason for street disposal	Interview
		Individual action described as pointless given state inaction	Interview
	2.3 Distribution of responsibility	Responsibility assigned jointly to state, firms, and citizens	Interview
		Responsibility assigned to citizens as those who bear the consequences	Interview
		Specific state obligations named, including bins, sorting at collection, and processing	Interview
	2.4 Conditions named for restored cooperation	Willingness conditioned on evidence that separation is maintained after collection	Interview
		Requests for fiscal incentives such as property tax and insurance rebates	Interview
		Observation of neighbours' conduct cited as motivator	Interview
		Support for fines on improper disposal	Interview
3. Organic diversion outside standardised methods	3.1 Materials and routines	Diversion of vegetable peels, eggshells, and used tea to household pots	Both
		Drying and crushing before application to soil	Both
		Steeping peels and grains in water for plant use	Interview
		Practised by elder women who also manage household waste	Both
		Practice reported as sustained over many years	Interview
		Collection of discarded market peels for plant use	Interview
		Reasons given as nutrients and improved growth	Interview
		Balcony space used for sorting material for plants	Observation
	3.2 The unused kits	Non-use of distributed kits recorded at revisit	Both
		Formal composting procedure described as overwhelming	Interview
		No time located within existing routines to begin	Interview
		Satisfaction with the existing method given as reason	Interview
		Prior official composting abandoned owing to odour and lack of space	Interview

(Continued on the next page)

Table 2. Continued

Theme	Category	Code	Source
		Insects, odour, building rules, and space cited as barriers	Interview
		No prior knowledge of composting reported by some participants	Interview
	3.3 Limits of the practice	Incomplete decomposition leaving peels in soil	Both
		Insect attraction and foul odour	Interview
		Plant death following application	Interview
		Balcony space limiting the quantity handled	Both
4. Contrast case: infrastructural absence in Yavatmal	4.1 Disposal under irregular collection	Absence of building-level collection points	Interview
		Open field adopted as default disposal site	Both
		Disposal from windows into the adjacent field	Both
		Collection reported once or twice monthly without fixed timing	Interview
		Animals feeding at the dumping site	Both
	4.2 From accumulation to open burning	Burning of accumulated waste over approximately three hours	Observation
		Predominantly plastic content of the burned material	Observation
		Scorched and blackened ground following burning	Observation
		Described as a recurring practice sustained over years	Interview

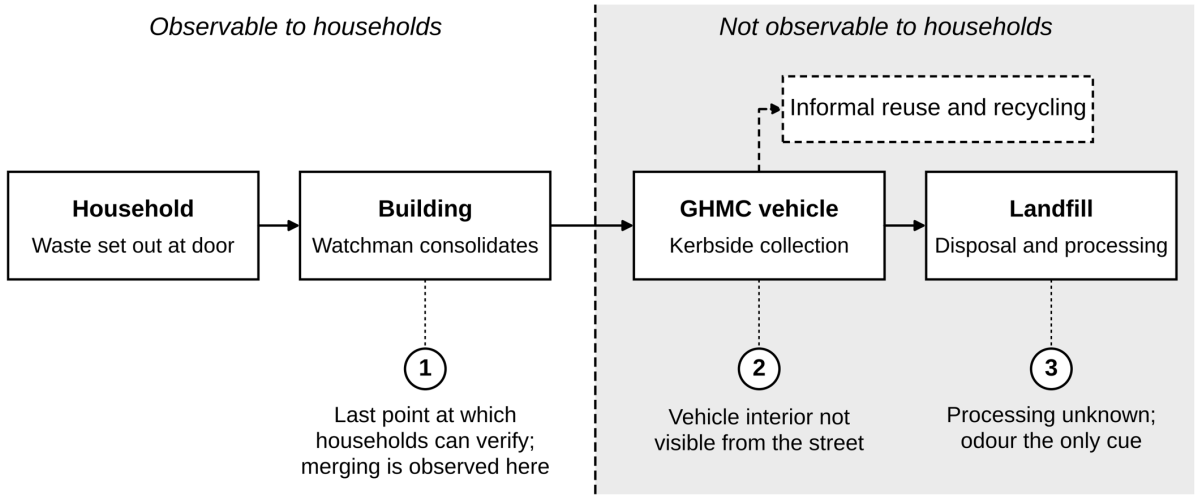

Figure 1. Waste Transfer Chain in Hyderabad and Points of Visibility Breakdown. GHMC = Greater Hyderabad Municipal Corporation. Numbered points mark where verification of sorted waste breaks down. Source: authors' construction based on field observation and participant accounts.

been suspended by the other party's failure to meet its own.

"Many citizens think the government is doing nothing, so they feel like, 'what can we even do?'" (HH10)

That this is a claim about fairness rather than a disclaimer of duty becomes clearer in what the same participants said about responsibility. Asked who is responsible for waste, most participants described responsibility as jointly held by the government, citizens, and the companies that produce packaging, and several named specific obligations on each side. From the state they expected adequate public bins, separation maintained at collection, and proper processing. From residents they expected proper cooperation. One participant located responsibility with citizens on the grounds that citizens are the ones who live with the consequences. Withdrawal of cooperation is therefore not a denial that the obligation exists but a suspension of performance pending performance by the other side. Asked what would restore their cooperation, participants named evidence that separation is maintained after collection before anything else. Others proposed fiscal incentives such as property tax or health insurance rebates, penalties for improper disposal, and pointed to the conduct of neighbours as something that would make them reconsider. Compliance here is quasi-voluntary in Levi's (1988) sense, willingly given but contingent

on the state meeting its own commitments.

What is withheld, however, is cooperation with the municipal waste system. They did not stop dealing with their food waste. Households that failed every official measure of segregation were, at the same time, sorting part of their food waste for purposes of their own.

Organic diversion outside standardised methods

By the measures used to assess programme performance, the households in this study were not practising segregation. Only one household maintained a systematic separation of household waste, and at revisit the composting kits distributed two and a half months earlier had not been used by anyone. On these criteria the group registers as a near-total failure of uptake. What the home visits found was that five of the ten households were nonetheless diverting a portion of their food waste away from the collection stream, into the soil of their own plants.

The materials were specific and the routines were established. Banana peels, onion and potato skins, eggshells, used tea leaves, and the water left from soaking rice or almonds were applied to household pots (Figure 2). Eggshells were dried and crushed first. Peels were sometimes steeped and the water used rather than the solid. One household described the practice as continuous over fifteen years. The work fell to the same person who managed waste for the household generally, in most cases the mother or grandmother, and it was carried out in whatever space existed, which in these apartments meant a balcony. One participant had gone as far as asking a vegetable seller for the onion peels he was discarding so that she could take them home for her plants.

"I use things like rice water, tea leaves water, egg shells, and soaked almonds water for my plants." (HH01)

"Yes, we have been practising composting for over 15 years on a regular basis." (HH03)

The reasons participants gave were not environmental. Nobody described the practice as waste reduction or as a response to landfill pressure. They described it as feeding the plants, and the plants mattered because they were cared for. Households kept between five and thirty of them, with many participants expressing considerable attachment and care toward these plants.

Meanwhile, participants who explained their non-use of the distributed composting kits described being overwhelmed by the layering procedure, unable to find a point in the day at which to begin, and uncertain how to start at all. Further constraints included insects and odour, along with building rules and the space a bin would occupy. One participant had attempted formal composting previously and abandoned it for exactly these reasons before settling on the method she now used. By comparison, the existing practice asks for no dedicated container, no schedule, and no procedure to learn. It used the pots that were already on the balcony and fitted into work someone was doing anyway.

Figure 2. Household Diversion of Organic Material to Plants in Hyderabad. (A) Vegetable peels dried on a balcony ledge before use. (B) Eggshells and peels placed on the soil of household pots. (C) Peels being worked into the soil of a pot.

Figure 3. Waste Disposal at Yavatmal. (A) Open burning of accumulated waste. (B) Livestock feeding on waste dumped beside residential buildings. Identifying signage has been obscured.

Cooperation with municipal segregation requires households to accept, without evidence, that their effort survives handover. However, within the domestic organic diversion process, the material is placed in a pot the household owns, in a room the household occupies, and the result is identifiable within weeks. Whether the plant grows or dies is not a matter of trust. The practice persists in part because it operates entirely inside the zone the household can still see.

Contrast case: infrastructural absence in Yavatmal

This section sets the Hyderabad material against observations from a second site, Yavatmal in Maharashtra. The two sites fall under different state administrations and were not studied to equivalent depth, so the material is presented as a contrast rather than as a comparative case. What it shows is how practices shift when the constraint is not opacity but the absence of provision.

