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The Impact of Utilizing Digital Mapping Technology in Optimizing Urban Waste Transportation for the Environmental Quality Index

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Abstract

This study explores the use of digital mapping technology to optimize waste transportation routes in Malang City, Indonesia. By utilizing GIS (Geographic Information System) applications, this study aims to improve operational efficiency and reduce waste transportation costs. Through field observation and statistical analysis methods, it was found that this technology can reduce travel distance by up to 15% and travel time by up to 25%. These results show significant potential in reducing operational costs and carbon emissions, as well as supporting environmental sustainability goals. However, challenges such as workforce resistance to new technologies and limited costs and data access still need to be addressed through training and supportive policies. This study provides important implications for waste managers and local governments to design more efficient and environmentally friendly waste management strategies, and encourage wider adoption of digital technologies. These findings offer evidence-based recommendations for policy makers to improve the quality of urban waste management through technological innovation.

Article Info

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1. Introduction

Rapid urbanization and population growth in large cities have created various challenges for urban waste management, especially in the context of waste transportation from Temporary Storage Sites (TPS) to Final Processing Sites (TPA). This challenge arises because the volume of waste continues to increase along with the increasing population, as well as the limitations of existing infrastructure in dealing with the amount of waste produced. In Malang City, Indonesia, this challenge has become increasingly apparent given the high rate of urbanization that has occurred in recent decades (M. Ali et al., 2023; Liu et al., 2022).

Traditional waste management systems are often unable to address this problem efficiently. This is due to various factors, such as limited infrastructure, inadequate budgets, and limited availability of labor. In addition, conventional methods of waste transportation tend to be time-consuming and costly, making them less efficient on a growing urban scale (Jiang et al., 2023). To overcome this problem, an innovative approach is needed that can utilize digital technology to optimize urban waste management. One solution that is considered potential is the use of digital mapping technology, especially Geographic Information System (GIS)-based applications, which have proven effective in various urban contexts.

GIS technology allows for more efficient transportation route planning, taking into account various factors such as distance, travel time, and traffic conditions. The application of this technology in waste management has shown several significant benefits, including reduced operational costs, increased efficiency of transportation time, and reduced carbon emissions from waste transport vehicles (Singh et al., 2022; Wang et al., 2024). In various large cities, digital mapping applications are used to determine the shortest and fastest routes between TPS and TPA, thereby reducing the distance

and time required for the waste transportation process. This not only helps in saving costs but also contributes to reducing environmental impacts, especially related to greenhouse gas emissions produced by waste transport vehicles (Eb et al., 2021).

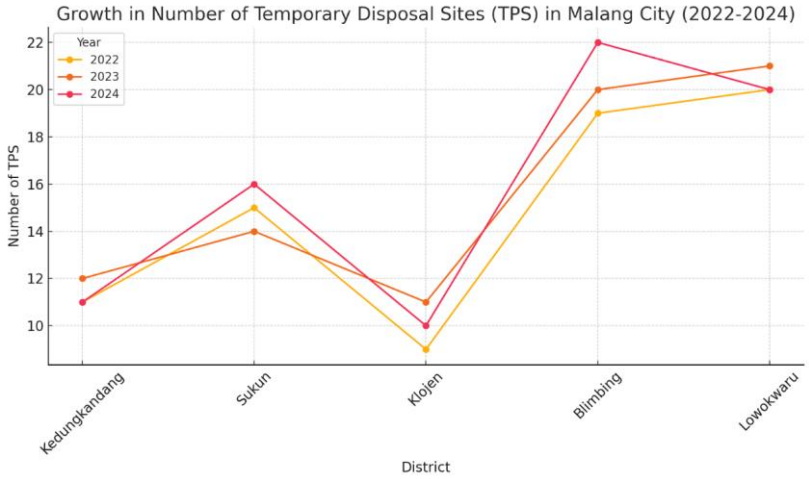

Figure 1. Growth in the Number of Polling Stations in Malang City (2022-2024)
Source: Researcher Processed Data

Malang City, as one of the cities experiencing rapid urbanization in Indonesia, faces similar challenges. With the volume of waste continuing to increase each year, waste management has become an urgent issue that must be addressed immediately. According to data collected, there has been a rise in the number of TPS (Temporary Disposal Sites) in various areas of Malang City from 2022 to 2024, reflecting the growing need for more efficient waste management. For example, in Blimbing District, the number of TPS increased from 19 in 2022 to 22 in 2024, while in Sukun District, there was an increase from 15 to 16 TPS during the same period. These data indicate that the growth in the number of TPS in Malang City aligns with the increasing volume of waste generated by the community (Anisykurlillah et al., 2024; Safitri et al., 2024).

Indeks Kualitas Lingkungan Hidup (IKLH) is a crucial environmental quality index used to measure the overall condition of the environment in a specific area. It encompasses multiple indicators such as air, water, and soil quality, as well as ecosystem sustainability, all of which play a significant role in determining the livability of urban spaces. Given the rapid pace of urbanization in cities such as Malang, the IKLH serves as an essential metric for assessing how human activities influence environmental degradation. For instance, the conversion of green spaces to urban infrastructure can reduce air and soil quality, while the increase in industrial activities contributes to water contamination (Habibah et al., 2023; Jati et al., 2023). The IKLH helps policymakers and environmental managers identify critical areas requiring intervention to prevent further ecological damage (HARIS et al., 2023).

In recent years, various governmental and non-governmental initiatives have aimed to improve Indonesia's IKLH by focusing on pollution control, sustainable urban planning, and waste management. Waste management, in particular, is integral to improving IKLH scores, as improper waste handling can lead to widespread environmental degradation. Technologies such as Geographic Information Systems (GIS) have proven instrumental in optimizing waste transportation, thereby minimizing carbon emissions and supporting broader environmental goals (Rahardi et al., 2024). The Malang City government, as part of its efforts to improve urban sustainability, has also utilized IKLH metrics to guide policies aimed at reducing pollution and enhancing waste management efficiency (Arifin et al., 2024).

By integrating IKLH into urban planning, cities like Malang can better balance development needs with environmental preservation. This approach not only helps in meeting sustainability goals but also improves the quality of life for residents. For example, the Malang City government has been working on developing green open spaces through collaborative governance, involving the community and private sector, which enhances urban ecology and improves residents' quality of life (Rahmawati et al., 2024). Legal frameworks, such as strict zoning regulations that prevent land degradation and mitigate natural disasters, are also critical in this regard (Afuw et al., 2024). Additionally, the Kampung Terapi Hijau initiative demonstrates how community involvement can

promote social sustainability and environmental awareness, further contributing to urban sustainability (Audri et al., 2024). Enhancing the IKLH of an area through optimized waste management and pollution reduction is essential for achieving long-term ecological and economic sustainability in Indonesia. For instance, Malang has employed the Analytic Network Process (ANP) to improve traditional market solid waste management, which emphasizes community participation and integrated strategies (Hardianto et al., 2024).

