Review of Application of Systems Engineering Approaches in Development of Integrated Solid Waste Management for a Smart City

V. R. Sankar Cheela and Brajesh Dubey

Abstract In the development of waste management systems in a smart city, systems planning and decision-making should include economic, environmental, and social sustainability indicators. Integrated solid waste management (ISWM) involves multiple operations by interconnecting a wide range of stakeholders. The constraints in decision-making process are posing a challenging task for the urban local bodies. Integration of the modern technologies and systems engineering approach provides a scope for synergizing the constraints, experts, and stakeholders. The output generated from this approach will provide better solutions for effective decision-making in an implementation of the solid waste systems for the development of smart sustainable cities. In this paper, three systems engineering approaches geographic information system (GIS), multi-criteria decision-making (MCDM), and life-cycle analysis (LCA) applications in solid waste management systems were reviewed. The holistic approach and framework for integrating these systems engineering approaches and technologies in development of ISWM for a smart city were presented.

Keywords Integrated solid waste management · Multi-criteria decision-making
Geographic information system · Life-cycle analysis
Spatial decision support systems

1 Introduction

The development activities in India are increasing to create solutions for better living. The economic, social, industrial, and environmental factors govern the progress of any development activity. Population densities, resource consumption, and economic activities increase in the cities due to urbanization and demographic transfers [1]. The initiatives of the Indian government such as Make in India, Smart Cities, Digital India,

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and Swachh Bharat Abhiyan (Clean India Mission) focus on transforming India into a developed nation [2]. The smart city initiatives are aimed to provide sustainable solutions to e-governance and citizen services, waste management, water management, energy management, urban mobility, capacity building, and skill development centers. The waste management component focuses on waste to energy and fuel, waste to compost, wastewater to be treated, recycling and reduction of construction and demolition (C&D) waste [3].

In India, 62 million tonnes of waste is being generated annually. The collection efficiency of the waste is about 70% of the generated waste. About 22–28% of the waste collected is being treated, and rest is dumped on open land [4]. In the annual report compiled by Central Pollution Control Board (CPCB), it is reported that 553 compost and vermicompost units, 56 bio-methanation plants, 22 RDF plants, and 13 wastes to energy plants have been set up by municipal authorities. CPCB has developed a National Action Plan for solid waste management in compliance with National Green Tribunal (NGT). This is a time-targeted approach in transforming a city, to make it clean and green. The report constituted an approach for both state- and city-level waste management [5].

To enhance the existing waste management practices, Government of India conglomerated policies and structure for solid waste management. They are entitled Solid Waste Management (SWM) Rules 2016. The rules emphasize roles and responsibilities of stakeholders, criteria for setting up solid waste treatment and processing facilities, waste to energy, and time frame for implementation. In comparison with Municipal SWM rules 2000, new rules include segregation at source, community-based segregation, development of composting or bio-methanation at the source, integration of informal sector, recycle or recovery of resources, development of buffer zones for disposal, treatment, and processing of waste, process mechanism for periodical reviews. The main emphasis of these rules accounts on roles and responsibilities of stakeholders, and criteria for setting up of solid waste treatment and processing facilities. Standards and specification for disposal and treatment units, preparation of integrated solid waste management (ISWM) plan, formulation of bylaws, capacity building, and awareness programs are included as schedules.

Material and energy flows, pollution reduction, resource recovery, and utilization define the behavior of urban production and consumption. Sustainability of a system is critically affected by the urban metabolisms due to interactions of material inflow and waste outflows [6]. The behavior of urban waste streams can be characterized by the relationship between anthropogenic urban activity, man-made networks, and natural processes [7]. Waste management systems should be handled through engineered perspectives linking information intensive platform to enable policymakers and stakeholders to develop ecologically and economically sound urban planning systems [8]. Pollution prevention, energy recovery, material, and ecological conservation magnify the importance of the application of systems approach in integrated solid waste management (ISWM) [9]. Application of systems engineering approaches enables the process to identify, analyze, and predict the relationship between resource use, human activities, and environment [10]. They provide a wide scope for the effective decision-making process to shape urban ISWM in a more smart and sustainable way [11]. In systems engineering approaches, spatial technologies, data handling, processing, and decision-making approaches are used for analyzing economic and environmental and social components. Spatial technologies facilitate capturing, processing, and communication of information to provide an innovative way of addressing the issue. Data acquisition, processing, transmission, and ability to handle large datasets using spatial technologies provide scope for the development of effective, efficient, automated, and intelligent solid waste management system [12].

