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BUILDING A SMART GREEN CITY: MULTI-ACTOR COLLABORATION IN IoT-BASED FOR WASTE MANAGEMENT

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ABSTRACT
The development of modern cities faces increasingly complex challenges, including rapid population growth, rising waste volumes, pollution, and escalating energy demands. Urbanization, higher consumption, and shifting waste generation patterns further complicate waste management. The Smart City concept emphasizes integrating ICT to enhance efficient, inclusive, and sustainable urban governance, while the Green City framework focuses on environmental sustainability within governance. Combining these approaches, the Smart Green City model merges technological innovation with ecological principles, with the Internet of Things (IoT) serving as a key instrument. This study examines the technological dimension alongside sustainability and community well-being. Using a qualitative case study, Malang City was selected for its role as a creative and educational hub in East Java, actively promoting Smart City initiatives with a focus on sustainable environmental management. Implementation challenges include limited budgets, inadequate technological infrastructure, and low community participation. These issues are analysed through major theoretical perspectives to provide a comprehensive understanding of Smart Green City development in Malang, highlighting both the potential and constraints of integrating technology and sustainability in urban planning.

INTRODUCTIONS

Urban areas in Indonesia are facing increasingly complex challenges in waste management due to rapid urbanization, rising consumption levels, and shifting waste generation patterns. Malang City, as one of the

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administrative and educational centre in East Java, is experiencing a steady increase in both domestic and commercial waste volumes, which puts pressure on existing waste management capacities. The city's reliance on conventional collection and disposal methods has resulted in operational inefficiencies, high management costs, and negative environmental impacts such as pollution and methane emissions. This situation calls for a more efficient, sustainable, and adaptive approach to urban waste management. The concept of a smart green city offers an integrative framework that combines information and communication technologies (ICT), green governance, and community participation to enhance environmental quality and public services. In the context of waste management, the Internet of Things (IoT) provides real-time monitoring of waste container levels, collection routes, and environmental conditions at collection points. The implementation of IoT can optimize collection routes, reduce unnecessary trips, lower operational costs, and minimize environmental impacts, aligning with the principles of a green and sustainable city.

However, technological innovation alone is insufficient. Effective urban waste management requires multi-actor collaboration involving local government, waste service operators, local communities, private technology providers, and non- governmental organizations. Each stakeholder contributes distinct capabilities, resources, and interests. Without proper coordination, these differences can lead to duplication of efforts, uneven service delivery, and regulatory or social acceptance challenges. Therefore, it is crucial to explore collaborative models that are responsive to Malang's local context: emphasizing incentive mechanisms, clear role distribution, and secure, inclusive data governance. Although studies on IoT-based waste management and smart city initiatives are growing (Afkarien et al., 2025), there remains a research gap in understanding how technical IoT systems can be integrated with institutional and social dimensions, particularly in medium-sized cities such as Malang. Empirical exploration is needed to understand how multi-actor partnerships can accelerate the adoption of IoT solutions while ensuring economic sustainability, affordability, and community participation. This research seeks to fill that gap by examining collaboration models, implementation barriers, and the operational and environmental impacts of IoT-based waste management systems in Malang City. By focusing on the synergy between technology and governance, this study aims to develop policy recommendations and operational frameworks that can be adopted by stakeholders in Malang and similar cities. These include collaborative frameworks, feasible minimum technical architecture, financing schemes, and social and environmental performance indicators to evaluate the success of smart green city initiatives in the field of waste management.

Despite the increasing attention given to the concept of smart and green cities in Indonesia, many urban areas, including Malang City, still face significant challenges in implementing integrated and technology-based waste management systems. The existing waste management practices remain largely manual, fragmented, and dependent on conventional collection schedules that are often inefficient and unresponsive to real-time needs (Ichsan et al., 2023; Kurniawan et al., 2024). Moreover, the lack of effective coordination among key actors, such as local government agencies, private waste operators, community groups, and technology providers has led to gaps in policy implementation, limited data sharing, and overlapping responsibilities. In this context, the main problem lies not only in technological readiness but also in the governance and collaboration mechanisms that support IoT-based waste management. The absence of a well-structured multi-actor collaboration framework hinders the optimization of IoT applications and slows the city's transition toward a sustainable smart green city model.

Previous studies on smart city and IoT-based waste management have primarily focused on technological innovation, such as sensor deployment, route optimization algorithms, and digital monitoring systems (Permana & Raharjo, 2023). However, fewer studies have explored the socio-institutional aspects of implementing these technologies particularly how collaboration among multiple stakeholders influences system effectiveness and sustainability. In the context of Indonesia, most research remains concentrated in major metropolitan areas like Jakarta, Surabaya, or Bandung, while medium-sized cities such as Malang are underrepresented. This creates a contextual

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research gap regarding how medium-scale cities, with limited resources but growing urban pressures, can design and sustain collaborative governance models for IoT-based waste management.