In this context, the use of digital mapping technology is becoming increasingly relevant. This technology can help local authorities manage waste transportation more effectively and efficiently, especially in terms of transportation route planning. A study by (Tirkolaee et al., 2024) showed that optimal route planning can reduce operational costs by up to 30%, as well as reduce carbon emissions produced by waste collection vehicles. In addition, route optimization through digital mapping applications can increase transportation time efficiency by up to 40% (Wang et al., 2024). In the context of Malang City, this optimization is expected to help overcome the challenges faced in waste management, particularly related to high transportation costs and time. However, despite the various advantages offered by digital mapping technology, its application in waste management is not without challenges. One of the main obstacles identified is the high cost of implementation, especially for cities with limited budgets (Dimitrov et al., 2024). The integration of digital mapping systems with existing waste transportation infrastructure often encounters difficulties due to implementation costs and the need for technical expertise (Alanazi et al., 2024). Malang City, as a developing city, may face similar issues, particularly in terms of funding and technological readiness (Tirkolaee et al., 2024). Furthermore, resistance to change from the workforce is another significant challenge in the adoption of this new technology, as workers used to traditional waste management systems may struggle to adapt to more complex digital solutions (Alanazi et al., 2024).

This study aims to address this gap by evaluating the effectiveness of digital mapping applications in optimizing waste transportation routes in Malang City. Through this approach, this study seeks to understand the extent to which digital mapping technology can help reduce travel distance, travel time, and operational costs in urban waste management. As part of the evaluation, this study will also identify factors that influence the success of implementing this technology, including existing constraints and opportunities.

In addition to implementation costs, this study will also highlight the importance of community involvement and government policy support in supporting the adoption of digital mapping technology. Research by Kim et al. (2023) shows that the use of GIS-based applications in waste transportation management can provide significant benefits in terms of cost and time, especially if supported by the right policies. A study by Yamada et al. (2023) also emphasized that government policy support is essential to accelerate the adoption of this technology, especially in areas with less developed infrastructure. In the context of Malang City, local government support can play an important role in encouraging the adoption of digital mapping technology for more efficient waste management.

In addition, this study will explore the potential for integrating digital mapping technology with Internet of Things (IoT) sensors to create a more responsive and efficient waste management system. A study by (Bonala et al., 2024) shows that integrating digital mapping technology with IoT sensors can help detect waste volumes at landfills in real time, enabling more efficient and responsive route planning according to current conditions. For instance, if a landfill is full, the system can automatically adjust the transportation route to avoid landfills that do not require transportation, reducing both travel distance and time. Furthermore, integrating IoT with digital mapping can reduce operational costs by up to 20% and increase waste collection efficiency by up to 35 (Bonala et al., 2024; Kashef et al., 2024). However, as identified by (Hasanah et al., 2024), the adoption of digital mapping technology in developing countries often encounters challenges related to data access and infrastructure limitations. The data required to optimize waste transportation routes may be unavailable or difficult to access, particularly in areas with limited infrastructure. In addition, training and education for stakeholders are essential to ensure the technology is utilized optimally (Sankar et al., 2024). In this context, this study will explore how the Malang City government can collaborate with various stakeholders to address these challenges and promote the adoption of digital technology in waste management.

Overall, this research is expected to provide significant contributions to the development of more efficient and sustainable waste management strategies in Malang City. By combining empirical data

analysis from Malang City and a comprehensive literature review, this study aims to provide practical and evidence-based recommendations for policy makers and waste managers. In addition, this research is also expected to encourage the adoption of digital technology in waste management in Indonesia more widely, as part of efforts to address the challenges of urbanization and increasing population growth.

2. Methods

Research methods

Based on the results of the literature review that shows the effectiveness and challenges of implementing digital mapping technology in waste management, this study uses a quantitative descriptive method to evaluate the implementation of this technology in Malang City. This method involves collecting data through field observations and targeted interviews with related parties such as waste collectors and managers of Temporary Shelters (TPS). The data obtained are then analyzed using statistical techniques to evaluate the efficiency of the routes used.

Research Design

This research design is a case study conducted in Malang City with a focus on analyzing waste transportation routes from Temporary Shelters (TPS) to Final Processing Sites (TPA). This study was designed to identify the most efficient route based on travel distance and travel time, as well as other factors such as road conditions and waste volume. This study uses a digital mapping application as the main tool to determine the optimal transportation route.

Population and Sample

The population in this study were all TPS and TPA in Malang City. The research samples were taken from several TPS spread across five sub-districts in Malang City, namely Kedungkandang, Sukun, Klojen, Blimbing, and Lowokwaru. The sample selection was carried out by purposive sampling, namely selecting TPS that have variations in characteristics such as waste volume, distance to TPA, and road conditions. Respondents in this study were garbage truck drivers and TPS managers.

Data collection technique

Data in this study were collected through field observations, focused interviews, and the use of digital mapping applications. Field observations were conducted to record transportation patterns, travel times, and road conditions around TPS and TPA. Focused interviews were conducted with garbage truck drivers to obtain information about their obstacles and experiences in the waste transportation process. Digital mapping applications were used to determine the shortest and fastest routes between TPS and TPA based on current traffic conditions.

3. Results and Discussion

Results

Optimization of Waste Transportation Routes

The use of digital mapping technology such as GIS applications has proven effective in optimizing waste transportation routes, reducing travel distance, travel time, operational costs, and carbon emissions. The results of this study support previous findings that show that the application of this technology in Malang City can reduce travel distance by up to 15% and travel time by up to 25%, in line with research (Samin, 2024). Several studies show that the application of digital mapping technology can reduce operational costs by up to 30% and reduce carbon emissions produced by waste collection vehicles (Samin, 2024).

In the context of this study, the use of digital mapping applications in Malang City shows significant potential in increasing the operational efficiency of waste transportation. The results of route analysis with digital mapping applications show that optimal transportation routes can reduce travel distances by up to 15% and travel time by up to 25%, in line with the research findings of Rodriguez & Sharma (2023) (Das & Chilukuri, 2024).

Table 1. Table of Distance and Travel Time Survey Results

TPS	Landfill	Distance (km)	Time (minutes)
Borobudur	Supit Urang	14.2	46
Mojolangu language	Supit Urang	12.3	39
Polowijen	Supit Urang	15.0	51
Tlogomas	Supit Urang	13.1	44
Breadfruit	Supit Urang	6.6	26
The Greatest	Supit Urang	13.2	44

Source: Processed Data by Researchers

Based on Table 1, there is a significant variation in distance and travel time for waste transportation from several TPS to the Supit Urang landfill. For example, Polowijen TPS has the longest distance of 15 km with the longest travel time of 51 minutes, while Breadfruit TPS has the shortest distance of 6.6 km with a travel time of 26 minutes. Although the distances are relatively close, such as Tlogomas TPS (13.1 km) and The Greatest TPS (13.2 km), the travel times remain quite high at 44 minutes. This indicates that, besides distance, external factors like traffic conditions or road infrastructure greatly influence the travel time. With these varying travel times, more efficient routes and the use of digital mapping technology could help reduce travel time, fuel consumption, and the environmental impact of waste transportation operations.