This study aims to review the application of multi-criteria decision-making (MCDM), geographic information system (GIS), and life-cycle analysis (LCA) in solid waste management. This review provides an overview of the systems engineering approaches applications to develop a decision support tool in planning and designing an integrated solid waste management system for an urban local body.

2 Geographical Information Systems

GIS is a computer-based tool designed to store, organize, visualize, question, analyze, interpret, and display to understand the patterns and relationships of geographic and spatial data. Spatial and temporal analysis of real-world data can be modeled using GIS [13]. The definition of the GIS is more focused on technological approach and less toward decision-making process. For effective decision-making, non-spatial elements such as social, economic, cultural, and environmental datasets can be linked to spatial reference.

Spatial data acquired from different sources is entered into computer hardware system through digitization, entry of data by typing or scanning. Data available from the standard data sources and agencies can be used for developing the base files. The waste collection and bin location points, waste recycling, and treatment facilities of a given locality shall be updated through manual mode. The data collection is done based on the scope of the project for inclusion into the GIS interface. Administrative boundaries, demographics, road networks, land use patterns, facility locations, soil types, and hydrology layers are developed for creating the base map. The data developed is stored in the data management module as well as ensures the data integrity. The data retrieval, update and storage of the spatial data, and non-redundant data are organized and shared by different stakeholders. Spatial analysis, 3D analysis, spatial statistical analysis, and network analysis can be executed through retrieval, measurement, overlay, neighborhood, connective operations for analyzing the GIS data. Querying component enables the users to reach required geographic zones under the study. Data collection, digitization, and creation of base layers contribute to the development of the base map. Administrative boundaries, demographics, road networks, land use patterns, facility locations, soil types, and hydrology layers are used in creating the base map. Data inventory in the form of maps is developed for solid waste facilities including both spatial (location of bins, transfer station, recycling facilities, processing units, and landfill) and non-spatial elements (capacity, compacting abilities, volume, etc.). Map overlays and spatial allocation methods

Table 1 Applications of geographical information systems in solid waste management systems

Application	GIS	GPS	GPRS and GSM	RFID	Sensors and servers	RS	Location	Ref.
Collection systems	Yes	Yes	Yes	No	No	No	Vellore, India	[15]
	Yes	Yes	No	No	No	No	Pudong, China	[16]
SWM systems planning	Yes	Yes	No	No	No	No	Thailand	[17]
Route optimization	Yes	Yes	No	No	No	No	Pudong, China	[18]
	Yes	Yes	No	No	Yes	No	Trabzon, Turkey	[19]
Site selection	Yes	No	No	No	No	Yes	Mohammedia, Morocco	[20]
	Yes	No	No	No	No	Yes	Kolkata, India	[21]
	Yes	No	No	No	No	Yes	Nyahururu, Kenya	[22]
	Yes	No	No	No	No	Yes	Mysore, India	[23]
	Yes	No	No	No	No	Yes	Mafraq City, Jordan	[24]

GIS geographic information system; *GPS* global positioning system; *GPRS* general packet radio service; *GSM* global system for mobile communication; *RFID* radio frequency identification; *RS* remote sensing; *Ref.* reference

in GIS are applied for creating the suitability maps of the area under consideration [14]. Table 1 represents the applications of geographical information systems in solid waste management systems. Table 1 represents the applications of geographical information systems in solid waste management systems.

