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Geographic Information System Model Design for Sustainable Municipal Solid Waste Management: A Case of Migori Municipality, Kenya

By

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Abstract
The purpose of this study was to design and implement a Geographic Information System (GIS) model tailored to address these challenges and achieve sustainable MSWM. The contention of the study is that rapid urbanization and population growth in Migori Municipality have intensified the challenges of municipal solid waste management (MSWM), resulting in inefficiencies in waste collection, disposal, and environmental impact. The study is grounded in Systems Theory, which emphasizes the interdependence of components within a system, the study integrates both technological and environmental factors in its approach. A case study approach was employed, concentrating solely on qualitative data to provide an in-depth understanding of MSWM practices in Migori Municipality. The case study method was selected for its ability to explore complex phenomena in a real-world context, offering detailed insights into the challenges and potential solutions for sustainable waste management (Yin, 2018). Data were collected through semi-structured interviews and focus group discussions with key stakeholders, including local authorities, waste management professionals, and IT specialists. Purposive sampling was used to ensure participation from individuals with direct involvement in MSWM, and thematic analysis was conducted to identify recurring themes and challenges. The study findings indicate that the proposed GIS model can optimize solid waste collection routes, improve resource allocation, and minimize environmental degradation. Furthermore, community engagement was identified as crucial for the successful adoption of sustainable MSWM practices. This GIS model provides a tailored, data-driven approach to address the specific needs of Migori Municipality's waste management system, promoting long-term environmental sustainability.

Keywords: Kenya, Migori County, Geographic Information Systems, Municipal Solid Waste Management, Sustainability, Environmental Technology, Systems Theory

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Introduction

The use of Geographic Information System (GIS) technology in Municipal Solid Waste Management (MSWM) has been widely recognized as a critical tool for addressing complex environmental challenges. Globally, the adoption of GIS has played a significant role in improving the efficiency of solid waste management systems by optimizing collection routes, identifying suitable landfill sites, and facilitating real-time monitoring of solid waste generation and disposal activities (Chen et al., 2023). For example, in China, GIS technology was integrated into municipal solid waste management, enhancing route optimization and reducing fuel consumption and operational costs (Chen et al., 2023). Similarly, in Brazil, GIS applications have been used to improve solid waste segregation and promote effective recycling practices, ultimately reducing the amount of solid waste sent to landfills (Santos et al., 2024). These implementations demonstrate that GIS can be a transformative tool for achieving sustainable solid waste management practices.

In Sub-Saharan Africa, the adoption of GIS in MSWM was still in its early stages. Countries like South Africa and Nigeria had initiated the use of GIS for solid waste mapping and landfill site identification. However, these efforts were often hampered by financial constraints, inadequate infrastructure, and a shortage of skilled personnel (Dlamini et al., 2019; Oyedele et al., 2022). For example, in South Africa, GIS technology was employed to identify optimal solid waste collection routes, but its application was limited by a lack of consistent funding and technological infrastructure (Dlamini et al., 2019). In Nigeria, GIS was used for mapping landfill sites, but the lack of comprehensive spatial data and technical expertise restricted its effectiveness (Oyedele et al., 2022). These barriers have slowed the full-scale adoption of GIS in MSWM across the region.

In Kenya, there has been some progress in integrating GIS into MSWM, particularly in municipalities like Thika and Nyahururu. Studies conducted in these areas showed promising results, with GIS technology being used to optimize solid waste collection routes and reduce operational costs (Kimwatu & Ndiritu, 2016; Nduati, 2020). For example, in Thika, GIS technology helped reduce fuel consumption by creating more efficient solid waste collection routes, while in Nyahururu, it was used to identify solid waste generation hotspots, improving resource allocation (Kimwatu & Ndiritu, 2016; Nduati, 2020). Despite these achievements, the adoption of GIS in Kenya has been constrained by challenges such as data availability and accuracy. The dynamic nature of urban growth in many Kenyan towns makes it difficult to maintain up-to-date GIS data, which limits the potential of GIS applications to provide accurate and timely solid waste management solutions (Kimwatu & Ndiritu, 2016).

Research Gap

Despite advancements in GIS adoption for MSWM in larger municipalities, there is limited research on its application in smaller urban centers like Migori Municipality. Migori faces unique socio-economic and infrastructural challenges, such as a lack of structured waste management systems and limited financial resources, which differ from those in larger municipalities. This study aimed to bridge this gap by designing a GIS model tailored to the local context of Migori Municipality, addressing its specific waste management needs and constraints. By focusing on a smaller urban center, the research contributes to the broader understanding of how GIS technology can be adapted to improve solid waste management in diverse settings, thereby offering insights for its application in similar towns across the region.