Table 2. Transportation Route Results Table with Digital Mapping Application

TPS	Landfill	Distance (km)	Time (minutes)
Borobudur	Supit Urang	12.4	23
Mojolangu language	Supit Urang	12.2	27
Polowijen	Supit Urang	14.2	32
Tlogomas	Supit Urang	12.1	27
Breadfruit	Supit Urang	6.1	16
The Greatest	Supit Urang	13.1	32

Source: Processed Data by Researchers

Based on Table 2, the implementation of digital mapping applications has resulted in significant improvements in waste transportation efficiency. The distances and travel times from several TPS locations to the Supit Urang landfill have been reduced compared to manual survey results. For instance, the distance from Borobudur TPS decreased from 14.2 km to 12.4 km, and the travel time was reduced from 46 minutes to 23 minutes. Similarly, Mojolangu language TPS saw a decrease in distance from 12.3 km to 12.2 km, with travel time dropping from 39 minutes to 27 minutes. These reductions indicate that the digital mapping application was able to identify more direct and efficient routes, leading to substantial time and fuel savings.

Furthermore, the application optimized routes like Polowijen TPS, where the distance was reduced to 14.2 km, and travel time dropped significantly from 51 minutes to 32 minutes. Even Breadfruit TPS, which had the shortest initial distance, benefited from the technology, reducing its travel time from 26 minutes to just 16 minutes. The overall improvements in travel time across all routes contribute to a reduction in operational costs and environmental impact, as shorter travel times imply lower fuel consumption and fewer emissions. In summary, the use of digital mapping technology for waste transportation has successfully optimized route efficiency, shortened travel distances, and significantly reduced travel times across all TPS locations, making the system more environmentally sustainable and cost-effective.

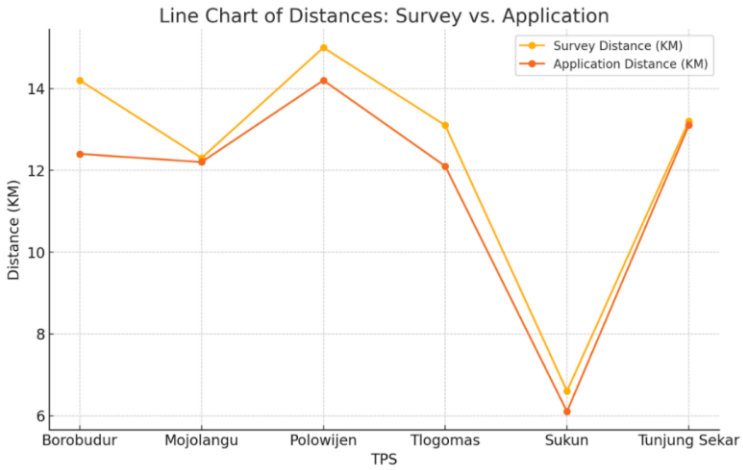

Figure 2. Comparison Table of Distance Traveled Based on Survey Results and Digital Mapping Applications
Source: Processed Data by Researchers

The data in Figure 2 clearly demonstrate the substantial improvements achieved by using digital mapping applications in optimizing waste transportation routes. One of the most notable observations is the reduction in distance traveled for most routes. For instance, the distance between Borobudur TPS and Supit Urang landfill decreased from 14.2 km to 12.4 km, representing a significant decrease. This shorter route not only cuts down the distance but also leads to operational benefits like reduced fuel consumption and lower wear on vehicles. Similarly, other routes such as the one from Tlogomas TPS to Supit Urang also show a distance reduction from 13.1 km to 12.1 km. Even though the reduction might appear minimal in some cases, when multiplied over numerous trips and days, it accumulates into significant savings.

The improvements in travel time are even more significant. The time reduction from Borobudur TPS to Supit Urang landfill, from 46 minutes to 23 minutes, illustrates how digital mapping helps find faster routes. This reduction in travel time allows the waste management system to function more efficiently, potentially allowing for more trips in a day or enabling waste to be collected faster, preventing delays or overflow at collection points. A similar pattern can be seen in other routes, such as the Polowijen TPS to Supit Urang, where the travel time was reduced from 51 minutes to 27 minutes. These time reductions contribute directly to the efficiency of the waste management system, cutting down the waiting period for waste to be transported and processed.

Another observation from the data is that even smaller routes see significant time savings, such as the Breadfruit TPS to Supit Urang route, which decreased in distance from 6.6 km to 6.1 km and time from 26 minutes to 16 minutes. While the distance change is relatively small, the 10-minute reduction in time is a clear example of how digital mapping not only shortens routes but also finds less congested paths, allowing vehicles to travel more smoothly and avoid bottlenecks. This further ensures that operations are not delayed by traffic, which is a common issue in urban waste collection.

Furthermore, the travel time improvements from routes like The Greatest TPS to Supit Urang landfill, reduced from 44 minutes to 32 minutes, showcase how digital mapping applications enhance overall operational efficiency. In waste management, time is a crucial factor because any delay can lead to an accumulation of waste at collection points, resulting in sanitation issues. By significantly cutting down on travel time, waste management teams can operate more effectively, clearing waste before it causes environmental or health risks in the city.

In summary, the reduction in both distance and time across the routes analyzed in the tables highlights the efficiency gains brought about by digital mapping technology. Waste management operations become faster, less resource-intensive, and more environmentally friendly by reducing fuel use and emissions. The findings in these tables illustrate how crucial digital tools are in overcoming logistical challenges in urban waste management systems.

Although the distance reduction varies from significant to minimal, the overall trend shows positive benefits in reducing travel distance, fuel consumption, and carbon emissions. Thus, the adoption of this digital mapping technology has proven effective in supporting more efficient and sustainable waste management in Malang City.