3 Multi-criteria Decision-Making

DSS is a computer-based information system designed to facilitate the better understanding of the components and process involved to improve the decision-making process. A model-based management system module in DSS consists of optimization, forecasting, and simulation models. This module equips the users to analyze and interpret the data. Site selection, regional planning, vehicle routing, and facility location are the major applications in SWM. In DSS process, an objective function is developed by using systems engineering models like linear programming (LP) and mixed integer programming (MIP) models. Then, the multi-criteria decision-making (MCDM) approaches are used for analyzing the data.

Multi-criteria decision-making is a branch of operations research that is capable of addressing complex problems featuring high uncertainty, multi-interests, and large data forms. The expectations of the decision-makers and other constraints are considered to identify and decide the alternatives. Alternatives are identified and evaluated against a set of attributes/constraints which are hard to quantify to develop the efficient solution. In MCDM, criteria are selected in a coherent, measurable, and independent manner. Based on the criteria, available, comparable, feasible, and practical alternatives are selected. Analytical hierarchy process (AHP), elimination and choice expressing reality (ELECTRE), preference ranking organization method for enrichment of evaluations (PROMETHEUS), fuzzy multi-criteria decision-making process (FMCDM), etc., are commonly used methods for performing MCDM. Pairwise comparison of the multiple criteria and multi-level hierarchical structure is applied to determine the relative weights for each alternative. The best alternative will be chosen using the method of aggregation.

MCDM methods provide a better scope for developing the criteria and alternatives by considering the experience and expert opinions for different stakeholders. Scenarios are assessed using both qualitative and quantitative criteria involving the participation of decision-makers of diverse thought processes in defining the indicators. The method is flexible for expanding the model from single to multiple decision-making models. Assigning the weights for each criterion includes the point of views of all the stakeholders. The results obtained by application of the different MCDM models may differ in prioritization, but the top alternatives remain constant with variation in the priorities. The scope for development of waste minimization, prevention, and management plans using MCDM analysis is limited. Evaluation analysis is subjected to variation with the addition and deletion of the criteria and the assignment of weights. Figure 1 represents the model of MCDM framework for selection of waste disposal facility in an urban local body.

4 Spatial Decision Support System

Spatial Decision Support System (SDSS) is an interactive, computer-based system designed to support stakeholders to achieve efficacy in decision-making. This combines conventional data, spatially referenced data, and decision logic for problem-solving and situational analysis. This support system provides a user-friendly interface to communicate, analyze, and process data among the stakeholders. GIS and MCDA are integrated to develop decision support system in a systematic approach to perform an extensive evaluation for making effective decisions. The applications of SDSS include natural resources management, health care, solid waste management, emergency management, water resources management, disaster management, tourism facility planning. In ISWM, applications of SDSS include solid waste systems planning, policy evaluation, collection route optimization, facility location and allocation problems, site selection for waste processing and disposal units, transfer stations, transportation problems, and waste systems planning.

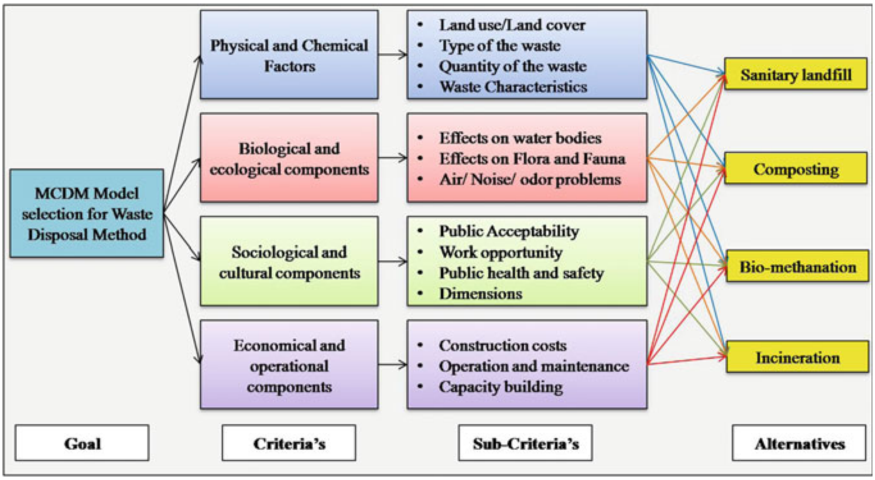

Fig. 1 Multi-criteria decision-making framework for selection of waste disposal facility in an urban local body