Statement of the Problem

The waste management system in Migori Municipality is marked by significant inefficiencies in solid waste collection, illegal dumping, and inadequate recycling practices. These issues have resulted in increased environmental degradation, which poses a serious threat to public health and safety. The ineffective handling of solid waste has contributed to pollution of water sources, the proliferation of disease vectors, and the accumulation of solid waste in undesignated areas, causing adverse effects on both the environment and the community's well-being (Adeleke et al., 2021).

A major contributing factor to these challenges is the lack of integrated IT solutions, such as Geographic Information Systems (GIS), to streamline solid waste management processes. The absence of technology-based solutions has made it difficult to optimize solid waste collection routes, manage landfill sites effectively, and promote proper solid waste segregation (Vu et al., 2019). This lack of integration not only leads to inefficient resource utilization but also hampers the municipality's ability to monitor and enforce solid waste management policies.

Moreover, rapid urbanization in Migori Municipality has compounded these challenges by increasing solid waste generation without a corresponding upgrade in the solid waste management infrastructure (Migori County, 2023). The existing system struggles to cope with the growing solid waste volume, resulting in extended collection routes, unregulated dumping sites, and limited recycling facilities.

Given these circumstances, there is an urgent need for a sustainable and efficient solid waste management model that leverages technology to address these challenges. Therefore, this study sought to design a GIS-based model tailored to the specific needs of Migori Municipality. The proposed model aims to optimize solid waste collection processes, improve resource allocation, and enhance overall environmental sustainability. By incorporating GIS technology, the study addresses the need for an integrated, data-driven approach to solid waste management that can be scaled and adapted to similar municipalities across the region (Soni, 2024).

Theoretical Framework: Systems Theory

This study adopted Systems Theory as its guiding framework due to its holistic approach to analyzing complex systems. Systems Theory suggests that the efficiency and effectiveness of a system depend on how well its various components interact with one another. In the context of this research, the integration of Geographic Information System (GIS) technology in Municipal Solid Waste Management (MSWM) was viewed as part of a larger system that includes technological, environmental, and social elements (Bertalanffy, 1968). By considering the interdependencies among these components, Systems Theory provides a comprehensive framework for understanding how GIS can be effectively implemented to optimize solid waste management practices in Migori Municipality (Awuah et al., 2021).

The integration of Systems Theory also highlighted the importance of stakeholder collaboration in MSWM. Effective solid waste management requires coordination between various stakeholders, such as government agencies, private solid waste collectors, community members, and environmental organizations (Dlamini et al., 2019). GIS supports this collaboration by providing a shared platform for data visualization and decision-making. For instance, stakeholders can use GIS maps to monitor solid waste collection activities, identify service gaps, and plan interventions more efficiently, thereby enhancing the overall functionality and sustainability of the MSWM system (Nguyen & Khominich, 2023).

Applying Systems Theory in this study revealed how the interdependence of MSWM components influences the sustainability of the system. Inefficiencies in solid waste collection routes can lead to increased fuel consumption and emissions, which negatively impact environmental sustainability. By leveraging GIS technology, such inefficiencies can be identified and mitigated through route optimization, leading to reduced operational costs and environmental benefits (Chen et al., 2023).

Objective

The study aimed to evaluate the current status of municipal solid waste management in Migori Municipality by identifying barriers hindering the adoption of Geographic Information System (GIS) technology, and design a GIS-based model that optimizes solid waste collection routes, enhances decision-making, and promotes sustainable solid waste management practices tailored to the unique needs of the municipality.

Research Question

How can a GIS-based model be designed to improve the efficiency and sustainability of municipal solid waste management in Migori Municipality by addressing current challenges and optimizing solid waste management processes?

Literature Review

Globally, the use of GIS technology in MSWM has demonstrated significant benefits in optimizing solid waste collection routes, improving site selection for landfills, and enhancing resource allocation (Maraqa et al., 2018; Chen et al., 2023). In countries like China and Brazil, GIS technology has been widely adopted to streamline solid waste management processes. For example, in China, the integration of GIS in urban solid waste management has led to better identification of solid waste generation patterns, which allows for more effective resource distribution and improved solid waste collection efficiency (Chen et al., 2023). Similarly, Brazil has used GIS to facilitate the siting of landfill sites, taking into consideration environmental and social factors to minimize negative impacts on local communities (Santos et al., 2024). These implementations reflect the capacity of GIS to address complex challenges in MSWM when supported by robust infrastructure and data systems.