Although various studies have demonstrated the effectiveness of IoT in improving waste management efficiency, such as real-time monitoring of waste volume through smart bins equipped with ultrasonic sensors (Pamudji et al., 2025) and automated waste sorting using machine learning to support the recycling process (Ginting & Apnena, 2024). Existing research is still dominated by technical approaches such as sensor design, prototyping, and optimisation algorithms. Research by Gymnastiar et al. (2023) also emphasises that smart bin innovations generally focus on device development, while the aspect of system integration into municipal waste management governance has not been widely discussed. This is reinforced by Sosunova & Porras (2022) which states that research on smart waste management is still weak in terms of institutional dimensions, community participation, and coordination between stakeholders, even though technology has developed rapidly. In Indonesia itself, IoT studies for waste management mostly still examine technical aspects such as weight detection or fullness levels without examining the relationship between technology and sustainable urban management practices (Andang & Efendi, 2024). Thus, there is a clear research gap regarding the integration of IoT technology with multi-actor collaboration models, data governance, and socio-ecological sustainability, particularly in medium-sized cities such as Malang, which are still underrepresented in the literature. Furthermore, there is limited empirical evidence on how multi-actor partnerships affect public participation, data transparency, and long-term operational efficiency within green city initiatives.

THEORETICAL FRAMEWORK

Smart City

Smart city concept emphasizes the integration of digital technology, data analytics, and citizen engagement to enhance the efficiency and sustainability of urban services (Caragliu et al., 2013). A smart city is characterized by the intelligent use of ICT and IoT systems to optimize resource utilization, improve governance, and increase the quality of life for its citizens. In the context of waste management, smart city principles support real-time data collection from sensors, predictive analysis for waste generation patterns, and smart routing systems for waste collection. This technological base enables cities to improve operational efficiency and environmental sustainability while promoting citizen participation in maintaining cleanliness and recycling initiatives.

Green City Framework

The Green City Framework (World Bank, 2015) emphasizes environmentally responsible urban planning that integrates ecological principles into infrastructure, mobility, and public services. A green city prioritizes low-carbon development, circular economy practices, and the conservation of natural resources. Applying this framework to waste management means shifting from linear waste disposal models (collect–transport dump) to circular and sustainable approaches (reduce–reuse–recycle). By integrating IoT systems, city can enhance the transparency and traceability of waste streams, contributing to reduced landfill dependency, lower greenhouse gas emissions, and progress toward Sustainable Development Goals (SDGs) 11 and 12.

Collaborative Governance Theory

Collaborative Governance Theory (Ansell & Gash, 2008) provides a conceptual lens for analysing how multiple actors: government, private sector, community organizations, and technology providers jointly manage public issues through shared decision-making. This theory highlights the importance of trust-building, transparent communication, and institutional arrangements in achieving collective goals. In IoT-based waste management, collaborative governance ensures that technology implementation is not only technically sound but also socially legitimate and institutionally supported. The success of smart waste initiatives depends on how well these actors coordinate resources, align incentives, and share responsibilities to sustain innovation and accountability (Barney,

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1991). Collaborative governance emphasizes multi-actor decision-making, requiring dialogue, trust, shared motivation, and joint capacity for action (Ansell & Gash, 2008; Emerson et al., 2012). It is essential in managing complex environmental issues that span national–local boundaries. There are three mechanisms emerge: 1) Resource complementarity; 2) Institutional alignment of national local policies; and 3) Sustainable collaboration reinforced through repeated interaction.

Integrated Conceptual Linkage

The integration of these theories suggests that building a smart green city through IoT-based waste management requires technological innovation, environmental sustainability (green city framework), and multi-actor collaboration (Collaborative Governance Theory). These dimensions are interdependent: 1) IoT technology provides the tools for real-time monitoring and efficiency; 2) The green city perspective defines the goals of sustainability and resilience; and 3) Collaborative governance ensures the process of shared decision-making and inclusiveness. Thus, the theoretical framework views multi-actor collaboration as the mediating mechanism linking IoT adoption to green city outcomes.

RESEARCH METHODS

This study employs a qualitative research design using a case study approach. The qualitative design is selected to gain an in-depth understanding of how multi-actor collaboration supports the implementation of IoT-based waste management in Malang City. The case study method enables the exploration of real-world dynamics, interactions, and institutional mechanisms among stakeholders involved in smart and green city initiatives. The research emphasizes contextual analysis rather than quantification, allowing rich descriptions of technological, organizational, and social processes that shape collaborative governance in the development of a smart green city. This study uses both primary and secondary data. Primary data are obtained through in-depth interviews, field observations, and focus group discussions (FGD) with key actors. Secondary data include government documents, policy reports, local regulations, academic studies, and media publications related to smart city, waste management, and environmental governance in Malang. In-Depth Interviews. Semi-structured interviews are conducted with representatives from: Local Government (DLH and BAPPEDA Malang); Waste Management Operators; Community Organizations (Bank Sampah, local RT/RW, ProKlim participants); and Private Sector Partners. The interviews explore perceptions, experiences, and strategies of collaboration in implementing IoT-based systems.