In the areas observed in Yavatmal, there was no building-level collection arrangement of the kind found in Hyderabad. Residents placed waste in a large open field beside the buildings, in some accounts throwing it from windows, and municipal collection was described as occurring once or twice a month without a fixed schedule. Service within Yavatmal was uneven. Some areas had collection about once a week, and others had none. Dogs, cows, horses, buffaloes, and monkeys were observed feeding at the site and scattering material across it (Figure 3B).

The research team observed how accumulation was resolved. Waste gathered in the field was burned on site for approximately three hours (Figure 3A). The material was predominantly plastic, the ground afterwards was blackened, and the vegetation growing there was destroyed. Residents described this as a recurring procedure followed for years.

The two sites make different demands on households. In Hyderabad the infrastructure exists and functions, and the problem for households is that they cannot see inside it. Their withdrawal is a response to a system they are asked to trust without evidence. In Yavatmal that question does not arise, because there is no system to trust. Waste goes to the open field because there is nowhere else for it to go, and it burns because it accumulates. The problem in the first case is opacity, and in the second it is absence.

4. Discussion

Reconsidering the diagnosis of missing awareness and tools

Policy in this area has largely addressed two presumed deficits on the household side. Campaigns and outreach tar-

get knowledge (Press Information Bureau, 2022), and the municipality distributed colour-coded bins to address equipment. Neither deficit was present here in the form the policy assumes. Most participants could state which materials belong in which stream and explain why separation matters. Equipment had been supplied twice over, by the municipality after the pandemic and by this study two and a half months before the revisit, and neither was in use. What was missing was of a different kind. Households could not verify what happened to sorted waste after handover, the state had not sustained the services it began, and the equipment supplied did not fit the space or the daily schedule of an apartment household.

How opacity and grievance reinforce one another

Opacity and withdrawn cooperation resulting from a sense of reciprocity are separate findings and neither causes the other, but each strengthens the other. Because households cannot observe what happens after handover, the judgement that the state is failing to do its part is reinforced. Because that judgement is already in place, the gap left by opacity is filled with the least favourable available assumption, namely that the vehicle undoes the sorting. Section 3.1 indicates that this assumption is probably mistaken. The participants who described compartmentalised collection were those who had looked inside or asked the crew, and those who described mixing had not, so the difference between them was not what they believed about the municipality but what they had seen. The data on vehicle operation are limited and this is offered as an observation rather than a settled finding. If it holds, what failed at this point in the chain was not the infrastructure but the transparency and delivery of information.

Withdrawal as a policy signal

The grievance was consistent with the service record participants described. Bins were distributed once and not replaced when they deteriorated, some households received none, collection times were not kept, and in one building residents had to pool money before a complaint could be filed. Participants also did not disclaim their own obligation, since most participants described responsibility as shared between the state, citizens, and the firms that produce packaging. They asked the state to act first rather than asking to be excused.

Section 3.2 recorded what would restore their cooperation, and the first item was evidence that separation is maintained after collection, followed by property tax rebates, insurance rebates, penalties for improper disposal, and the visible conduct of neighbours. Campaigns and outreach are largely designed to change what households think (Press Information Bureau, 2022). These participants identified a defect in delivery and were able to say where it lay.

What the standard performance metric does not register

Under the current Swachh Survekshan framework, source segregation is assessed primarily through an indicator on segregation at source and segregated transportation, scored as the proportion of sampled points that pass, with validation carried out at residential areas, transfer stations, and processing facilities together with citizen validation interviews (Ministry of Housing and Urban Affairs [MoHUA], 2025). Applied to Section 3.1, the difficulty is that a single pass rate represents two different situations, households that did not sort and households whose sorting was merged at the building gate, and nothing in the score separates them.

A second category is absent from the framework altogether. Diverting food waste to household pots requires the household to separate organic from non-organic material first, and this separation never enters the collection stream. Five of the ten households here were diverting organic material in this way at the moment they were recorded as non-compliant. The quantities are small and bounded by the number of pots a balcony holds, so the claim is not that this practice is a sole solution. The claim is that a framework which cannot register a practice cannot learn from it, and there was something here to learn.

Conditions for a practice that lasts

Municipal segregation was abandoned, the composting kits were never begun, and the diversion of peels and shells to household plants was sustained, in one case for fifteen years. Setting them side by side identifies what the surviving arrangement had that the other two lacked.

The first condition is that the result be observable. A household that applies eggshells to a pot sees within weeks whether the plant responds. A household that hands a sorted

bag to the watchman sees only the merging described in Section 3.1. Visibility matters here because it is what allows a household to determine whether its own effort accomplished anything.

The second condition is that the labour yields a return. What the household does to its pots produces something the household keeps, such as edible plants including curry leaves, mint, chilli, and papaya, and ornamental ones including roses, hibiscus, and bonsai. Municipal segregation offers no return of this kind. The sorted bag leaves the building and nothing comes back. Section 3.2 recorded participants asking for property tax rebates and health insurance rebates. Households were asking to receive something for work they had done.

The third condition is that the arrangement uses what the household already has. The kits required three things that did not exist beforehand. They needed room for a bin, in apartments where participants named space as a constraint and where building rules sometimes prohibited one. They needed a layering procedure to be learned. And they needed a point in the day at which to begin, which participants described being unable to find. The pots were already on the balcony and plant care was already part of someone's routine, so adding organic material created no new task.

The fourth condition is that the other party performs. Municipal segregation requires the state to collect on schedule, to replace bins that wear out, and to keep separation intact after handover. Section 3.2 recorded participants citing each of these as something that had not happened. The plant arrangement has no counterpart to fail. Where an arrangement depends on another party, whether that party performs determines whether the arrangement holds.

Relation to previous research

Trushna et al. (2026) document post-collection opacity and its effect on institutional trust across three small Indian cities, together with a form of accountability among residents that is contingent on system performance. Sahoo et al. (2022, 2024) report related constraints in Ujjain. This study finds similar patterns in a metropolitan setting and indicates the pattern is not specific to small-city administration.

What is added lies in how the material was generated. Previous work has relied on focus groups and interviews conducted away from the home, and Trushna et al. (2026) report practices that bypass the municipal stream as participant statements. Entering households made it possible to observe what was done in the kitchen. Distributing a standard technology and returning to the same households recorded the conditions against which that technology was rejected.

5. Conclusion

This study asked how urban households in Hyderabad handle organic waste and what understandings of the waste management system those practices rest on. Households could state the rules and had received containers twice, once from the municipality and once from this study, and were using neither. At the same time, five households were directing part of their food waste into the soil of their own plants, in one case for fifteen years. In these households, the capacity and the willingness to separate organic material were present.

What households could not do was verify. Observation stops at the building gate, where the single visible stage is the watchman consolidating separated bags, and participants filled the remaining gap with the assumption that sorting is undone in the truck. The team's observations and the accounts of participants who had looked inside indicate that compartmentalised collection does occur, though the evidence on vehicle operation is limited. Alongside this, participants accounted for their departure from official segregation by citing the state's record, naming bins distributed once and never replaced, collection times not kept, and a complaint that required residents to pool money before it was heard. These accounts suspend the obligation without denying it, since most participants described responsibility as shared among the state, citizens, and packaging producers. Cooperation here is quasi-voluntary in Levi's (1988) sense. Meanwhile the organic material moved through an arrangement that asked for neither verification nor a counterparty, into pots the household owned and tended for reasons participants described as caring for plants rather than managing waste.

Two implications follow for how the existing system is administered.

The first concerns the direction of information. Programmes have largely been designed to send information to households, and participants named the reverse flow as what would restore cooperation, meaning evidence that separation survives handover. If compartmentalised collection is

taking place, the defect lies in what households can observe rather than in how waste is transported. What follows is that the target of intervention is the visibility of the chain, whether through vehicles that can be seen into, sorting performed where residents are present, or some form of reporting back on what was collected. Which of these is workable is a question for operational research beyond the scope of this study.