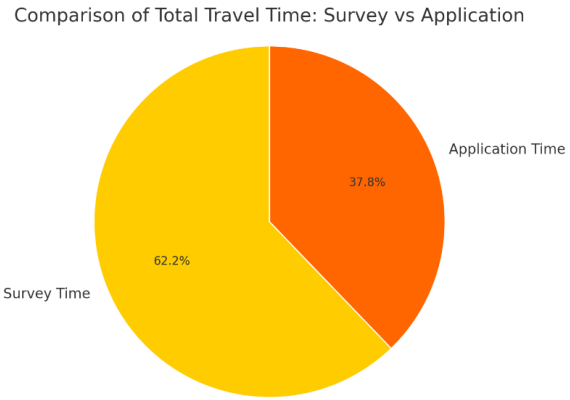

Figure 3. Chart Pie of Travel Time for Survey Results and Digital Mapping Applications
Source: Processed Data by Researchers

The pie chart clearly illustrates the substantial impact that digital mapping applications have on reducing travel time in waste transportation operations across Malang City. As shown, the application-based routes account for 37.8% of the total time, significantly less than the 62.2% recorded from manual survey-based routes. This indicates that the digital mapping technology identifies more efficient routes, drastically cutting down the time spent on waste collection journeys. Reduced travel time directly translates into several operational benefits, such as decreased fuel consumption and lower wear and tear on vehicles. These factors not only optimize the logistics but also contribute to the financial sustainability of waste management systems in Malang.

The most striking example of time reduction is observed in routes like TPS Borobudur, where the application dramatically cuts down travel time compared to traditional survey methods. This sharp reduction highlights how digital mapping can pinpoint more direct and less congested routes, allowing waste transportation vehicles to complete their trips more quickly. By minimizing delays and optimizing pathways, this technology significantly enhances the speed and efficiency of the waste collection process. In turn, faster collection times mean that waste can be processed sooner, reducing the risk of overflow at collection points and minimizing health hazards in the city. The improvement in operational speed ultimately helps to maintain a cleaner urban environment.

In addition to improving efficiency, the use of digital mapping also provides substantial environmental benefits. Shorter travel times lead to a reduction in fuel consumption, which consequently lowers the emission of pollutants such as carbon dioxide (CO^2). Given the rapid urbanization of Malang City, reducing emissions is a critical factor in mitigating the city's overall carbon footprint. The shift to more efficient routes reduces the number of vehicles on the road for extended periods, decreasing traffic congestion and air pollution. Therefore, the environmental advantages offered by this technology contribute to more sustainable urban development by aligning waste management practices with broader environmental conservation goals.

Another important aspect of the time reduction is the economic benefit it brings to the city. Shorter and more efficient routes lead to a direct decrease in operational costs for waste management services. Fuel is a significant operational expense for any transportation-based service, and the ability to cut fuel consumption through optimized routes provides immediate cost savings. Furthermore, with vehicles spending less time on the road, maintenance costs also decrease, as there is less wear and tear on the fleet. This creates a positive cycle where the reduced time and cost lead to increased operational efficiency, allowing the local government or waste management companies to reallocate resources toward other necessary improvements, such as upgrading infrastructure or expanding services.

Finally, the consistent reduction in time across all routes suggests that the application has wide-ranging implications for the future of waste management in Malang City. This technology ensures that all parts of the city, including more remote or congested areas, receive timely waste collection services. By leveraging digital mapping, cities can address service gaps, ensuring that underserved areas receive the same level of attention as central urban zones. This ensures a more equitable distribution of waste management services across the city, which is crucial for maintaining public health and sanitation standards. In conclusion, the use of digital mapping applications not only increases operational efficiency but also supports the city's environmental and economic goals, making it an invaluable tool for modern waste management.

Challenges in Implementing Digital Technology

There are several challenges in implementing new technologies, namely limited implementation costs, lack of training, and resistance from the workforce to change. In Malang City, similar challenges were also found, including limited implementation costs and resistance from the workforce. For example, several garbage truck drivers reported lack of training as a barrier to adopting this new technology. This is in line with research showing that resistance to change among the workforce, such as garbage truck drivers, is often caused by a lack of training and understanding of new technologies (Sugangga et al., 2024) . In addition, limited resources, including financial constraints and inadequate infrastructure, are also major barriers to implementing an integrated system in Malang City (Purnama et al., 2024) .

Some garbage truck drivers are still reluctant to use new technologies due to lack of training and understanding of the benefits offered by digital mapping applications. To overcome these challenges, a comprehensive training strategy and increased awareness of the benefits of using technology in waste management are needed.

Operational Efficiency and Environmental Impact

This study identified that optimizing waste transportation routes not only has an impact on reducing operational costs, but also has a significant contribution to reducing environmental impacts. By designing more efficient routes, fuel consumption by waste transportation vehicles can be minimized, thereby reducing greenhouse gas emissions such as carbon dioxide (CO^2) and other air pollutants. In addition, optimizing routes can reduce vehicle trip frequency and travel time, which contributes to reducing noise and congestion on urban roads. Other positive environmental impacts include reducing energy and resource consumption and improving air quality in urban areas. Therefore, optimizing waste transportation routes is not only economically beneficial, but also supports environmental sustainability and community quality of life.

The results of this study have important policy implications for waste management in Malang City and other areas facing similar challenges. One strategic step that needs to be taken by the Malang City Government is to formulate a policy to provide incentives for waste management companies that adopt digital mapping technology. These incentives can be in the form of tax breaks, subsidies, or direct assistance that encourages companies to invest in new technologies that can improve operational efficiency and reduce environmental impacts. In addition, the government must also provide financial support for training and purchasing equipment needed by the workforce, including garbage truck drivers, so that they are better prepared and skilled in using the technology.

In addition to incentives and financial support, policies should also include efforts to raise public awareness of the benefits of using technology in waste management. Educational campaigns involving various parties, such as schools, communities, and the media, can be an effective step to increase public understanding of the importance of implementing digital technology in waste management and how this can reduce environmental impacts. The government can also facilitate public discussions and invite the public to be more actively involved in the process of sustainable waste management. Thus, this comprehensive policy not only encourages the adoption of new technologies by waste management companies, but also builds awareness and active participation from the community in efforts to maintain a clean and healthy environment.

Discussion

The findings of this study demonstrate the significant potential of digital mapping technology in optimizing urban waste management processes, particularly in Malang City. By integrating Geographic Information System (GIS) applications, the efficiency of waste transportation routes has improved considerably. A reduction in travel distance by up to 15% and travel time by up to 25% is clear evidence of the improvements generated by this technology (Rahardi et al., 2024). In urban areas that frequently face challenges like traffic congestion, varying road conditions, and fluctuating waste volumes, this technology offers practical solutions to reduce fuel consumption and carbon emissions. This technology enables dynamic route adjustments based on real-time conditions, which indirectly minimizes resource waste and environmental impact (Herwanto et al., 2024).

The application of digital mapping technology in waste management not only enhances operations but also has significant environmental implications. The reduction in fuel consumption due to more efficient routes directly contributes to lower carbon dioxide (CO^2) emissions, a major factor in climate change (Kurniawan et al., 2024). As waste collection vehicles travel shorter distances

and spend less time on the road, their contribution to urban air pollution decreases, ultimately improving air quality in densely populated areas (Hasanah et al., 2024). This is crucial as increased urbanization in Malang City has also contributed to higher vehicle emissions. Therefore, implementing this technology becomes a key step in supporting sustainable and environmentally friendly urban development. Moreover, the decrease in fuel consumption and travel time contributes to reduced operational costs, making the waste management system more economically sustainable (Vijayalakshmi et al., 2024).