However, the global success of GIS in solid waste management is not without challenges. Effective GIS implementation relies heavily on the availability of accurate spatial data and technical expertise. In developed countries, maintaining high-quality spatial data and recruiting skilled personnel are not major barriers due to established technological infrastructure and capacity (Chen et al., 2023). In contrast, developing regions often struggle with data quality issues and lack the technical skills required to fully utilize GIS technology.

This disparity in technological capabilities limits the potential for GIS to contribute meaningfully to sustainable solid waste management in less developed contexts.

In Sub-Saharan Africa, the adoption of GIS in MSWM is still in its infancy. Several countries, such as South Africa, Nigeria, and Ghana, have made initial efforts to integrate GIS into their solid waste management systems. In South Africa, GIS has been used to identify optimal solid waste collection routes and to plan new landfill sites (Dlamini et al., 2019). However, these efforts have been hampered by financial constraints and the lack of adequate technological infrastructure. In many cases, municipalities lack the resources to invest in the necessary hardware and software for effective GIS deployment. Furthermore, the lack of skilled personnel to operate and maintain GIS systems has been a persistent barrier (Awuah et al., 2021).

Ghana's experience with GIS adoption in solid waste management also illustrates the broader challenges faced by African countries. While the implementation of GIS improved solid waste collection efficiency in some urban areas, infrastructural deficits and limited data availability prevented its full utilization (Awuah et al., 2021). Inadequate public awareness and low levels of stakeholder engagement further compounded these challenges, resulting in resistance to the adoption of new technologies in solid waste management. This highlights the importance of not only investing in technology but also in capacity building and community engagement to ensure sustainable outcomes.

Kenya has made some progress in integrating GIS into MSWM, particularly in municipalities such as Thika and Nyahururu. Research conducted in these areas has shown that GIS technology can significantly enhance solid waste management by identifying solid waste generation hotspots and optimizing collection routes (Kimwatu & Ndiritu, 2016; Nduati, 2020). In Thika, for example, the use of GIS to create more efficient solid waste collection routes led to a notable reduction in fuel consumption and operational costs (Kimwatu & Ndiritu, 2016). In Nyahururu, GIS technology was used to map solid waste generation patterns, enabling the municipality to allocate resources more effectively and improve overall service delivery (Nduati, 2020).

Despite these positive outcomes, the adoption of GIS in Kenyan municipalities has been constrained by several factors. Key among these is the issue of data inaccuracy, which arises from the lack of up-to-date spatial data and the absence of standardized data collection methods (Kinoti & Muchiri, 2016). Additionally, limited technical capacity and the high costs associated with acquiring and maintaining GIS software and hardware have restricted the broader application of this technology in smaller municipalities. These challenges underscore the need for a more integrated approach to GIS adoption that includes capacity building, stakeholder collaboration, and improved data management practices.

From the literature reviewed, it is evident that while GIS has significant potential to transform MSWM, its implementation in developing countries, including Kenya, faces numerous barriers. The lack of technical expertise, financial constraints, and poor data management practices are recurring themes that hinder the successful adoption of GIS in many African municipalities (Dlamini et al., 2019; Awuah et al., 2021). In the researcher's view, these barriers can only be overcome through a multi-pronged approach that includes capacity building, policy support, and sustained stakeholder engagement. Moreover, the study acknowledges that while GIS can optimize solid waste management processes, it is not a standalone solution. The technology must be integrated into a broader solid waste management strategy that considers social, environmental, and economic factors (Nguyen & Khominich, 2023).

Methodology

This study employed a case study approach, focusing exclusively on qualitative data to gain an in-depth understanding of municipal solid waste management (MSWM) practices in Migori Municipality. The case study method was selected for its ability to provide detailed insights into complex phenomena within a real-life context, allowing for a thorough exploration of the challenges and potential solutions for sustainable solid waste management (Yin, 2018).