The second concerns what performance measurement records. Source segregation is scored as the proportion of sampled points that pass an assessment conducted at residential areas, transfer stations, and processing facilities (MoHUA, 2025), so a building where households sort and the watchman consolidates registers the same way as one where no household sorts. Assessment that recorded the stage at which separation breaks down would show municipalities where to intervene, and in these buildings that stage was the consolidation point rather than the household. In practice, this would mean recording segregation separately at the household door, at the building consolidation point, and on the collection vehicle, rather than as a single pass rate for each sampled point. Counting organic material diverted at home would register practices the current framework treats as absent, since five of the ten households here were separating organic material at the moment they were recorded as failing to do so. This would require a separate category within the household-level assessment for organic material retained for home use, verified during residential validation visits and recognised as source segregation rather than recorded as non-compliance. The quantities are limited by what a balcony holds and are no substitute for municipal processing, but a framework that cannot register a practice cannot learn from it.

6. Limitations

Four limitations bear on how far these findings extend. The ten households were recruited by snowball sampling through a single community network and personal connections, so participants were linked to one another and shared a residential and social context that shaped what could be observed, and the findings are not intended to generalise to Indian households at large. The interval between visits was two and a half months, long enough to establish that the kits went unused but not long enough to say whether the practices recorded here persist or how they change. Observations of vehicle operation were incidental to the fieldwork and rest on a small number of sightings and participant accounts, which is why the divergence between what participants assumed and what appeared to occur is offered as an observation requiring vehicle specifications and operational records to confirm. Finally, the researchers who asked about kit use were the researchers who had supplied the kits, and while participants reported non-use readily, the same relationship may have shaped what was said about the reasons.

Funding

This research was supported by the Social Engagement Fund of the Institute for Global Engagement and Empowerment, Yonsei University (Grant No. 2025 SEF-11).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Interview transcripts and field notes are not publicly available. The households in this study were recruited through a single community network, and the accounts include details of residence, household composition, and relations with municipal staff that could identify participants even after removal of names. Anonymised excerpts beyond those reported here may be made available by the corresponding author on reasonable request, subject to the terms of the ethics approval.

Use of AI-assisted Technologies

The authors used Claude to edit language and grammar and to assist in producing Figure 1. The tool was not used for study design, data collection, coding, analysis, or the formulation of conclusions. The authors reviewed all such material and take full responsibility for the content of this article.

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Oct. 2026, Volume.3 No.3

igee proceedings

pISSN: 3022-5183 eISSN: 3022-5191

IGEE Proc 2026;3(3):180-194
https://doi.org/10.69841/igee.2026.018

Article

Can Electric Motorcycles Save Lives? Evidence from Uganda and Rider-Level Barriers to Electric Transition

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Urban motorcycle taxis, or boda bodas, dominate mobility in Kampala, Uganda, where aging internal combus-tion engine fleets are a primary driver of PM2.5 pollution and associated mortality burdens, yet the transition to electric vehicles (EVs) remains limit-ed. Under a hypothesis that a transition of internal combustion engine motorcycles into electric vehicles will decrease the PM2.5 pollution and eventually generate health benefits, the authors incorporate quasi-experimental method with qualitative thematic analysis. Using a Differ-ence-in-Differences framework that exploits an Ebola-induced mobility lockdown in Mubende district in 2022 as an exogenous shock, we estimate that transportation accounts for approximately 13.9% of ambient PM2.5, implying that full boda boda electrification could reduce total PM2.5 by 5% and avert approximately 58 premature deaths annually in Kampala. Drawing on nine in-depth interviews with boda boda riders analyzed through thematic analysis, we further investigate that adop-tion hesitancy reflects not attitudinal resistance but three structural barriers: 1) insufficient battery-swap infrastructure generating spatial uncertainty, 2) a policy misalignment between government objectives and riders, and 3) extractive financial structures that amplify income volatility under daily-income dependence. These findings suggest that realizing the public health gains from elec-trifying motorcycles requires rider-centered policy interventions targeting infrastructure reliability and flexible financing, rather than hardware substitution alone.

Keywords Boda boda, Electric vehicle transition, PM2.5, Uganda, Mixed methods

Received: June 1, 2026 **Revised:** September 10, 2026
Accepted: October 7, 2026
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This article was supported by the IGEE Social Engagement Fund 2025. The contents were developed as a part of an undergraduate educational initiative and are presented for educational and internal academic reporting purposes only. Because the publication and SEF project is academic in nature, this article did not receive IRB ethical approval for the interview of nine motorcycle drivers.

1. Introduction

Rapid urbanization across low- and middle-income countries (LMICs) has in-tensified urban air pollution, with motorcycles powered by aging internal combustion engines (ICE) emerging as a principal driver of particulate matter concentrations and respiratory disease burdens (Leong et al., 2001; Tran et al., 2022; Dandapat et al., 2020). Uganda stands out as a salient example in this global trend. The “boda boda” motorcycle taxi sector, now accounting for approximately 98% of Uganda's more than one million registered motorcycles, forms the backbone of national urban mo-bility and serves a majority of the population well beyond private use (Daily Monitor, 2024; Yi, 2016). Beyond its transport function, the boda boda sector represents one of the largest sources of youth employment in an economy characterized by persis-tent informality (East Africa Venture Capital Association, 2022; Amone, 2021). Boda bodas are thus not merely a transport mode; they constitute a livelihood system embedded in the social and economic foundation of Ugandan urban life.

At the same time, the rapid proliferation of boda bodas has generated severe environmental and public health externalities. In Kampala, poorly regulated and inadequately maintained ICE motorcycles are a primary contributor to PM2.5 con-centrations that routinely exceed WHO guidelines (MEIR Engineering & Research Ltd, 2021; Okello et al., 2024). Prolonged exposure to such pollution has been as-sociated with elevated premature mortality and a rising burden of non-communicable respiratory diseases, particularly among low-income populations (Okello & Tatah, 2025; Park et al., 2021). As shown in Figure 1, motorcycles also account for a sig-nificant share of road traffic fatalities, reflecting structural deficiencies in road safety governance (Uganda Police Force, 2023).

In response to these challenges, electric motorcycles have emerged as a poten-tially high-impact intervention capable of abating tailpipe emissions, improving ur-ban air quality, and lowering public health costs (Okello & Tatah, 2025; Craig et al., 2021; Vanatta et al., 2022). Private sector actors, most notably Zembo and Spiro, have led early deployment of electric boda bodas in Kampala utilizing bat-tery-swapping models, and an official report documents growth from fewer than 20 electric motorcycles in 2019 to approximately 4,200 by 2024 (STI Secretariat, 2024). The Ugandan government has reinforced this trajectory through a National E-Mobility Strategy, tax exemptions on EV components and charging equipment, and early charging infrastructure investments (Parliament of Uganda, 2024a; 2024b; Mobility Bureau, 2024). Despite this enabling context, EV adoption remains limited relative to the over-one-million ICE fleet, and the question of what constrains tran-sition has not been systematically answered.

Existing research on electric boda bodas in Uganda can be grouped into three strands: environmental and emissions modeling (Craig et al., 2021; Vanatta et al., 2022), health impact assessment (Okello & Tatah, 2025), and feasibility and scaling analysis (FTVG, 2025; GIZ, 2023; Okello & Reynolds, 2022). While this literature establishes the desirability of electrification and identifies broad infrastructure and financing frictions, it leaves two critical gaps unaddressed. First, the causal contri-bution of motorcycle traffic to ambient PM2.5 concentrations and the resulting mortality burden has not been empirically identified with a credible identification strategy. Most estimates rely on modeling assumptions rather than observed exog-enous variation. Second, while government initiative and policy approach to increase the deployment of EV motorcycles are actively ongoing, the behavioral mechanisms that shape individual riders' adoption hesitancy have received little attention. Most studies rely on policy analyses rather than systematic rider-level evidence (Bbaale et al., 2025; PREO, 2023). As a result, existing literature explains why EV transition is desirable in aggregate, but not why riders, who face daily income dependence, li-quidity constraints, and operational uncertainty, continue to hesitate.

Figure 1. Downtown Kampala (taken by researchers).

This study addresses both gaps through a mixed-methods design. The quanti-tative component employs a Difference-in-Differences (DiD) framework, exploiting the Ebola-induced two-month mobility lockdown in Mubende district in 2022 as an exogenous shock to transportation activity, to estimate the causal share of transport-attributable PM2.5 in Kampala and translate this into health impact pro-jections using the WHO AirQ+ model. The qualitative component draws on nine semi-structured in-depth interviews conducted with boda boda riders in Kampala in October-November 2025, analyzed through thematic analysis, to examine the structural and behavioral barriers that constrain EV adoption at the rider level.