Despite its many benefits, the implementation of digital mapping technology faces several challenges, particularly in cities with limited infrastructure or technical expertise. One of the main barriers is workforce resistance to the adoption of new technologies. Many waste management workers, such as garbage truck drivers, are unfamiliar with digital tools and may feel threatened by the shift toward automation (Mahboub et al., 2024). This resistance is often exacerbated by a lack of comprehensive training programs, leaving workers without sufficient understanding of the benefits of the technology or how to use it effectively (Oudbier et al., 2024). Therefore, it is crucial for local governments and waste management companies to invest in workforce training and change management strategies to ensure a smoother transition to digital systems (Gunawan et al., 2024; Maione, 2024).

Another challenge is the high cost associated with implementing advanced digital mapping and IoT technologies in waste management. The initial investment required for software, hardware, and training can be prohibitive for many municipalities, especially in developing areas (Bonala et al., 2024; Nwokediegwu et al., 2024). Although the long-term benefits of reduced operational costs and environmental impacts are clear, obtaining the necessary funding for the initial stages of implementation can be difficult (Patil et al., 2024). This highlights the need for government policies that provide financial incentives, subsidies, or grants to help alleviate these costs (Bonala et al., 2024; Nwokediegwu et al., 2024). Collaboration between the public and private sectors could also be a solution, with private companies providing technical expertise and investment while the government focuses on creating a regulatory framework that promotes innovation and sustainability (Bonala et al., 2024; Cicala et al., 2024).

In terms of infrastructure, the availability of reliable digital networks and accurate mapping systems is essential for the successful deployment of GIS-based solutions in waste management. In many urban areas, including Malang, network accessibility and data reliability can be significant obstacles. Without consistent access to real-time data, the effectiveness of digital mapping applications in optimizing routes and improving operational efficiency becomes limited (Rahardi et al., 2024; Utomo et al., 2023). Therefore, local governments must invest in upgrading their digital infrastructure to fully support the adoption of these technologies. Regular maintenance and updates to the system are also necessary to ensure the technology continues to function effectively and adapt to the dynamic urban environment (Haryanti et al., 2024).

The broader social implications of implementing digital technologies in waste management are also worth noting. By streamlining waste collection processes, these technologies can help ensure a more equitable distribution of waste management services across urban areas. In many cities, underserved areas often experience irregular waste collection, leading to sanitation issues and increased health risks for residents. The use of digital mapping can address this by ensuring that waste collection is evenly distributed, reducing social disparities in service provision (Azeez et al., 2024; Nwokediegwu et al., 2024). Additionally, real-time data on waste collection schedules can increase public awareness and participation in waste management initiatives (Bonala et al., 2024). Communities can become more engaged in recycling efforts and more compliant with waste disposal regulations when they have access to accurate and timely information (Periyasamy et al., 2024).

From a policy perspective, the adoption of digital mapping technologies for waste management presents an opportunity for governments to promote environmental sustainability while improving urban infrastructure. Policymakers should focus on creating a regulatory environment that encourages innovation and the use of digital technologies in public services. Incentive-based policies, such as tax breaks or subsidies for companies that adopt sustainable waste management technologies, can drive the broader adoption of these solutions (H. Li et al., 2024; P. Li, 2024). Moreover, integrating technology adoption into urban planning and sustainability goals ensures that these efforts align with larger environmental objectives (Bhattacharya, 2024). By incorporating digital mapping technology into urban waste management strategies, local governments can position themselves as leaders in

smart city initiatives, promoting both economic and environmental sustainability (A. Ali et al., 2024).

The discussion surrounding the implementation of digital mapping technologies in waste management also underscores the need for a systems-based approach to urban planning. Waste management cannot be viewed in isolation; it intersects with issues such as transportation, public health, and environmental protection. As cities continue to grow and urbanize, the demand for more efficient, scalable, and environmentally friendly waste management systems will only increase. A systems-based approach that integrates digital technologies, stakeholder collaboration, and community engagement is essential for creating resilient urban waste management systems capable of withstanding the pressures of population growth and environmental change(Nwokediegwu & Ugwuanyi, 2024; Vardhan & Vijaya, 2024). Digital technologies such as IoT and AI play a critical role by optimizing waste collection and improving operational efficiency, contributing to cleaner urban environments and better public health outcomes (Addas et al., 2024; Vardhan et al., 2024).

In conclusion, while the implementation of digital mapping technology in urban waste management faces several challenges, the benefits in terms of operational efficiency, environmental impact, and social equity are substantial. By addressing barriers such as workforce resistance, financial constraints, and infrastructure limitations, local governments and waste management companies can fully realize the potential of these technologies. IoT-enabled systems can optimize waste collection routes, improving route efficiency by 32% and reducing fuel consumption by 29% (Addas et al., 2024). The use of AI and real-time data also reduces operational costs and environmental footprints, promoting sustainability (Azeez et al., 2024; Bonala et al., 2024). Engaging communities through smart technologies fosters civic responsibility and participation, enhancing social equity in waste management (Azeez et al., 2024). The role of supportive government policies in facilitating the adoption of these technologies cannot be overstated, as they provide the necessary framework for innovation and sustainability. As urban areas continue to expand, the need for efficient, technology-driven waste management systems will become increasingly critical in ensuring both the environmental health of cities and the well-being of their inhabitants.

4. Research Implications

Practical Implications

This study provides several important practical implications for waste managers and local governments, especially in an urban context such as Malang City. By adopting digital mapping technology, such as GIS applications, waste managers can design more efficient transportation routes, which have a direct impact on reducing operational costs. This efficiency is achieved by reducing travel distance and travel time, which ultimately reduces spending on fuel, vehicle maintenance, and labor costs. The use of shorter and more efficient routes not only saves costs, but also extends the life of waste transport vehicles, reduces the frequency of maintenance, and reduces the resulting carbon footprint.

Furthermore, the implementation of digital mapping applications allows for more responsive transportation route management to changing traffic conditions. This technology can help waste managers avoid congestion or closed roads, thereby speeding up travel times and optimizing resource use. The ability to dynamically adjust transportation schedules and routes according to actual conditions in the field also increases operational flexibility. In addition, the implementation of this technology also provides significant environmental benefits, as the reduction of greenhouse gas emissions from waste transport vehicles is in line with global sustainability goals.

The use of digital applications integrated with real-time data also has the potential to increase community participation and involvement in waste management. Communities can gain access to relevant information about transportation schedules, temporary storage locations (TPS), and the cleanliness status of their area. Thus, communities can more easily follow established waste disposal rules and actively participate in recycling initiatives. This technology can also be used to report problems directly to authorities, thereby encouraging faster and more responsive improvements to community needs.