Data Collection Methods

Data was collected through semi-structured interviews and focus group discussions with 10 purposively selected participants. These participants included local authorities, solid waste management professionals, and Information Technology (IT) specialists. The selection criteria were based on their direct involvement and expertise in MSWM and Geographic Information System (GIS) technology. The interviews aimed to gather rich, qualitative data about the challenges faced in implementing GIS technology, while the focus group discussions encouraged participants to share experiences, perspectives, and collaborative insights regarding MSWM practices in the municipality (Guest et al., 2020).

Sampling Strategy

A purposive sampling strategy was utilized to select participants who possessed relevant knowledge and experience. This method ensured that the insights gathered were closely aligned with the study's objectives and provided a meaningful representation of the challenges faced in MSWM in Migori Municipality (Palinkas et al., 2015).

Data Analysis

Thematic analysis was employed to analyze the qualitative data obtained from the interviews and focus group discussions. This process involved coding the data and identifying recurring themes that highlighted key issues, such as inadequate infrastructure, lack of technical expertise, and financial constraints (Braun & Clarke, 2019). The qualitative findings were interpreted within the context of the broader MSWM challenges faced by Migori Municipality, thereby informing the development of a tailored GIS-based model to optimize solid waste management processes.

Presentation and Discussion of Findings

Results from Interviews

The interviews explored the feasibility and requirements for implementing a Geographic Information Systems (GIS) model in municipal solid waste management (MSWM) in Migori Municipality. The insights provided by key stakeholders, including solid waste management professionals, local authorities, IT specialists, community representatives, and commercial solid waste collectors, revealed critical barriers and necessary considerations for successful GIS adoption.

Challenges in GIS Implementation

One of the primary challenges identified was the lack of skilled personnel to operate the GIS system. Respondents emphasized that insufficient training and frequent staff turnover hindered the sustainability of GIS operations. This aligns with findings from Shabani et al. (2024), who noted that the lack of technical expertise is a persistent barrier to GIS adoption in developing regions. Continuous professional development and retention strategies were suggested to address this issue. Furthermore, infrastructural and technical constraints such as unreliable internet, insufficient GIS hardware, and power outages were highlighted as obstacles. Similar constraints have been reported by Das et al. (2024), who found that infrastructural deficiencies limited the effectiveness of GIS systems in comparable settings.

Additionally, the lack of financial resources to purchase and maintain GIS software and hardware was cited as a significant challenge. The respondents' concerns mirror the views of Dlamini et al. (2019), who pointed out that inadequate funding is a major hindrance to the implementation of GIS technology in Sub-Saharan Africa. This suggests that financial planning and sustainable funding models, such as public-private partnerships or government grants, should be considered to support GIS deployment in Migori Municipality.

Stakeholder and Community Perspectives

The attitudes of stakeholders towards GIS adoption varied widely. Local authorities expressed cautious optimism, acknowledging the potential benefits of GIS for enhancing solid waste management efficiency but raising concerns over high costs and the need for systemic changes. This echoes the sentiments of Santos et al. (2024), who observed similar resistance in Brazilian municipalities due to financial and organizational challenges. Solid waste management teams had mixed reactions; while some were eager to embrace the technology, others were apprehensive about the additional workload and training requirements. Such skepticism has been observed in other studies, where new technologies are often viewed as disruptive rather than supportive (Nguyen & Khominich, 2023).

Community members, on the other hand, largely lacked awareness of GIS and its potential benefits. This lack of awareness contributed to skepticism and limited engagement, which could undermine the long-term success of GIS projects. The findings suggest that increasing community education and involvement is essential for garnering broader support, as noted by Awuah et al. (2021), who emphasized the importance of public engagement in successful solid waste management initiatives.

Data and Information Accessibility

Data availability and quality emerged as critical issues. Respondents highlighted inconsistencies in data collection and a lack of historical data on solid waste generation, which impeded the effective use of GIS for decision-making. This concern was also raised by Kimwatu and Ndiritu (2016), who noted that outdated or incomplete spatial data limits the potential of GIS to provide accurate analyses and insights. To overcome these challenges, respondents suggested implementing standardized data collection methods and integrating real-time data to ensure continuous updates and improve the reliability of GIS models.

Regulatory and Policy Hurdles

The absence of clear policies and guidelines for GIS implementation was cited as a major barrier. Respondents reported that institutional bureaucracy and fragmented regulatory frameworks delayed approval processes and impeded the timely adoption of GIS. This aligns with the findings of Oyedele et al. (2022), who pointed out that weak regulatory support often leads to inconsistent application of GIS technology in solid waste management. Establishing well-defined policies and streamlining bureaucratic processes were recommended to mitigate these challenges.