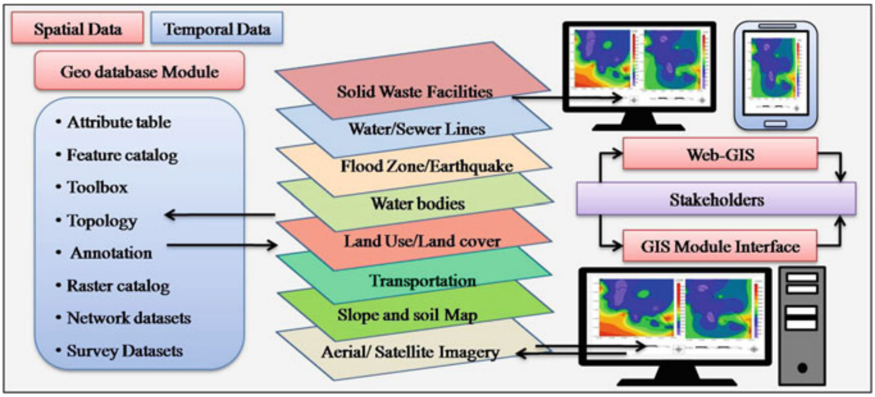

Fig. 2 Architecture of GIS and Web GIS-based spatial decision support systems

The GIS-based SDSSs have often been criticized for not providing tools for involving public participation factor. The GIS is successful in terms of the software and computing hardware. Due to the closed, synchronous, and place-based nature, public participation in community-based GIS-based projects was limited. This was addressed by introducing decision support tools that are accessible to stakeholders. Web-based SDSS, collaborative and participatory GIS technologies are designed for supporting decision-makers and other stakeholders. Figure 2 represents the architecture of GIS and Web GIS-based spatial decision support systems.

Application of GIS and MCDM approaches provides a better solution for site selection, location of collection and recycling points, and systems planning. Initial screening was performed by researchers by developing land use maps for potentially suitable areas using GIS. The selection of the most suitable site was performed by developing priorities for evaluation and weighting of criteria using MCDM. Table 2 presents the application of spatial decision support systems in solid waste management systems.

5 Spatial Decision Support Systems Framework

The GIS operations in combination with MCDA methods and techniques resolved the problem of integrating stakeholders and computing techniques for better decision-making. This combination is capable of addressing, handling, and diminishing disagreements over facts, values among the stakeholders. The output is developed in the form of maps and other graphic displays by combining geographic data and the decision-maker's preferences, facilitating the end users for better interpretation and analysis of the data.

In Fig. 3, model framework for integration of GIS with MCDM is represented, in which the GIS application is integrated into the development of the criteria an evaluation of the alternatives. The decision-makers during the evaluation process can visualize the complete scenario through the maps developed. The module of a spatial query, buffer zone development provide the scope to understand the impact zones. The flood hazard plains, special economic zones, water bodies, disaster-prone zones, and national importance projects can be understood during a selection of final alternatives. The role of GIS in development of pair-wise matrix and weighting procedure is deficient. The best alternative selection is dependent on the effectiveness of the weights developed. To equip this component, the researchers have applied the results obtained from LCA for pair-wise comparison and development of weights.