Theoretical Implications

Theoretically, this study strengthens the relevance of route optimization theory in the context of urban waste management. The results of this study indicate that the application of digital technologies such as GIS can significantly reduce operational costs and environmental impacts by planning more efficient transportation routes. This study provides empirical evidence that digital mapping

applications are effective in improving the efficiency of waste management systems, supporting the hypothesis that this technology can play a key role in route optimization efforts.

In addition, this study broadens the understanding of the integration of new technologies, such as IoT sensors and digital mapping applications, into the broader waste management system. By combining these technologies, a systems approach to waste management can be realized, which includes coordination between infrastructure, policy, technology, and society. This systems approach shows that the effectiveness of waste management does not depend on just one aspect, but on the synergy between various interconnected elements.

The study also provides new insights into the barriers faced in the adoption of new technologies, such as cost issues, workforce resistance, and training needs. By highlighting these challenges, the study offers a more comprehensive view of how these barriers can be overcome through appropriate policies and adequate training strategies. This contribution helps enrich the literature on technology adoption in the public sector, particularly in the context of waste management.

The study also has significant social implications. By improving the efficiency of waste management, governments can ensure a more equitable distribution of services across urban areas, including in areas that may have previously been underserved. This can reduce social disparities in the distribution of public services and improve overall quality of life, especially in densely populated areas that often face problems with suboptimal waste collection.

The application of digital mapping technology can also be an effective means of public education, increasing environmental awareness among the community. When people have access to up-to-date information about waste management in their area, they are more likely to understand the environmental impacts of their waste disposal habits and are encouraged to change their behavior to be more environmentally friendly. This awareness can be strengthened through public campaigns that use data from the application to demonstrate the positive impacts of reduced emissions and better waste management.

On the other hand, digital applications used in waste management can also function as a forum for interaction between the community and the government. This creates a space for residents to convey complaints, provide suggestions, or report violations related to waste disposal. By improving two-way communication between the community and waste managers, this technology can help build stronger trust and collaboration between the government and residents, which is critical to the long-term success of any waste management initiative.

This study emphasizes the importance of policies that support the application of digital mapping technology in waste management. Local governments need to develop policies that not only encourage but also facilitate the use of this technology at all levels of waste management. These policies can include financial incentives for companies or organizations that implement digital mapping technology, such as subsidies for software purchases or training programs for workers.

In addition, policies that encourage technological innovation need to be accompanied by regulations that govern the use of these technologies. For example, the government could consider creating regulations that require the use of digital mapping applications in all municipal waste management contracts. This could be combined with tax incentives or results-based financing for companies that demonstrate cost reductions and efficiency improvements through the use of these technologies.

Furthermore, governments and waste managers must invest sufficient resources to train the workforce in the use of these technologies. Without adequate training, the adoption of these new technologies may face resistance from less skilled workers or those who feel threatened by the change. Therefore, a well-designed ongoing training program is essential to ensure that these technologies are implemented effectively and efficiently.

The importance of collaboration between the public and private sectors cannot be overstated. Governments can partner with technology companies to develop solutions that are more tailored to local needs, while the private sector can provide the investment and technical expertise needed to support the implementation of these technologies. This collaboration not only accelerates the adoption of technology, but also ensures that the solutions developed are the most effective and efficient.

The study also highlights the need for better infrastructure planning to support the adoption of these technologies. This includes investing in digital infrastructure, such as reliable data networks and mapping systems that are accessible to all stakeholders. Strong infrastructure will ensure that the

technology can be optimally adopted and used across the city, without facing technical hurdles that often hinder the implementation process.

To ensure the effectiveness of the implemented policies, ongoing monitoring and evaluation mechanisms are also needed. Annual audits or periodic evaluations of the city's waste management, technology use, and impact on operational efficiency and the environment will help identify areas where policy improvements or adjustments are needed. This data-driven approach will ensure that the implemented policies remain relevant and effective in addressing the evolving challenges of waste management.

5. Conclusion

This study proves that the use of digital mapping technology such as GIS applications is very effective in optimizing waste transportation routes in urban areas, especially in Malang City. The results of the study show that the application of this technology can significantly reduce travel distance and travel time, which has an impact on reducing operational costs and carbon emissions. The use of digital mapping applications allows waste managers to determine the most efficient transportation routes, reduce fuel consumption, and extend vehicle life. This provides significant economic benefits, especially in reducing costs associated with fuel, vehicle maintenance, and labor.

In addition to economic benefits, the study also emphasizes the importance of digital technology in supporting environmental sustainability goals. Reducing travel distance and travel time has a direct impact on reducing greenhouse gas emissions produced by waste collection vehicles. Thus, digital mapping technology not only helps improve operational efficiency but also supports global efforts to reduce carbon footprint and maintain urban air quality.

From a social perspective, this study suggests that the adoption of digital mapping technology can increase community involvement in waste management. Digital applications that are easily accessible to the public allow people to view waste collection schedules and cleanliness status in their area, encourage compliance with waste disposal regulations, and participation in recycling programs. This has the potential to increase public awareness of the importance of good waste management and encourage more environmentally friendly behavior.

However, the study also identified several challenges that must be overcome to fully benefit from the implementation of this technology. One of the main challenges is workforce resistance to change and adoption of new technologies. Some workers may feel unprepared or under-skilled in using digital mapping technology. Therefore, efforts are needed to improve the skills and knowledge of the workforce through comprehensive and ongoing training programs. In addition, the issue of cost and limited access to data are also barriers that need to be addressed with supportive policies and adequate investment in digital infrastructure.

The policy implications of this study are clear. Local governments need to develop policies that support the adoption of digital technologies in waste management, including providing financial incentives and technical assistance to companies or organizations that adopt these technologies. Policies should also include regulations that encourage innovation and use of technology, as well as building the necessary infrastructure to support optimal technology implementation. In addition, collaboration between the public and private sectors is essential to ensure that the technological solutions developed are tailored to local needs and can be implemented effectively.

Overall, this study provides valuable insights for policymakers, waste managers, and communities in designing more efficient, sustainable, and environmentally friendly waste management strategies. By addressing existing challenges and making optimal use of digital technologies, cities can improve operational efficiency, reduce costs, and achieve greater sustainability goals. The study also emphasizes the importance of a systems approach to waste management that involves synergies between technology, policy, and community participation to create cleaner, healthier, and more sustainable cities.