RESULTS AND DISCUSSION

Resource Complementarity

The study found that the success of IoT-based waste management initiatives in Malang City depends largely on the complementarity of resources among collaborating actors. Each stakeholder contributes distinct assets that, when combined, create mutual reinforcement for sustainable innovation. Local government agencies (DLH and BAPPEDA) provide regulatory authority, funding support, and coordination frameworks. Technology providers (IoT companies) offer technical expertise in sensor design, data analytics, and system integration. Community organizations (Bank Sampah units and Kampung Iklim) contribute social capital, community mobilization, and behavioural change in waste sorting. Private sector waste operators supply operational capacity and logistical infrastructure for collection and transport. This pattern reflects the concept of Resource-Based View (RBV) and Network Theory, where synergy emerges from the complementary, not identical, resources of partners (Gellweiler & Krishnamurthi, 2022; Powell, 2025). Empirical data from interviews reveal that the DLH collaboration with local IoT developers allowed both actors to overcome resource constraints technical for government, and financial-legitimacy for private innovators.

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The Ministry of Public Works and Public Housing has completed the revitalization of three final waste processing sites in East Java Province, the Supit Urang Waste Landfill in Malang City, Jabon in Sidoarjo Regency, and Sekoto in Kediri Regency. These three landfills use a sanitary landfill system to minimize the impact of pollution, both water, land, and air, making them more environmentally friendly. The development of the Supit Urang Landfill sanitary landfill system was carried out since July 2018 and was completed in 2020. This landfill has an area of 32 hectares, of which 16 hectares of land are currently in the sanitary landfill project. The Supit Urang Landfill has a capacity of 953,340 m3 to serve the household waste of Malang City residents of 707,015 people or equivalent to 400 tons/day. The landfill is estimated to function well for 5-7 years. The development of the Supit Urang Landfill is a collaboration between the Indonesian Government through the Directorate General of Human Settlements, Ministry of Public Works and Housing, and the German Government under the Emission Reduction in Cities–Solid Waste Management (ERIC-SWM) Program. The following are some of the developments in the Supit Urang Landfill's sanitary landfill system in Malang:

1) Equipped with a weighbridge for weighing garbage trucks, a siding area for waste sorting and composting, and a landfill lined with three protective layers: a geosynthetic clay liner, a geomembrane, and a geomatic, with filter gravel to prevent leachate leakage;
2) A Leachate Treatment Plant (IPL) with membrane bioreactor technology effectively reduces pollutant parameters such as COD by up to 97%, BOD by 99%, NH_4-N by 100%, and TSS by 97%;
3) The implementation of the sanitary landfill has successfully reduced waste generation by up to 50 tons per day. The sorting and composting process also produces free compost for residents and contributes to the greening program;
4) All garbage trucks are systematically recorded, via weighbridges, including weight data, waste source, and license plate numbers, which are directly recorded in a computerized system for daily and monthly evaluation; and
5) The Supit Urang Landfill has been designated a national model for integrated waste management (one-stop waste management). Agencies such as the Ministry of Home Affairs and the Ministry of Public Works consider this landfill a worthy model for other cities/regencies in developing sustainable waste management systems.

This complementarity enhances collective capacity, reflecting interdependence-based collaboration where actors' heterogeneous assets become strategic enablers for smart green city transformation.

Institutional Alignment of National and Local Policies

A major finding concerns the alignment between national environmental policies and local implementation frameworks. Nationally, the Ministry of Environment and Forestry (KLHK) promotes Smart City Roadmap Indonesia 2025. Local government of Malang city as local policies, through DLH and BAPPEDA, operationalize these frameworks by integrating IoT-based monitoring in waste management. However, the study reveals partial institutional alignment. At the policy level, national programs emphasize climate mitigation and digitalization, while local agencies prioritize daily waste collection efficiency and community participation. At the implementation level, coordination between national technical standards and local capacities remains fragmented, creating gaps in data integration and budget allocation. This situation aligns with Institutional Theory (Strang & Sine, 2017), which posits that institutional congruence between macro (national) and local levels determines the effectiveness of innovation diffusion. The findings indicate that when local policies explicitly align with national frameworks, implementation proceeds more smoothly. Thus, institutional alignment acts as a policy bridge ensuring that IoT-based innovations contribute simultaneously to local efficiency and national sustainability goals.