The two components are designed to be analytically complementary. The quantitative analysis establishes the public health stakes of the transition providing an empirically grounded estimate of the mortality burden attributable to motorcycle traffic and the potential gains from electrification. The qualitative analysis then sit-uates the adoption question within the everyday realities of boda boda work, iden-tifying the mechanisms that make EV transition precarious for riders even when its aggregate benefits are widely acknowledged. Together, this mixed-methods ap-proach responds to a recognized gap in the lower middle income countries e-mobility literature, where cross-country syntheses consistently emphasize that effective EV transition requires not only vehicle availability but ecosystem coordination including infrastructure, business models, finance, and institutional support to move in tandem (Agora Verkehrswende, 2025; Republic of Kenya, 2024).

The remainder of this paper is organized as follows. Section 2 describes the data sources and methods employed in both the quantitative and qualitative components. Section 3 presents the results of the DiD analysis and the health impact assessment, followed by the thematic findings from the rider interviews. Section 4 discusses the implications and limitations of the research method and concludes with recom-mendations for rider-centered transition strategies.

2. Materials and Methods

Research Design

This study employs a mixed-methods design combining quantitative causal inference with qualitative field research. The two components address distinct but complementary questions: the quantitative strand estimates the causal contribution of motorcycle traffic to ambient PM2.5 concentrations and translates this into health impact projections, while the qualitative strand investigates the structural and be-havioral mechanisms that constrain individual riders' adoption of electric motorcy-cles. This integration reflects the recognition that understanding EV transition in the boda boda sector requires both an empirical account of the public health stakes and a rider-level analysis of why adoption remains limited despite demonstrated aggregate benefits.

Quantitative Component

1) Data

This study uses hourly PM2.5 concentration data collected by ground-based air quality sensors operated by AirQo (https://airqo.net/home), aggregated to the daily level. PM2.5 was selected as the primary outcome variable because it is a well-established indicator of urban air pollution with direct implications for respira-tory and cardiovascular health, particularly in LMIC contexts. As shown in Figure 2, the treatment group is Mubende district, while the control group comprises Kampala, Kawempe, Kira Municipality, Makindye, Masaka, Mityana, Nakawa, Rubaga, and Wakiso, all located within Uganda's Central Region to ensure geographic and cli-matic comparability. Humidity and temperature are included as control variables, as both are known to influence particulate matter concentrations independently of human activity. The data spans from November 2021 to December 2023 among which the data from April 15, 2022 to September 13, 2022, was missing for all dis-tricts due to its unavailability in AirQo dataset. In empirical nature, the 6-month data gap is non-negligible in analyzing true effect of lockdown on air quality, and authors acknowledge this gap as the major limitation of this research. Nonetheless, in the following section, this research endeavors to mitigate this limitation and support the existing hypothesis by conducting robustness check with various data starting points and looking at the consistency of coefficients.

For the health impact assessment, baseline mortality and population-at-risk data were drawn from the WHO Global Health Estimates (2019 reference year to avoid COVID-19 effect) and a previous Kampala-specific AirQ+ assessment (Atuyambe et al., 2025): a baseline natural-cause mortality rate of 1,095 per 100,000 among persons aged 30 years and older, and an estimated population at risk of 431,453

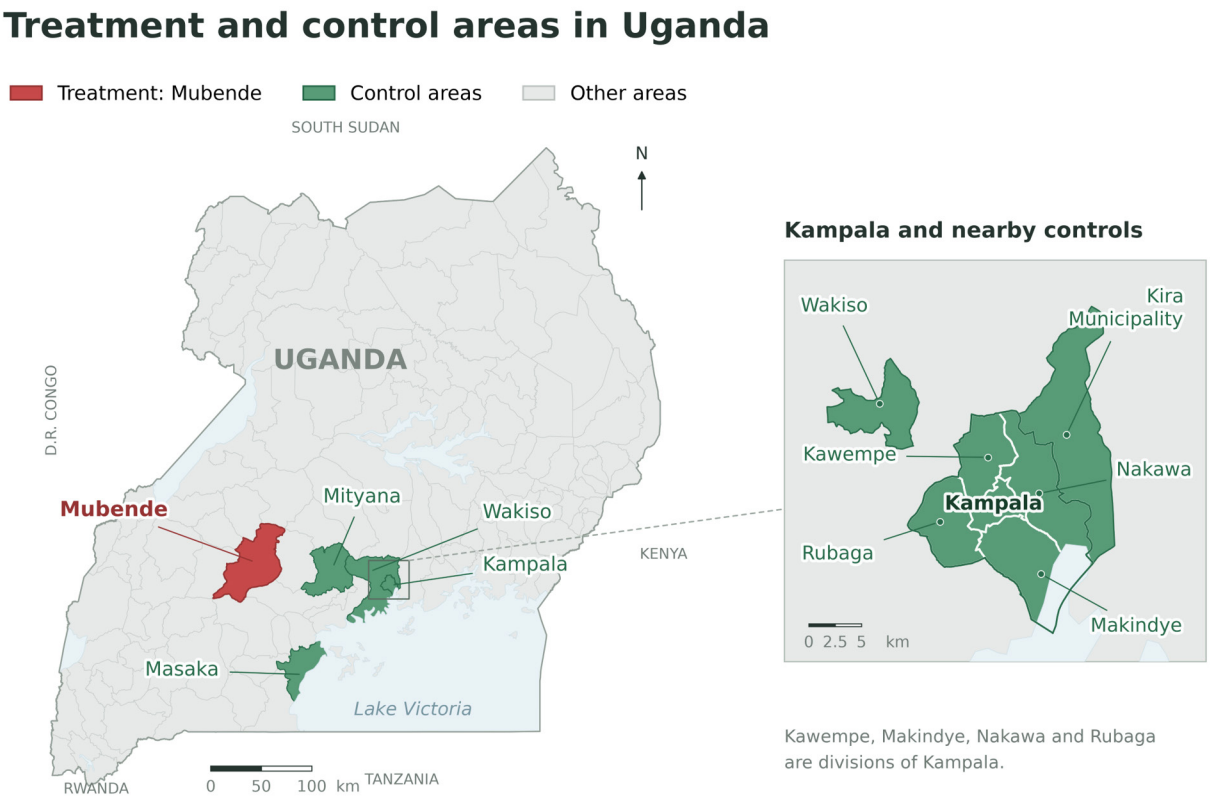

Figure 2. Treatment (Mubende) vs. Control Group.

persons, representing approximately 24% of Kampala's total population of 1.80 million. The share of transport-attributable PM2.5 contributed specifically by motorcycles was derived from the report of African Development Bank (AfDB, 2025), which estimates that motorcycles account for 36% of transport-related PM2.5 in Kampala.

2) Identification Strategy: Difference-in-Differences

To isolate the causal contribution of transportation activity to ambient PM2.5, this study exploits the lockdown caused by Ebola outbreak in Mubende district that occurred in September 2022 as an exogenous shock to mobility. The outbreak triggered a government-imposed lockdown initially for three weeks from October 15, 2022, to November 5, 2022 (Daily Monitor, 2022). However, the government extended the initial 21-day lockdown to tighten the control on the disease and later lifted all movement restrictions on December 17, 2022 (Voice of America, 2022). The research exploits this two-month mobility lockdown as an exogenous shock for difference-in-differences to identify whether this natural experimental setting has contributed to the reduction in PM2.5 observed in Mubende.

The identifying assumption is that, absent the Ebola-induced lockdown, PM2.5 trends in Mubende would have evolved in parallel to those in the control districts. The DID estimator is specified as follows. Let PM_{it} denote the PM2.5 concentration in district i at time t, $Treated_i$ an indicator equal to one for Mubende, and $Post_t$ an indicator equal to one for the post-intervention period. The baseline specification is:

$$PM_{it} = \alpha + \beta(Treated_i \times Post_t) + \gamma_{i,m} + \delta_t + X'_{it}\theta + \varepsilon_{it}$$

where δ_t denotes and time (year) fixed effects, γ_i denotes city × month fixed effect, controlling for seasonality, X_{it} includes meteorological controls (humidity and temperature), and β is the average treatment effect on the treated (ATET), the estimated reduction in PM2.5 attributable to the mobility shock. A log-transformed specification is also estimated to allow for proportional interpretation of the effect. All regres-

sions were estimated using Stata BE 19.5.