References

Addas, A., Khan, M. N., & Naseer, F. (2024). Waste management 2.0 leveraging internet of things for an efficient and eco-friendly smart city solution. *PLOS ONE*, *19*(7), e0307608. https://doi.org/10.1371/journal.pone.0307608

Afuw, T., Koeswahyono, I., & Masykur, H. (2024). Efforts to Prevent Land Changes Due to Natural Disasters in Tridi Village Malang City. *International Journal of Business, Law, and Education*, *5*(2), 1529–1542. https://doi.org/10.56442/ijble.v5i2.594

Alanazi, F., & Alenezi, M. (2024). Driving the future: Leveraging digital transformation for sustainable transportation. *Journal of Infrastructure, Policy and Development*, *8*(3), 3085. https://doi.org/10.24294/jipd.v8i3.3085

Ali, A., Hadeed, M. Z., Safavi, S., & Ahmad, M. (2024). Leveraging GIS for Environmental Planning and Management. *Advances in Environmental Engineering and Green Technologies Book Series*. https://doi.org/10.4018/979-8-3693-2845-3.ch016

Ali, M., Zhang, X., & Lee, K. (2023). Urban waste management challenges in fast-growing cities. *Journal of Environmental Management*, *321*, 115–130. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.115130

Anisykurlillah, R., Sampe, S., & Bataha, K. (2024). Evaluation of Waste Management Policy in Malang City. *Ganaya : Jurnal Ilmu Sosial Dan Humaniora*, *7*(1), 31–37. https://doi.org/10.37329/ganaya.v7i1.2791

Arifin, R., Masyhar, A., Sumardiana, B., Ramada, D. P., Kamal, U., & Fikri, S. (2024). Indonesian sustainable development policy: How the government ensures the environment for future generations. *IOP Conference Series: Earth and Environmental Science*, *1355*(1), 012005. https://doi.org/10.1088/1755-1315/1355/1/012005

Audri, D. S., Fanda, A. M., & Kusdiwanggo, S. (2024). MEMBACA TINGKAT KEBERLANJUTAN SOSIAL PADA KAMPUNG TERAPI HIJAU KOTA MALANG. *LANGKAU BETANG: JURNAL ARSITEKTUR*, *11*(1), 66. https://doi.org/10.26418/lantang.v11i1.74573

Azeez, R., Afolabi, V. B., Adeniy, A. E., Sakpere, W., Adepoju, I. G., Oluwatuyi, R. F., Adekanbi, J., & Osalor, W. (2024). *Combating Urban Dirt: A Systematic Internet of Things Approach to Waste Management*. https://doi.org/10.1109/seb4sdg60871.2024.10630133

Bhattacharya, S. (2024). Government Strategies for Sustainability, Socioeconomic Progress, and Gender-Biased Citizen Participation in Global Digital Governance. *Advances in Electronic Government, Digital Divide, and Regional Development Book Series*. https://doi.org/10.4018/979-8-3693-2363-2.ch008

Bonala, K., Saggurthi, P., Kambala, P. K., Voruganti, S., Utukuru, S., & Sugamya, K. (2024). Efficient Handling of Waste Using Deep Learning and IoT. *2024 2nd International Conference on Sustainable Computing and Smart Systems (ICSCSS)*, 368–373. https://doi.org/10.1109/ICSCSS60660.2024.10625621

Cicala, L., Gargiulo, F., Parrilli, S., Amitrano, D., & Pigliasco, G. (2024). Progressive Monitoring of Micro-Dumps Using Remote Sensing: An Applicative Framework for Illegal Waste Management. *Sustainability*. https://doi.org/10.3390/su16135695

Das, A. K., & Chilukuri, B. R. (2024). Bi-objective optimization for last-mile routing of garbage trucks: Aesthetics and Public exposure. *Waste Management & Research: The Journal for a Sustainable Circular Economy*. https://doi.org/10.1177/0734242X241252914

Dimitrov, D., & Manchev, I. (2024). METHODOLOGICAL AND TECHNICAL ASPECTS OF MODELS FOR DIGITAL MANAGEMENT OF TRANSPORT SYSTEMS. *ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference*, *2*, 79–82. https://doi.org/10.17770/etr2024vol2.8049

Eb, A., Mad, R., & Sa, A.-A. (2021). *Rational Approach to Optimization of Solid Waste Collection Routing*

Using GIS: A Case Study of Adentan West Residential Area of Accra.

Gunawan, A. P., & Niyu, N. (2024). Obstacles to the Implementation of Digital Transformation: A Case Study of the Yayasan Al Huda Islamic Education Center Metropolitan. *Jurnal Inter Act*. https://doi.org/10.25170/interact.v12i2.4916

Habibah, A., Farid, F. M., & Annisa, S. (2023). METODE REGRESI GULUD UNTUK MENGATASI MASALAH MULTIKOLINEARITAS PADA KASUS INDEKS KUALITAS LINGKUNGAN HIDUP DI INDONESIA TAHUN 2021. *RAGAM: Journal of Statistics & Its Application*, *2*(1), 70. https://doi.org/10.20527/ragam.v2i1.10041

Hardianto, H., Tjahjadi, M. E., Sunaryo, D. K., Sudiasa, I. N., & Manaha, Y. P. (2024). Analytic network process in traditional market solid waste management in Malang Regency, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1312*(1), 012016. https://doi.org/10.1088/1755-1315/1312/1/012016

HARIS, A. T. L. P. L., ISHAK, A. D., ENTONG, A., & HARIS, A. T. E. (2023). PENGARUH INDEKS PEMBANGUNAN MANUSIA TERHADAP INDEKS KUALITAS LINGKUNGAN HIDUP DI INDONESIA. *GANEC SWARA*, *17*(3), 1149. https://doi.org/10.35327/gara.v17i3.555

Haryanti, T., & Fierza, F. (2024). *Sistem informasi kependudukan untuk peningkatan layanan prima kecamatan widang jawa timur*. https://doi.org/10.35721/jitpemas.v4i1.71

Hasanah, S. R., & Purwanda, E. (2024). Waste Bank Innovation Management Using Digital Innovation System Management in Cicadas Village, Gunung Putri District, Bogor Regency. *Majalah Bisnis & IPTEK*, *17*(1), 10–22. https://doi.org/10.55208/bistek.v17i1.534

Herwanto, R., Susanto, F., Dwi, R., Prayoga, M. H., Dinata, R. M., & Wamiliana, W. (2024). Haversine Geo-Spasial Data Android Model Untuk Optimasi Rute Kebersihan Lingkungan Terdekat. *Jurnal Pepadun*. https://doi.org/10.23960/pepadun.v5i1.201

Jati, D. R., Gultom, B. J., & Affrilyno, A. (2023). Evaluasi Kualitas Lingkungan Daerah Pesisir Kota Singkawang sebagai Kota Tangguh. *Jurnal Wilayah Dan Lingkungan*, *11*(3), 296–309. https://doi.org/10.14710/jwl.11.3.296-309

Jiang, P., & Zhang, R. (2023). Limitations in traditional waste management infrastructure in emerging economies. *Sustainability*, *15(2)*, 456–469.