Mitigating Challenges and Recommendations

To address the identified challenges, respondents proposed several strategies. The development of clear policies tailored to GIS technology and the allocation of dedicated resources for infrastructure upgrades were among the top recommendations. Increasing stakeholder engagement and public awareness through educational campaigns was also suggested to ensure broader acceptance and support for GIS projects. These recommendations are consistent with the suggestions of Vu et al. (2019), who stressed the need for comprehensive policy frameworks and stakeholder buy-in for the successful implementation of GIS in MSWM systems.

Results from Focus Group Discussions

The focus group discussion explored critical aspects of solid waste management in Migori Municipality and identified specific requirements for the effective integration of a Geographic Information Systems (GIS) model. Participants included top officials, ICT personnel, and operations managers from the municipality. The thematic analysis revealed insights into current challenges, GIS model needs, and essential design elements.

Current Solid Waste Management Challenges

One of the primary issues highlighted by participants was the inconsistent solid waste collection schedules, which often led to the accumulation of solid waste in undesignated areas. This challenge was consistent with previous findings from the interviews and questionnaires, where respondents noted that irregular collection times significantly hindered solid waste management efficiency. The participants in the focus group emphasized the need for a streamlined approach to scheduling and monitoring, similar to the solution proposed by Asefa et al. (2022), where a GIS model was used to optimize solid waste collection times and improve service predictability.

Inadequate solid waste collection coverage, especially in the outskirts of the municipality, was another major concern. Participants mentioned that these areas are frequently underserved, leading to the proliferation of illegal dumping sites. This observation aligns with Das et al. (2024), who reported that in developing regions, inconsistent coverage is a common challenge due to logistical constraints and lack of resources. Furthermore, participants highlighted improper segregation of solid waste at the source, which hindered recycling efforts. This challenge was echoed in the literature, where the need for community education and awareness on solid waste segregation was emphasized (Shabani et al., 2024). Participants recommended increased public awareness campaigns to promote better solid waste sorting practices.

Specific Needs and Requirements for the GIS Model

The focus group discussion also revealed several key needs and requirements for the proposed GIS model to address the existing solid waste management issues. Optimizing solid waste collection routes to minimize travel time and fuel consumption was identified as a top priority. This need corresponds with the findings of Vu et al. (2019), who demonstrated that route optimization through GIS technology could lead to significant cost savings and reduced environmental impact. Participants suggested that the GIS model should incorporate algorithms to calculate the most efficient routes based on traffic conditions, road accessibility, and vehicle capacity.

Ensuring comprehensive coverage of all regions, including underserved areas, was another critical requirement. Participants emphasized that the GIS model should facilitate equal service provision throughout the municipality. Real-time tracking of solid waste collection vehicles was also proposed as a way to enhance operational efficiency and transparency, ensuring that trucks adhere to their schedules and routes.

Participants stressed the importance of using the GIS model to collect data on solid waste generation patterns, which would enable better planning and resource allocation. This need aligns with findings from Kimwatu and Ndiritu (2016), who identified data on solid waste generation as a crucial factor in optimizing solid waste management processes. By integrating this data, the GIS model can support more effective sorting and recycling efforts, thereby enhancing overall system efficiency.

GIS Model Design Elements

The participants identified several essential components for the GIS model, which included real-time updates and tracking, mapping of solid waste collection points, and the integration of GPS and IoT sensors for precise location tracking. These features were deemed necessary for dynamic route adjustments and efficient monitoring of collection activities. Predictive analytics was also suggested as an integral part of the model, as it would allow the municipality to anticipate future solid waste management needs based on population growth and consumption patterns. This recommendation is supported by Awuah et al. (2021), who found that predictive analytics can significantly enhance the adaptability and resilience of solid waste management systems.

Data Sources and Information Needs

Participants identified solid waste generation rates, disposal site locations, and population data as critical inputs for the proposed GIS model. These data sources would allow for the development of tailored solid waste collection strategies for different neighborhoods. Accurate data on disposal site capacities and locations would also enable better management of solid waste processing infrastructure. This finding aligns with the views of Santos et al. (2024), who stressed the importance of integrating diverse data sources for effective GIS model development.