The estimated transport-attributable PM2.5 reduction from the DiD analysis was translated into mortality impacts using the WHO AirQ+ model. AirQ+ applies concentration-response functions derived from epidemiological evidence to estimate the number of premature deaths attributable to changes in ambient PM2.5 exposure. The counterfactual scenario modeled in this study assumes full electrification of the boda boda fleet, constructed in two steps. First, the DiD estimate is used to identify the transport-attributable share of total ambient PM2.5. However, even in the perfect scenario of full electrification, ambient emission is still likely to occur as driving on the road still flies off dust in the air. Acknowledging this limitation, authors strictly assume that the PM2.5 level under perfect electrification scenario will be equivalent to the level of mobility lockdown. Second, this share is multiplied by the motorcycle-specific contribution derived from the African Development Bank (AfDB, 2025), which attributes 36% of transport-related PM2.5 to motorcycles, to obtain the implied PM2.5 reduction under full electrification. The resulting counterfactual PM2.5 concentration is then entered into AirQ+ using all-cause natural mortality for the population aged 30 and above as the health outcome.

Qualitative Component

1) Study Design and Site Selection

The qualitative component was designed to examine how boda boda riders experience and evaluate the prospect of EV adoption in the context of their everyday work. A field-based approach grounded in semi-structured in-depth interviews was employed, as this method is well suited to capturing the experiential, relational, and institutional dimensions of adoption decisions that survey instruments cannot readily access. Kampala was selected as the primary field site given its status as the center of Uganda's boda boda sector and the primary geography of EV boda deployment to date.

2) Fieldwork and Participant Recruitment

Fieldwork was conducted in Kampala over seven days from October 25 to October 31, 2025. Prior to departure, the research team reviewed existing literature on boda bodas, EV transition, and urban health in Uganda, and developed a semi-structured interview guide focused on riders' occupational experiences, perceptions of EV motorcycles, and perceived barriers to adoption. Through correspondence with relevant researchers, contact was established with a local collaborator fluent in Luganda, who facilitated communication with participants and assisted with translation during interviews.

The fieldwork proceeded in two phases. In the initial phase, exploratory ob-servation was conducted to gain contextual understanding of the research environ-ment, and preliminary interviews were used to refine the interview guide in ac-cordance with the local context. In the main interview phase, participants were re-cruited through two channels. Four riders were approached directly after the research team had used their boda boda services for transportation. Following the trip, the researchers introduced the purpose of the study and asked whether the rider would be willing to participate in an interview. Those who consented were subsequently contacted to arrange a separate interview at a mutually convenient time and location, typically a café, as seen in Figure 3. The remaining five riders were recruited with the assistance of the Bodaboda Association and were interviewed at the Association's office. One additional interview was conducted with a boda boda association leader, as shown in Figure 4, who provided institutional-level perspectives on EV transition dynamics. All interviews were conducted on a one-on-one basis with the assistance of the local collaborator.

3) Participants

A total of nine boda boda riders and the president of Kampala Bodaboda As-sociation participated in the study, comprising six internal combustion engine mo-torcycle riders and three electric boda boda riders. The inclusion of both ICE and EV riders was deliberate to compare the perspectives of current EV users with those who have not yet adopted, allowing for a richer account of both the perceived advantages and the experienced barriers of the transition. Participant profiles varied in terms of years of experience, ownership arrangements (owner-operators versus renters), and stage affiliation. All participants provided verbal consent to participation and to audio recording of the interview.

4) Data Collection and Analysis

All interviews were audio-recorded and subsequently transcribed in full. Where interviews were conducted in Luganda, real-time translation was provided by the local collaborator and incorporated into the transcription. Thematic analysis was conducted following the approach described by Braun

Figure 3. Interview with an ICE Rider.

Figure 4. Interview with the President of Bodaboda Association.

and Clarke (2006), pro-ceeding through phases of familiarization with the data, initial coding, theme de-velopment, review, and interpretation. Coding focused on recurrent patterns across rider narratives, including perceived advantages and challenges of boda boda work, barriers to EV adoption, and perceptions of electric motorcycles. Four primary thematic categories were identified: (1) perceived advantages of boda boda work, (2) perceived challenges of boda boda work, (3) barriers to EV transition, and (4) per-ceived advantages of EV motorcycles. These categories informed the analytical framework developed in the results and discussion sections.

3. Results

Quantitative Results

Prior to presenting the DID estimates, the validity of the parallel trend assump-tion was assessed through visual inspection of PM2.5 trajectories in the treatment and control groups over the pre-intervention period, and the result is illustrated in Figure 5. This pre-intervention window is restricted to September 14 to October 14, 2022, the final continuous stretch of daily observations immediately preceding the lock-down; the preceding six-month data gap (April 15 - September 13, 2022) precludes a longer continuous pre-trend assessment extending further back. The pre-intervention trends for Mubende and the control districts move closely together, with little evi-dence of systematic divergence before the Ebola outbreak. Minor short-term fluctu-ations are observable but appear common across both groups, consistent with shared meteorological drivers rather than location-specific shocks. This pattern supports the plausibility of the parallel trends assumption and provides confidence that post-treatment differences can be attributed to the mobility shock rather than pre-existing heterogeneity.

1) Difference-in-Differences Estimates

Table 1 presents the main result of DID estimates for the full sample period from November 13, 2021, to December 23, 2023 across entire cities in the sample dataset and the selected control group. Column (1) illustrates the DID estimate of the treatment city when compared with entire sample cities with temperature and humidity controlled. PM2.5 level decreased by 6.432μg/m^3 and it is statistically significant. When compared with the control group selected under geographical proximity and climatic similarity, columns (2) and (3) exhibit the PM2.5 level decreased by 7 to 8μg/m^3 when seasonality was not controlled and columns (4) and (5) report the estimates to be around -5 to -6μg/m^3 when seasonality was controlled. The decrease in magnitude of coefficients when seasonality is captured reflects the fact that October and November being the Uganda's wet season, during which rainfall washes out particulate matter, therefore seasonality absorbs a part of decline in PM2.5. One point worth noting is that, under the model where seasonality is controlled, standard error increases, or the estimate becomes less precise, from 0.976 to 1.301 as temperature and humid-

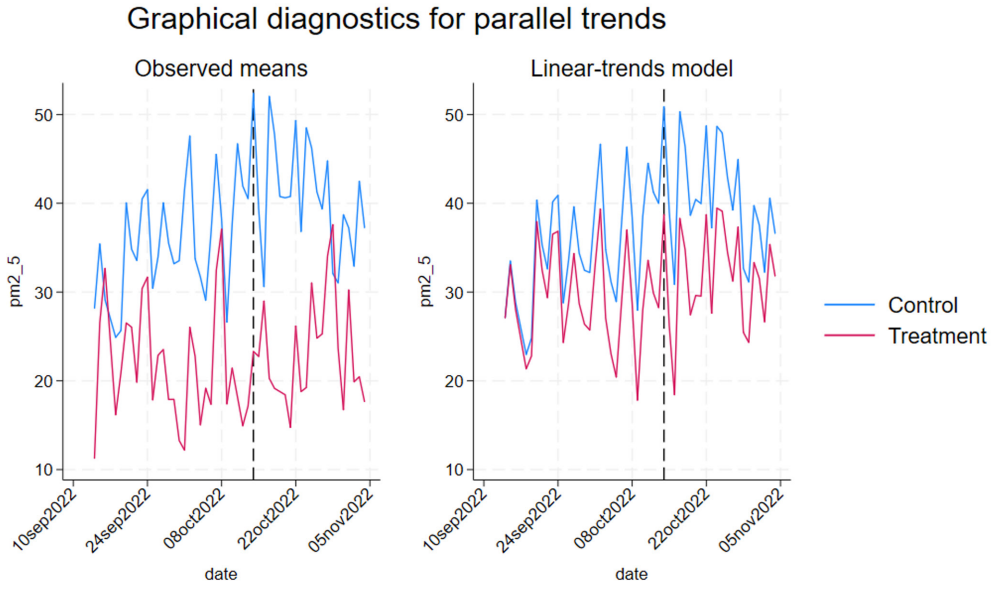

Figure 5. PM2.5 Pre-trend.