Kashef, R., Alegre, E. P., Prova, T., & Aggarwal, S. (2024). Automated Waste Management using a Customized Vision-based Transformer Model. *2024 IEEE World AI IoT Congress (AIIoT)*, 300–309. https://doi.org/10.1109/AIIoT61789.2024.10578946

Kurniawan, T. A., Meidiana, C., Goh, H., Zhang, D., Othman, M. H. D., Aziz, F., Anouzla, A., Sarangi, P. K., Pasaribu, B., & Ali, I. (2024). Unlocking synergies between waste management and climate change mitigation to accelerate decarbonization through circular-economy digitalization in Indonesia. *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2024.03.011

Li, H., Du, X., Yan, X., & Xu, N. (2024). Digital Transformation and Urban Green Development: Evidence from China's Data Factor Marketization. *Sustainability*. https://doi.org/10.3390/su16114511

Li, P. (2024). Digital Technologies, Environmental Governance and Environmental Performance: Empirical Evidence from China. *The Engineering Economist*. https://doi.org/10.5755/j01.ee.35.2.33429

Liu, Y., Wang, T., & Li, J. (2022). Waste transportation and management in metropolitan areas: A systematic review. *Waste Management*, *136*, 234–248.

Mahboub, H., & Sadok, H. (2024). *Barriers to Digital Transformation*. https://doi.org/10.18080/jtde.v12n1.814

Maione, G. (2024). Barriers to the Digital-Based Environmental Accountability of Local Governments. *Springer Proceedings in Complexity*. https://doi.org/10.1007/978-3-031-44721-1_54

Nwokediegwu, Z. Q. S., & Ugwuanyi, E. D. (2024). *Implementing ai-driven waste management systems in underserved communities in the usa*. https://doi.org/10.51594/estj.v5i3.903

Oudbier, S. J., Chen, B., Chen, B. S. J., Ziesemer, K. A., Oudbier, S. J., & Smets, E. M. A. (2024). Implementation barriers and facilitators of remote monitoring, remote consultation and digital care platforms through the eyes of healthcare professionals: a review of reviews. *BMJ Open*. https://doi.org/10.1136/bmjopen-2023-075833

Patil, S. C., & Gidde, M. R. (2024). An IoT-based waste management approach for environmental sustainability. *Journal of Integrated Science and Technology*. https://doi.org/10.62110/sciencein.jist.2024.v12.769

Periyasamy, K., Reddy, P. P. K., Sonukumar, Ramachandran, G. S., & Muthumanickam, T. (2024). *Analysis of IoT based Digital Waste Management Collections Garbage Disposal and its Applications*. https://doi.org/10.1109/icaaic60222.2024.10575201

Purnama, Y. P., Hariyanto, T., & Saudah, S. (2024). Analysis of Integrated Service and Reference Systems in Overcoming Poverty. *EAS Journal of Humanities and Cultural Studies*, *6*(03), 93–103. https://doi.org/10.36349/easjhcs.2024.v06i03.006

Rahardi, A., Estian Pambudi, R., Septiawan, Y., Ade Muktiawan, D., & Irfan, M. (2024). IMPLEMENTASI SISTEM INFORMASI GEOGRAFIS PEMETAAN LOKASI PEMBUANGAN SAMPAH LEGAL BERBASIS WEBSITE DI KOTA BANDAR LAMPUNG. *Jurnal SIMADA (Sistem Informasi Dan Manajemen Basis Data)*, *7*(1), 15–25. https://doi.org/10.30873/simada.v7i1.412

Rahmawati, R., Said, M., & Sekarsari, R. W. (2024). PERAN PEMERINTAH KOTA MALANG DALAMM MENGEMBANGKAN RUANG TERBUKA HIJAU DENGAN PENDEKATAN KONSEP COLLABORATIVE GOVERNANCE. *Publik: Jurnal Manajemen Sumber Daya Manusia, Administrasi Dan Pelayanan Publik*, *11*(2), 728–739. https://doi.org/10.37606/publik.v11i2.1120

Safitri, D., Suhendrayatna, S., & Arahman, N. (2024). Dynamic systems analysis of waste generation in Banda Aceh: a comprehensive evaluation. *IOP Conference Series: Earth and Environmental Science*, *1356*(1), 012059. https://doi.org/10.1088/1755-1315/1356/1/012059

Samin, S. (2024). Analisis Rute Pengangkutan Sampah Domestik Kota Malang Berbasis Aplikasi Google Map. *Jurnal Penelitian Inovatif*, *4*(3), 949–958. https://doi.org/10.54082/jupin.439

Sankar, G. R., & Fathima, G. (2024). IoT-Enabled Smart Waste Management: A Comprehensive Study on Sensor Technologies and Implementation Strategies. *2024 International Conference on Inventive Computation Technologies (ICICT)*, 1755–1764. https://doi.org/10.1109/ICICT60155.2024.10544982

Singh, M., & Gupta, D. A. (2022). Optimizing and Analyzing the Cost of Collection and Transportation of Solid Waste Using GIS. *International Journal for Research in Applied Science and Engineering Technology*, *10*(9), 1866–1872. https://doi.org/10.22214/ijraset.2022.46934

Sugangga, R., Rahman, I., Hermawan, A., Wardana, L. W., Banu, S., Putri, E. D. S., & Malik, M. M. (2024). THE ROLE OF DIGITALIZATION IN MICRO SMALL ENTERPRISES (STUDY ON SMALL ENTERPRISES IN MALANG CITY). *Nusantara Economics and Entrepreneurships Journals*, 227–232. https://doi.org/10.59971/necent.v1i3.25

Tirkolaee, E. B., Simic, V., Ghobakhloo, M., Foroughi, B., Asadi, S., & Iranmanesh, M. (2024). Integrated design of a sustainable waste management system with co-modal transportation network: A robust bi-level decision support system. *Journal of Cleaner Production*, *449*, 141760. https://doi.org/10.1016/j.jclepro.2024.141760

Utomo, K. P., & Sulastri, A. (2023). Optimalisasi Sistem Pengangkutan Sampah Di Kabupaten Bengkayang Berbasis Geographic Information System (GIS). *Jurnal Teknologi Lingkungan Lahan Basah*. https://doi.org/10.26418/jtllb.v11i2.64824

Vardhan, V., & Vijaya, D. G. S. (2024). Smart Cities, Cleaner Tomorrow: AI-Powered Waste Solutions for Sustainable Urban Living. *International Journal of Research Publication and Reviews*. https://doi.org/10.55248/gengpi.5.0424.0952

Vijayalakshmi, V., Radha, R., & Sharanya, S. (2024). Modern Technological Innovation in Digital Wase Management. *Advances in Computational Intelligence and Robotics Book*. https://doi.org/10.4018/979-8-3693-1552-1.ch008

Wang, S., & Zhang, L. (2024). A Review of GIS Technology Applications in Transportation Planning and Management. *Scientific Journal of Technology*, *6*(4), 108–113. https://doi.org/10.54691/e1s89w46