Sustainability and Environmental Impact

The focus group highlighted the potential of the GIS model to prioritize sustainability by optimizing collection routes to minimize fuel consumption and emissions. Participants also suggested using GIS to map recycling facilities, thereby improving access and encouraging recycling practices. Additionally, environmental monitoring of factors such as air and water quality was recommended to ensure that solid waste management activities do not negatively affect local ecosystems. These strategies are consistent with the recommendations of Dlamini et al. (2019), who emphasized the role of GIS in promoting environmentally sustainable solid waste management practices.

Participants Recommendations and Next Steps

To address the challenges identified, participants proposed several strategies, including continuous needs assessment, engaging local stakeholders throughout the design process, and conducting prototype testing in select areas before full-scale deployment. Training programs for GIS operation and data management were also recommended to build capacity among users. These recommendations mirror those of Nguyen and Khominich (2023), who argued that stakeholder engagement and capacity building are essential for the successful adoption of GIS technology.

Proposed GIS Model for Sustainable Municipal Solid Waste Management

The proposed Geographic Information Systems (GIS) model for Migori Municipality's solid waste management (MSWM) was designed to address the inefficiencies identified through interviews and focus group discussions (FGDs). A feasibility study conducted in the municipality highlighted major challenges, including inconsistent solid waste collection schedules, inadequate coverage, and poor infrastructure. The GIS model leverages geospatial data and predictive analytics to optimize solid waste collection routes, enhance operational efficiency, and promote sustainability. It integrates various modules that address the challenges identified in previous research and stakeholder consultations.

Problem Identification

The initial step in the GIS model is problem identification, where stakeholders, such as municipal authorities, environmental experts, and community representatives, collaborate to identify specific challenges within the existing solid waste management system. This step involves gathering input from diverse stakeholders to clearly define issues such as irregular solid waste collection and inadequate disposal practices. The problem identification module ensures that the GIS model is tailored to address the unique needs of Migori Municipality, as recommended by Awuah et al. (2021), who emphasized the importance of context-specific solutions in solid waste management.

Data Collection from Municipal Authorities

Accurate and comprehensive data collection is the backbone of the proposed GIS model. The module collects data on solid waste generation patterns, population density, collection routes, and disposal site locations, using multiple sources such as GPS data from collection trucks, community feedback, and historical records. This approach aligns with Kimwatu and Ndiritu (2016), who highlighted the need for reliable data to support effective GIS-based solid waste management. By integrating data from various sources, this module addresses concerns about data gaps and inconsistencies raised during the interviews and FGDs.

Expert Knowledge Acquisition and Consultation Environment

Expert knowledge acquisition is facilitated by consulting with waste management professionals, ICT specialists, and environmental scientists. This module incorporates expert insights into model design, ensuring that best practices and local conditions are factored into the system. The consultation environment serves as a collaborative platform where stakeholders analyse collected data through GIS maps and visualizations, making informed decisions. This process ensures that the model is based on a comprehensive understanding of data and expert input, as suggested by Shabani et al. (2024), who advocated for multi-stakeholder involvement in GIS planning.

GIS Data Mining and Knowledge Discovery

The data mining module uses advanced analytical tools to extract meaningful patterns and trends from the collected data. Spatial analysis and trend identification help uncover insights such as high solid waste generation areas and inefficiencies in collection routes. This information is essential for developing targeted interventions and optimizing solid waste management practices. The integration of data mining addresses concerns raised during FGDs about the need for better data utilization and analysis to support decision-making.

Sentiment Analysis and Community Engagement

Sentiment analysis assesses public opinion and attitudes towards solid waste management, using surveys, social media feedback, and community meetings. This module captures public sentiment, ensuring that the GIS model's recommendations are socially acceptable and sustainable. During FGDs, participants emphasized the importance of community engagement to increase compliance and support for solid waste management initiatives. This module aligns with findings from Nguyen and Khominich (2023), who noted that community involvement is crucial for the successful implementation of GIS-based solid waste management systems.

Optimization of Solid Waste Collection Routes

Optimizing solid waste collection routes is one of the core functionalities of the proposed GIS model. It leverages geospatial analysis and predictive analytics to design efficient routes, minimizing travel time and fuel consumption. The use of algorithms to calculate optimal routes based on road conditions, traffic patterns, and vehicle capacity addresses issues of inconsistent solid waste collection schedules identified in the interviews. This module is supported by the findings of Vu et al. (2019), who demonstrated the effectiveness of GIS in reducing operational costs through route optimization.