Table 1. Difference-in-Differences Estimates of PM2.5 Reduction (Full Period)

	Seasonality Controlled	Seasonality Uncontrolled		Seasonality Controlled	
	(1)	(2)	(3)	(4)	(5)
	Entire Cities	Comparison with Control Group			
did	-6.432*** (1.830)	-7.849*** (1.504)	-7.938*** (1.045)	-5.257*** (0.976)	-6.204*** (1.301)
temperature	-1.557*** (0.374)		-1.728*** (0.391)		-1.306*** (0.291)
humidity	-0.408*** (0.0682)		-0.190 (0.132)		-0.421*** (0.0834)
_cons	105.6*** (13.14)	41.64*** (0.0150)	96.03*** (18.25)	41.61*** (0.00972)	104.7*** (12.00)
N	12377	5827	5225	5827	5225

Standard errors in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01. Note: Column (1) compares treatment group (Mubende) with entire cities in the sample dataset. Column (2)-(5) compares the treatment city with arbitrarily selected nine cities based on geographical proximity and climatic similarities. Column (2) and (3) do not control seasonality and (4) and (5) control seasonality by the term (city × month) in regression formula.

ity are added as controls (column (4) to column (5)). This is because the city × month seasonality fixed effect already absorbs much of the systematic variation in temperature and humidity. Once this variation is netted out, the remaining variation in temperature and humidity overlaps with the remaining variation in the DID indicator, which is presumed to inflate the standard error of the DID coefficient. All the estimates were statistically significant (p-value less than 0.01) except for the humidity variable when seasonality was uncontrolled.

Table 2 exploits the log scaled PM2.5 as a dependent variable while maintaining everything else constant with Table 1. Since the dependent variable is in log scale and the DID coefficients are not small in magnitude, we transform the estimated coefficients as $100 \times (e^{\beta}-1)$ rather than interpreting β directly as a percentage. In Column (1), the lockdown is associated with approximately 11.7% decrease in PM2.5 when comparing the treatment city to all cities in the sample, and a 22.4-22.9% decrease when compared to the control group (Columns (2)-(3)), with seasonality-controlled specifications in columns (4)-(5) showing a smaller but still substantial 13.9% decrease. Researchers use column (5) estimate (-13.9%) that fully controls seasonality and other variables as a representative estimate to be later used in measuring health impact from air quality improvement.

2) Robustness Check

Since this research possesses a limitation that lacks considerable amount of pre-treatment period observations during April 15 to September 13, 2022, authors conducted

Table 2. Difference-in-Differences Estimates in Log Scale (Full Period)

	Seasonality Controlled	Seasonality Uncontrolled	Seasonality Controlled		
	(1)	(2)	(3)	(4)	(5)
	Entire Cities	Comparison with Control Group			
did	-0.125***	-0.260***	-0.254***	-0.150***	-0.150***
	(0.0300)	(0.0405)	(0.0259)	(0.0269)	(0.0368)
temperature	-0.0209***		-0.0397***		-0.0140
	(0.00674)		(0.0120)		(0.00956)
humidity	-0.00772***		-0.00395		-0.00787***
	(0.00143)		(0.00410)		(0.00209)
_cons	4.596***	3.632***	4.848***	3.630***	4.565***
	(0.243)	(0.000403)	(0.579)	(0.000268)	(0.356)
N	12377	5827	5225	5827	5225

Standard errors in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01. Note: Dependent variable is the level of PM2.5 in log scale. (1) compares treatment group (Mubende) with entire cities in the sample dataset. Column (2)-(5) compares the treatment city with arbitrarily selected nine cities based on geographical proximity and climatic similarities. Column (2) and (3) do not control seasonality and (4) and (5) control seasonality by the term (city × month) in regression formula.

Table 3. Robustness Check Without Seasonality Controlled

	(1)	(2)	(3)	(4)	(5)
	Jan	Feb	Mar	Apr	Sep
did	-7.938***	-7.823***	-5.838***	-3.686**	-3.636**
	(1.045)	(1.092)	(1.177)	(1.435)	(1.503)
temperature	-1.728***	-1.695***	-1.541***	-1.468***	-1.513***
	(0.391)	(0.390)	(0.286)	(0.229)	(0.280)
humidity	-0.190	-0.184	-0.130	-0.096	-0.099
	(0.132)	(0.128)	(0.103)	(0.090)	(0.108)
_cons	96.029***	94.485***	86.308***	82.012***	83.393***
	(18.249)	(17.364)	(12.723)	(10.739)	(13.968)
N	5225	4917	4654	4342	4216

Standard errors in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

robustness checks throughout different data starting points to identify consistency of estimate, and the results are illustrated in Table 3 and 4. Table 3 shows the robustness check without seasonality starting from January to September, whichever month in 2022 where data was available. In January the DID coefficient estimate reaches -7.9μg/m^3 but as time goes by, the absolute value gradually de-creases to -3.6μg/m^3. However, when the seasonality was controlled (Table 4), the coefficient estimates are very much consistent across the whole period from January to September, ranging approximately between -6 ~ -7μg/m^3. Figure 6 illustrates that coefficients without seasonality have higher variance while the values of coefficients with seasonality are stable throughout the whole period.

3) Health Impact Assessment

The DiD results are used to construct a counterfactual health impact scenario for full boda boda electrification in Kampala. The log-specification estimate implies that transportation activity accounts for approximately 13.9% of total ambient PM2.5 during the lockdown period, interpreted here as a proxy for the transport-attributable share of PM2.5 under normal mobility conditions. Combining this with the AfDB estimate that motorcycles contribute 36% of transport-related PM2.5 yields an im-plied reduction of approximately 5% (13.9% × 36% ≈ 5.0%) of total ambient PM2.5 under a scenario of complete boda boda electrification with a strong assumption that a complete electrification results in the same decline in PM2.5 level equivalent to mobility lockdown.

Applying this 5% reduction to Kampala's observed mean PM2.5 concentration of 41.72 μg/m^3 during 2022–2023 yields a counterfactual mean concentration of 39.63 μg/m^3.

Table 4. Robustness Check With Seasonality Controlled

	(1)	(2)	(3)	(4)	(5)
	Jan	Feb	Mar	Apr	Sep
did	-6.204***	-6.320***	-6.840***	-6.606***	-6.154***
	(1.301)	(1.468)	(1.442)	(1.425)	(1.445)
temperature	-1.306***	-1.090***	-0.923**	-0.501	-0.466
	(0.291)	(0.323)	(0.324)	(0.345)	(0.327)
humidity	-0.421***	-0.319***	-0.200*	-0.062	-0.026
	(0.083)	(0.092)	(0.102)	(0.083)	(0.082)
_cons	104.739***	91.256***	77.570***	56.883***	53.299***
	(11.996)	(13.585)	(14.369)	(13.241)	(12.287)
N	5225	4915	4652	4339	4213

Standard errors in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01. *Note: Minor sample-size differences arise from dropped singleton cells under the city × month fixed effects.

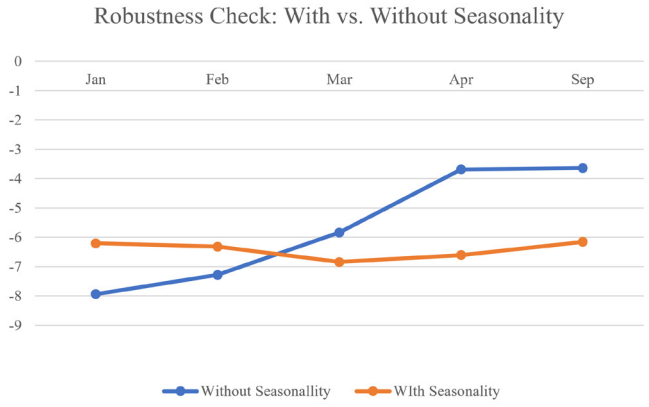

Figure 6. Robustness Check: With seasonality vs. Without Seasonality.

The associated mortality impacts were estimated using the World Health Organization's AirQ+ model. The health end-point was defined as all natural-cause mortality among adults aged 30 years and older, and a log-linear concentra-tion–response function was applied. A common reference concentration of 5 μg/m^3 was used for both the observed and counterfactual scenarios. This value corresponds to the WHO 2021 annual air-quality guideline for PM2.5 (WHO, 2021). The WHO guideline recommends an annual mean PM2.5 concentration of 5 μg/m^3, reflecting evidence of ad-verse health effects even at relatively low exposure levels.

The concentration–response function was parameterized using a relative risk of 1.08 per 10 μg/m^3 increase in long-term PM2.5 exposure, with a 95% confidence interval of 1.06–1.09. These estimates were taken from the systematic review and meta-analysis by Chen and Hoek (2020), which reported a pooled relative risk of 1.08 (95% CI: 1.06–1.09) for natural-cause mortality per 10 μg/m^3 increase in PM2.5.

Table 5. Health Impact Assessment Results (WHO AirQ+)

	Baseline	Counterfactual Scenario
PM2.5 Mean (μg/m³)	41.72	39.63
Attributable proportion	24.62%	23.40%
Attributable Deaths	1,163	1,105
Attributable deaths per 100,000 population at risk	269.6	256.2

Population: 1.80 million; Baseline natural-cause mortality rate:1,095 per 100,000 (Kampala, 2019), aged ≥ 30.