Sustainable Collaboration Reinforced through Repeated Interaction

Long-term collaboration among actors in waste management ecosystem is sustained not only by formal agreements but also through repeated interaction and trust-building processes. Over time, periodic meetings, co-design

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workshops, and pilot evaluations created shared understanding and social embeddedness among stakeholders. Drawing on Collaborative Governance Theory (Ansell & Gash, 2008), repeated interaction builds relational trust and mutual accountability, key factors for sustainable partnerships. The study observed that stakeholders initially collaborated on short-term pilot projects (e.g., smart bins and waste-sorting trials), but the continuation of interaction evolved into a semi-institutionalized network where roles and expectations became clearer. Community organizations, in particular, shifted from passive recipients of innovation to active co- designers. DLH officials reported that consistent engagement with Bank Sampah groups fostered ownership and reduced resistance to IoT tools, as communities began to see tangible benefits in waste tracking and incentive systems. This reinforces Social Capital Theory (Padua, 2016), where dense and recurring interactions generate trust networks essential for sustaining collective environmental initiatives. Consequently, repeated collaboration cycles serve as the institutional glue that maintains momentum for innovation beyond initial pilot stages transforming one-off projects into a long-term smart green city strategy.

This study demonstrates that the transition toward a smart green city in Malang is not merely a technological process but an institutional and social transformation requiring sustained collaboration among diverse actors. The integration of IoT-based waste management systems reveals that technological innovation achieves its full potential only when supported by complementary resources, coherent institutional alignment, and trust-based, long-term collaboration. First, resource complementarity among actors – local government, private technology developers, waste operators, and community organizations – has been essential in overcoming individual resource limitations. Through strategic collaboration, each stakeholder unique assets create a synergistic network that enhances the overall adaptive capacity of the waste management system. Second, institutional alignment between national and local policies strengthens policy coherence and accelerates IoT adoption. The integration of national frameworks such as the Program Kampung Iklim (ProKlim) and the Smart City Roadmap Indonesia 2025 into local environmental strategy ensures that technological initiatives align with both local priorities and national sustainability goals. This validates Institutional Theory (Scott, 2001), showing that congruence between policy levels is a precondition for effective innovation diffusion and governance stability (Liu et al., 2023). Third, sustainable collaboration is maintained through repeated interaction, dialogue, and trust-building among actors. Over time, these ongoing engagements have evolved into semi-institutionalized networks where mutual accountability and shared learning drive continuous improvement. The process reflects the core principles of Collaborative Governance Theory (Ansell & Gash, 2008) and Social Capital Theory (Putnam et al., 1994), illustrating how repeated social interaction and trust reinforce the durability and legitimacy of smart city partnerships.

The findings confirm that the smart green city model is best understood as an ecosystem of collaboration where technology, governance, and community engagement are interdependent. The IoT serves as an enabling infrastructure, but its success depends on collaborative mechanisms that ensure inclusiveness, accountability, and environmental responsiveness. For medium-sized cities such as Malang, the pathway toward smart and green transformation requires strengthening multi-actor partnerships, aligning regulatory frameworks, and institutionalizing participatory governance practices. From a policy perspective, the study suggests three strategic directions: 1) Enhancing resource integration through public–private–community partnerships and shared financing schemes; 2) Synchronizing national and local policy instruments to facilitate data standardization and cross-level coordination; and 3) Institutionalizing collaborative platforms that encourage continuous dialogue, citizen participation, and adaptive learning. Building a smart green city is not solely about adopting IoT technologies but about cultivating a governance culture grounded in collaboration, ecological awareness, and shared innovation. Through the synergy of technology, institutional support, and civic engagement, Malang City can evolve into a resilient, sustainable, and inclusive urban model for Indonesia's future smart green cities.

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CONCLUSION

The results of a systematic review indicate that industrial class programs in vocational high schools have a significant impact on improving graduates' hard skills, soft skills, and job readiness. The eight articles analyzed show that research on this topic is still limited, with a surge in publications only seen after 2022. This indicates that the issue of industrial classes is still relatively new and requires further in-depth study, particularly in relation to student job readiness. The success of this program is inseparable from several key factors, such as close collaboration between schools and industry, curriculum alignment with industry standards, teacher competence, facility availability, ongoing training, and structured internship access. Furthermore, student motivation and understanding of career prospects also determine the program's effectiveness. However, the implementation of industrial classes still faces challenges, ranging from limited human resources, facilities, and funding to suboptimal curriculum synchronization and commitment from industry. Students' mental readiness and enthusiasm for entering the workforce also require special attention. Overall, the empirical findings confirm that industrial classes not only improve technical skills but also build soft skills such as communication, teamwork, discipline, and work ethic. This program also acts as a bridge between the world of education and the needs of industry, making it an important strategy to strengthen the competencies of vocational school graduates and increase their competitiveness in the modern industrial era.

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