Predictive and Diagnostic Analytics

The predictive and diagnostic analytics module leverages machine learning algorithms to forecast future solid waste generation and identify inefficiencies in the current system. The models analyse historical data to predict trends in solid waste generation, while diagnostic tools identify areas for improvement, such as missed collections or vehicle breakdowns. This module incorporates feedback loops to refine and improve solid waste management practices continuously, ensuring that the system remains adaptable to changing conditions. The integration of machine learning and predictive analytics aligns with the recommendations of Das et al. (2024), who emphasized the potential of advanced technologies to enhance solid waste management efficiency.

Geospatial Data Analysis and Geo-mapping

Geospatial data analysis examines spatial relationships and patterns, using GIS tools to analyse factors such as population density, road networks, and land use patterns. Geo-mapping creates visual representations of solid waste collection points, disposal sites, and areas with high solid waste generation. This visual tool is essential for communicating complex data and facilitating informed decision-making. The use of geospatial analysis helps address the need for better visualization of solid waste management activities, as highlighted in the FGDs.

Sustainability and Environmental Impact Monitoring

The sustainability module integrates environmental monitoring of factors such as air and water quality, ensuring that solid waste management activities do not adversely impact local ecosystems. Real-time tracking of vehicle emissions and monitoring of disposal site activities help minimize environmental impact. This module's design reflects the emphasis placed on sustainability in the literature, particularly the findings of Santos et al. (2024), who noted the role of GIS in promoting environmentally sustainable solid waste management practices.

Validation and Continuous Improvement

The validation and continuous improvement module tests the GIS model in real-world scenarios, gathering feedback from stakeholders and making necessary adjustments. This iterative approach ensures that the model remains effective and sustainable over time. Regular updates based on new data and stakeholder input enable the system to adapt to changing conditions, ensuring long-term success.

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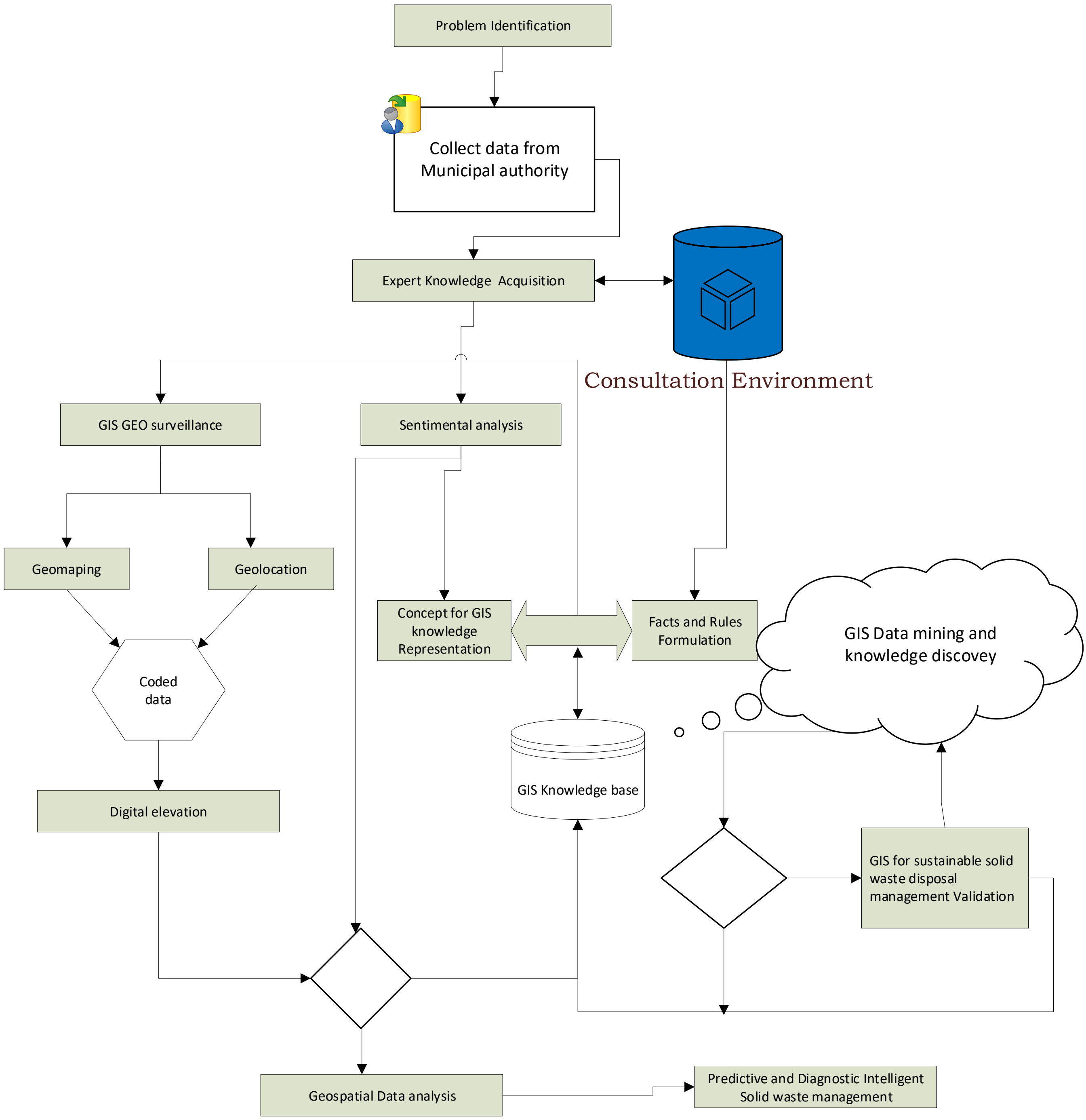