The baseline natural-cause mortality incidence was set at 1,095 deaths per 100,000 persons aged 30 years and older per year. This rate was derived from the WHO Global Health Estimates for Uganda using 2019 as the reference year. All-cause deaths were summed across the 30–49, 50–59, 60–69, and ≥70 age groups, and deaths classified under the broad category "III. Injuries" were excluded to ap-proximate natural-cause mortality. This yielded approximately 113,999 natu-ral-cause deaths among approximately 10.415 million persons aged 30 years and older, corresponding to an annu-al incidence of approximately 1,095 deaths per 100,000 pop-ulation at risk (WHO, 2024). The use of 2019 provides a pre-pandemic mortality baseline and avoids potential distor-tions associated with COVID-19 mor-tality and related dis-ruptions to health services.

The population at risk was restricted to persons aged 30 years and older, con-sistent with the selected AirQ+ end-point. Approximately 24% of Kampala's popula-tion was as-sumed to fall within this age group, following the age struc-ture used in the previous Kampala AirQ+ assessment by Atuyambe et al. (2025). This resulted in an estimated popu-

lation at risk of 431,453 persons.

The result of health impact is shown in Table 5. Under the observed PM2.5 concentration of 41.72 μg/m^3, AirQ+ estimated that 24.62% of natural-cause mor-tality among adults aged 30 years and older was attributable to PM2.5 exposure above the 5 μg/m^3 reference concentration. This corresponds to approximately 1,163 attributable deaths annually, with a 95% confidence interval of 910–1,282. Under the counterfactual scenario, in which mean PM2.5 declines by 5% to 39.63 μg/m^3, the attributable proportion falls to 23.40%, corresponding to approximately 1,105 at-tributable deaths annually (95% CI: 863–1,219). The difference between the two scenarios implies approximately 58 premature deaths avoided annually (95% CI: 47–63), equivalent to 13.36 avoided deaths per 100,000 persons aged 30 years and older. The attributable proportion declines by approximately 1.22 percentage points.

Qualitative Results

Thematic analysis of the nine rider interviews yielded four primary thematic categories: 1) perceived advantages of boda boda work, 2) perceived challenges of boda boda work, 3) barriers to EV transition, and 4) perceived advantages of EV motorcycles. This section presents each category in turn, with representative raw codes, sub-themes, and themes summarized in Tables 6–9, followed by narrative interpretation grounded in interview evidence.

1) Perceived Advantages of Boda Boda Work

Riders identified a consistent set of advantages associated with their occupation, organized under three overarching themes: economic incentives, affective and emotional rewards, and operational advantages (Table 6).

The most consistently cited advantage was the availability of daily income, which riders contrasted favorably with formal employment characterized by monthly salary schedules. Several interviewees also noted that boda boda work provides income levels higher than previous occupations and that access to Savings and Credit Cooperative Organizations (SACCOs) offers a degree of financial security during emergencies. This finding goes well along with the previous literature that revealed the associations function as mutual social networks, offering members economic security and social support (Mukwaya et al., 2022). Beyond economic considerations, riders emphasized the affective dimensions of the work, including enjoyment, self-fulfillment, and the social interactions facilitated by daily encounters with pas-sengers.

2) Perceived Challenges of Boda Boda Work

Alongside these advantages, riders identified substantial challenges organized under three themes: safety and health risks, negative social perception, and economic constraints (Table 7).

Safety and health risks were among the most salient concerns, with riders citing frequent exposure to traffic accidents, hazardous road conditions, and respiratory illness at-

Table 6. Perceived Advantages of Working as a Boda Boda Driver

Raw Codes	Sub-theme	Theme
Daily income, higher income, low income tax	Immediate cash flow	Economic incentives
Self-employed	Autonomy	
Job accessibility	Low entry barrier	
Enjoyment, self-fulfillment	Emotional reward	Affective / emotional rewards
Making friendship, searching partner	Social interaction	
Agility, mobility expansion	Functional advantage	Operational advantage

Table 7. Perceived Challenges of Working as a Boda Boda Driver

Raw Codes	Sub-theme	Theme
Exposed to accidents, slippery roads	Accident risk	Safety & health risks
Lung disease, wind causing disease, fumes	Health risk	
Perception of crime, perception of failure	Stigma	Negative social perception
Disrespect due to low entry barrier	De-professionalization	
High competition	Market saturation	Economic constraints
Extractive financial structure	Debt trap	
Difficulty transitioning to other jobs	Low mobility	

Table 8. Barriers to EV Transition

Raw Codes	Sub-theme	Theme
Few swap stations	Spatial scarcity	Infrastructural barriers
Long waiting time	Time loss	
Excess demand for batteries	Capacity mismatch	
Load shedding	Energy instability	
Short battery time	Limited endurance	Technological barriers
Unavailable spare parts	Maintenance risk	

Table 9. Perceived Advantages of EV Motorcycles

Raw Codes	Sub-theme	Theme
Cheap charging price	Saving operating cost	Financial benefits
Free repair, cheap servicing	Reduced maintenance cost	
Easy to ride, comfortable	Ease of use	Individual fulfillment
Satisfied with EV, willingness to change	Aspiration of adoption	
Not being stolen	Asset security	Safety benefit
No air pollution, no noise	Environmental benefit	Environmental & social benefit

tributed to wind exposure and exhaust fumes. Negative social perception constituted a second major challenge: in a context where boda bodas are publicly associated with criminal activity, and where the sector's low entry barriers contribute to a stigma of occupational failure, riders reported experiencing persistent social disrespect. Economic constraints were also prominent. Despite the value of daily income, riders widely regarded earnings as insufficient for capital accumulation, and many described being locked into exploitative debt arrangements: as one rider ex-plained through a translator, those without initial capital often end up repaying nearly double the market price of a motorcycle, spending years "working for someone else instead of yourself."

3) Barriers to EV Transition

Riders identified barriers to EV adoption organized under two themes: infra-structural barriers and technological barriers (Table 8).

Infrastructural constraints emerged as the most immediate and tangible barriers. Riders repeatedly emphasized the scarcity and uneven geographic distribution of battery swap stations, which constrains feasible trip routes and creates the risk of being stranded with a depleted battery: "You find you have got a bike and now you are in a place where there is no swap station. That means you are going to push it" (Interviewee 1). Even where stations exist, insufficient charging machines relative to demand generate long queuing delays that directly translate into lost fares. Riders noted that time spent waiting "could have been used to carry passengers and make more money" (Interviewee 2), and that batteries provided at swap stations are not always fully charged: "You pay for the full battery but they don't give you a full one" (Interviewee 3). Load shedding further undermines charging reliability in the absence of backup power at swap stations.

Technological barriers centered on battery performance. Riders reported usable riding times of only two to three hours per charge, necessitating multiple daily swaps and amplifying dependency on already constrained infrastructure. Concerns about battery degradation over time and the unavailability of spare parts raised additional doubts about the long-term operational reliability of EV systems under the intensity of daily boda boda work.

4) Perceived Advantages of EV Motorcycles

Despite the barriers identified above, riders across both ICE and EV groups acknowledged a substantial set of advantages associated with electric motorcycles, organized under four themes: financial benefits, individual fulfillment, safety benefits, and environmental and social benefits (Table 9).

Financial advantages were widely recognized: lower energy costs relative to fuel, with some riders citing an all-day battery charge at 8,000 UGX, and reduced maintenance expenditures from free remote servicing offered by EV operators. Riders also emphasized the operational ease of electric motorcycles, for example, automatic starting, smoother handling, and reduced mechanical complexity, as well as greater personal comfort during long working hours. A notable finding was the perception of enhanced asset security: riders

noted that EV batteries are linked to registered user identities within the swap-station system, deterring theft and reducing exposure to the catastrophic income shock of losing one's primary livelihood asset. Environmental benefits, including the absence of exhaust fumes and noise, were also recognized, with several riders contrasting EV operation favorably against the health consequences of ICE motorcycles they had described earlier. Taken together, these perceived advantages suggest that resistance to EV adoption is not rooted in attitudinal rejection of the technology, but in the structural and operational barriers documented in Section 3) Barriers to EV Transition.