Figure 1: Proposed GIS Model for Sustainable Municipal Solid Waste Management

Source: (Researchers, 2024)

Conclusion

The study evaluated the implementation of a Geographic Information Systems (GIS) model for sustainable municipal solid waste management (MSWM) in Migori Municipality, by addressing the key challenges identified through comprehensive qualitative research. Findings from interviews and focus group discussions (FGDs) revealed significant inefficiencies in the existing solid waste management system, such as irregular collection schedules, poor infrastructure, and limited public awareness on solid waste segregation and recycling. These challenges contributed to environmental degradation and public health risks.

The proposed GIS model was designed to address these issues by leveraging geospatial data, predictive analytics, and community engagement. The model incorporates multiple modules to optimize solid waste collection routes, improve service coverage, and support data-driven decision-making. It utilizes advanced spatial analysis to identify high-priority areas for solid waste collection and disposal, ensuring equitable service provision across the municipality. The integration of predictive and diagnostic analytics enables the municipality to anticipate solid waste generation trends, optimize resource allocation, and enhance operational efficiency. The model's emphasis on community involvement and real-time monitoring also fosters greater transparency and stakeholder support, essential for long-term sustainability. By addressing both logistical and environmental challenges, the GIS model presents a comprehensive solution for achieving effective and sustainable MSWM in Migori Municipality.

Recommendations

Enhance Data Collection and Management: The accuracy and reliability of the GIS model depend on high-quality data. It is recommended that Migori Municipality invest in robust data collection systems, including the use of GPS tracking, IoT sensors for solid waste bins, and digital platforms for data entry. Regular updates and the integration of real-time data should be prioritized to ensure the model remains effective and responsive.

Build Capacity and Technical Expertise: The success of the GIS model relies heavily on skilled personnel. It is recommended that the municipality implement continuous training programs for staff involved in GIS operations. This should include technical training on geospatial analysis, data management, and the use of predictive analytics tools. Collaborations with academic institutions and technical experts could be explored to build capacity and enhance local expertise.

Promote Community Engagement and Awareness: Community involvement is crucial for the successful adoption of the GIS model. It is recommended that the municipality conduct public awareness campaigns to educate residents on the benefits of GIS technology and proper solid waste segregation practices. Establishing platforms for community feedback and participation can also improve compliance and support for the solid waste management initiatives.

Secure Financial and Institutional Support: Implementing and maintaining the GIS model requires substantial financial investment. The municipality should explore diverse funding opportunities, such as public-private partnerships, grants from national and international organizations, and cost-sharing arrangements with local businesses. Institutional support is equally critical; policies and regulatory frameworks should be developed to facilitate the integration of GIS in solid waste management and ensure adherence to best practices.

Implement a Phased Roll-Out Strategy: To mitigate the risks associated with large-scale implementation, a phased roll-out strategy is recommended. The municipality should start by piloting the GIS model in select areas before expanding it to the entire municipality. This approach will allow for adjustments based on real-world performance and provide a learning opportunity to refine the model before full-scale deployment.

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