4. Discussion and Conclusions

Discussion

The DiD estimates provide quasi-experimental evidence that reductions in transportation activity led to substantial declines in ambient PM2.5 in Uganda's Central Region. This contributes to a growing literature on transport-related air pollution in Kampala and surrounding areas. Earlier studies documented sizeable reductions in PM2.5 during the COVID-19 mobility restrictions (Green et al., 2022). Galiwango's research on the effect of COVID-19 on air quality shows lockdown had resulted in PM2.5 decrease from 56.6 μg/m^3 to 27.6 μg/m^3, or by 51%, in Kampala, and 41μg/m^3 to 25.7μg/m^3 (37% decrease) in Wakiso following the implementation (Galiwango et al., 2022). This effect of lockdown is higher than the estimates obtained from our research presumably because Kampala and Wakiso are significantly bigger cities with more economic activities than Mubende.

More recent studies have approached the same question through atmospheric source-apportionment models (Okure et al., 2025) and policy simulations of motorcycle electrification and associated health impacts (Okello & Tatah, 2025). Okello's research method hypothesized perfect conversion of petrol-powered motorcycle into electric ones in Kampala and estimated the transport share of PM2.5 to be 22.8%, with motorcycle share of transport emissions to be 66%. Therefore, he assumed 15% (0.228 × 0.66 = 0.15) decrease of PM2.5 from electrification and connected the estimate with health impacts with results showing that all-cause mortality aged over 30 years will drop from 2,624 to 2,149, and mortality from circulatory diseases aged over 30 years drop from 500 to 413. Considering Mubende's smaller economy and a smaller number of motorcycle compared to Kampala, the estimate from our research (13.9%) combined with the estimated motorcycle's transport share of PM2.5 emissions (5%) is significantly in parallel with the previous research.

Moreover, our analysis advances beyond prior modeling-based estimates by grounding the transport-attributable PM2.5 share in an exogenous natural experiment. By incorporating meteorological controls and a DiD counterfactual, the analysis also addresses an important limitation of simple pre–post comparisons of pollution concentrations. In this sense, the study connects the source-attribution question examined by Okure et al. (2025) with the health-burden question considered by Okello and Tatah (2025), while grounding the change in ambient PM2.5 in an empirically estimated transport shock.

Although the degree to which air quality improvement is specifically attributable to motorcycle during the lockdown cannot be systematically measured in this research, the fact that Mubende is a predominantly agricultural district with limited industrial manufacturing activity, and that crop-residue burning in the region is typically concentrated in the dry season (June-October) rather than during the October-December lockdown period, lends some plausibility to the author's assumption there would have been nothing other than transport restrictions that could possibly explain the decrease in PM2.5. It should be noted, however, that the Ebola-induced lockdown encompassed restrictions beyond motorcycle movement, including the temporary closure of markets, schools, and non-essential businesses. The estimated decline in PM2.5 therefore reflects the combined effect of reduced mobility and broader economic activity during the lockdown, rather than motorcycle traffic in isolation.

Therefore, combining the 13.9% PM2.5 decrease with the AfDB estimate attributing 36% of transport-related PM2.5 to motorcycles, the implied health dividend of full boda boda electrification, approximately 58 premature deaths averted annually in Kampala, is large by any public health standard. The health impact estimate should nonetheless be interpreted as an upper bound, as partial electrification and heterogeneous adoption patterns as well as a realistic mitigation of author's strong assumption would attenuate realized gains. Even under conservative assumptions, however, the magnitude of the effect supports treating boda boda electrification as one of the highest-impact environmental health interventions available to Ugandan policymakers.

These quantitative findings substantially raise the stakes

of the qualitative barriers documented below. The 58 annual deaths attributable to motorcycle traffic are not merely a modeling artifact. They represent the public health cost of a transition that riders themselves want but cannot execute under current structural conditions. In this sense, the two components of this study are mutually reinforcing. The quantitative analysis establishes why electrification matters urgently, while the qualitative analysis explains why it is not happening.

Riders across both ICE and EV groups demonstrated clear awareness of EV advantages and several expressed explicit willingness to transition, ruling out attitudinal resistance as a primary explanation for limited adoption. Three interconnected structural mechanisms emerge from the thematic analysis as central barriers.

First, spatial and income uncertainty generated by insufficient battery-swap infrastructure frames EV adoption as an operational risk. When swap stations are scarce and unevenly distributed, riders must restrict feasible routes and absorb queuing delays that translate directly into lost daily earnings. In boda boda work, where immediate cash needs must be met within a single working day, these reliability shocks function as binding constraints on livelihood feasibility. This is a dynamic consistent with evidence on daily income targeting among transport workers in comparable LMIC contexts (Dupas & Robinson, 2013).

Second, a scale-and-purpose misalignment exists between government EV policy and rider-level realities. Uganda's national EV strategy concentrates on supply-side objectives, such as domestic manufacturing, ecosystem coordination, and fuel import reduction (Mobility Bureau, 2024; STI Secretariat, 2024) while underweighting the operational constraints that determine demand-side uptake. Without policy mechanisms that address the micro-level risk environment riders face daily, demand-side adoption will remain limited regardless of supply-side expansion, echoing regional evidence from Tanzania where electrification benefits depended critically on whether existing financial structures allowed riders to capture them (A2EI & Greenfoot, 2021; Simwaba & Qutieshat, 2026).

Third, extractive financial structures amplify income uncertainty and deepen resistance to EV adoption. High-cost debt arrangements inflate effective acquisition costs and leave minimal margin for savings, making riders especially sensitive to short-term income disruptions caused by charging delays or battery unreliability. Current EV transition models, which largely replicate the purchase-or-lease logic of ICE acquisition, do little to address this underlying financial vulnerability.

Limitations

Due to data availability, the research conducted DID with an incomplete dataset, missing observations from April 15, 2022 to September 13, 2022. To complement the missing observations, authors expanded sample period to 2021 and 2023 to secure sufficient amount of data for controlling seasonality. Moreover, when calculating the health impact of electrification, the research puts strong assumption that mobility lockdown induces the same effect as complete electrification bodaboda, while in reality, the electrified motorcycles can still cause air pollution by flying away dust on the road. These two limitations shall be dealt systematically with better identification strategy in future research.

Furthermore, the Ebola-induced lockdown entailed restrictions beyond motorcycle transport, including school and market closures and reduced general economic activity. Consequently, the DiD estimate captures the air-quality impact of the broader lockdown-induced reduction in urban activity, of which motorcycle transport is assumed to be the dominant but not exclusive component. To the extent that non-transport channels also contributed to the observed decline, our transport-attributable share and the resulting health-impact projections should be interpreted as an upper bound.

In addition, Mubende and Kampala differ in urbanization level, traffic density, and industrial composition, which may affect the comparability of transport-pollution relationships. However, both districts share the same ICE-dominated motorcycle fleet structure and rely on similar fuel supply chains, providing a reasonable basis for the extrapolation. Future work with Kampala-specific exogenous variation would further strengthen this estimate. The health impact estimate further depends on a single AfDB source for the motorcycle contribution figure. On the qualitative side, the sample of nine riders is appropriate for thematic analysis but is not statistically representative; findings are best understood as an analytical account of mechanisms rather than a survey of prevalence.

Conclusions and Policy Implications

This study provides converging evidence that boda boda

electrification would yield substantial public health benefits, but that realizing these gains requires addressing structural barriers that current policy inadequately targets. EV adoption hesitancy reflects rational responses to uncertainty under conditions of daily income dependence, liquidity constraint, and infrastructural unreliability rather than attitudinal resistance.

Two policy priorities follow from these findings. First, infrastructure investment should prioritize reliability over quantity. Expanding swap station numbers is insufficient if output capacity and service uptime do not keep pace with fleet growth; each additional adopter under constrained infrastructure increases queuing pressure for all users, generating a negative network externality that stalls diffusion. Backup power systems, battery interoperability standards, and guaranteed service quality should accompany quantitative expansion. Second, financing instruments must be redesigned around the daily-income logic of boda boda work. Flexible repayment schedules tied to realized earnings, income-smoothing mechanisms during transition, and affordable credit would lower adoption barriers and address the broader financial precarity that the qualitative findings identify as a structural feature of the sector.

More broadly, EV transition policy will be most effective when designed from the rider's perspective outward rather than from the technology inward. The boda boda sector is a livelihood system operating under specific constraints of daily income, physical risk, and debt obligation. Policies that engage with this experiential reality rather than treating electrification as a hardware substitution problem stand a substantially greater chance of realizing the public health gains that the quantitative evidence shows are within reach.

Data Availability Statement

The PM2.5 and meteorological data used in this study are publicly accessible through the AirQo platform (https://airqo.net/home)

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