6 Life-Cycle Analysis

The environmental interventions and potential impacts throughout a product's life study using environmental life-cycle analysis (LCA) as per International Organization for Standardization norms. The energy, materials used, and emissions released to the environment are used as inputs in LCA to assess the environmental burdens associated with a product or process. Human, health, ecological considerations, resource, and energy utilization factors are considered in determining the environmental impacts. The goal of LCA is to be decided initially based on the need and expected outcomes of the study. Development of the system boundary determines the scope of LCA. Based on the scope of the study, alternatives termed as scenarios are formulated. The functional unit is determined to for the LCA process so as to have a uniform platform to determine environmental impacts of the scenarios under consideration. Data inventory analysis is performed to determine the flow of energy,

Table 2 Application of spatial decision support systems in solid waste management systems

Application	Optimization method	GIS software	Location	Ref.
SWMP	MOMIP; MCDM	Yes	General	[25]
	MILP	Yes	Tehran, Iran	[26]
	MCA	No	Naples, Italy	[27]
	MINLP	No	Mexico	[28]
	MCDM	No	Bosnia and Herzegovina	[29]
	MILP	No	Hong Kong	[30]
	Funnel cost model	Yes	Parkland County, Canada	[31]
	NIL	Yes	Shenzhen City, China	[32]
	MILP	Yes	Coimbra City, Portugal	[33]
SWCT	MILP and ABM	Yes	Vietnam	[34]
	AHP	No	Da Nang City, Vietnam	[35]
	BILP and MILP	No	Campo Mourão, Brazil	[36]
	TSP and ABM	Yes	Kolkata, India	[37]
	GARP	Yes	Morelia, Mexico	[38]
	AHP	Yes	Davanagere, India	[39]
	HA and DA	Yes	Kampala, Uganda	[40]
	NIL	Yes	Ipoh City, Malaysia	[41]
RSW	MILP	Yes	Cogoleto, Italy	[42]
	IP	Yes	Taichung, Taiwan	[43]
	ANP	No	Area of Valencia, Spain	[44]
	NIL	Yes	Madrid, Spain	[45]
LSSA	Boolean technique	Yes	Victoria, Australia	[46]
	MCDA	Yes	Birjand, Iran	[47]
	AHP	Yes	Thrace region	[48]
	NIL	Yes	Bahir Dar Town, Ethiopia	[49]

(continued)

Table 2 (continued)

Application	Optimization method	GIS software	Location	Ref.
	MCDA	Yes	Bo, Sierra Leone	[50]
	MCDA	Yes	Polog, Macedonia	[51]
	MCDM	Yes	Province of Torino, Italy	[52]
	MCA	Yes	Konya, Turkey	[53]
	AHP	Yes	Karaj, Iran	[54]
	AHP	Yes	Beijing, China	[55]
	MCDA	Yes	Pondicherry, India	[56]
	Boolean technique	Yes	Cuitzeo Lake Basin, Mexico	[57]
	AHP	Yes	Jiroft City, Iran	[58]
HSSA	MCDA	Yes	Province of Avellino, Italy	[59]
	No	Yes	Qazvin Province, Iran	[60]
	MCDA	Yes	Kurdistan Province, Iran	[61]
	MCDM	Yes	Anatolian region, Turkey	[62]
	Nil	Yes	Turkey	[63]
TSSA	MCDA	Yes	Kilifi County, Kenya	[14]
	AHP	Yes	Santiago Island, Cape Verde	[64]
	AHP	Yes	Province of Avellino, Italy	[65]

ABM agent-based model; *AHP* analytical hierarchy process; *ANP* analytical network process; *BILP* binary integer linear programming; *CVM* contingent valuation method; *DA* deterministic approach; *FMCD* fuzzy multi-criteria decision-making; *GARP* genetic algorithm for rule-set production; *HA* heuristic approach; *HSSA* hazardous landfill site suitability analysis; *IP* integer programming; *LSSA* landfill site suitability analysis; *MCA* multi-criteria analysis; *MCDA* multi-criteria decision analysis; *MCDM* multi-criteria decision-making; *MILP* mixed integer linear programming; *MINLP* mixed integer nonlinear programming; *MOMIP* multi-objective mixed integer programming; *RSW* recycling of solid waste; *SWCT* solid waste collection and transportation; *SWMP* solid waste management planning; *TSP* traveling salesman problem; *TSSA* treatment plant site suitability analysis

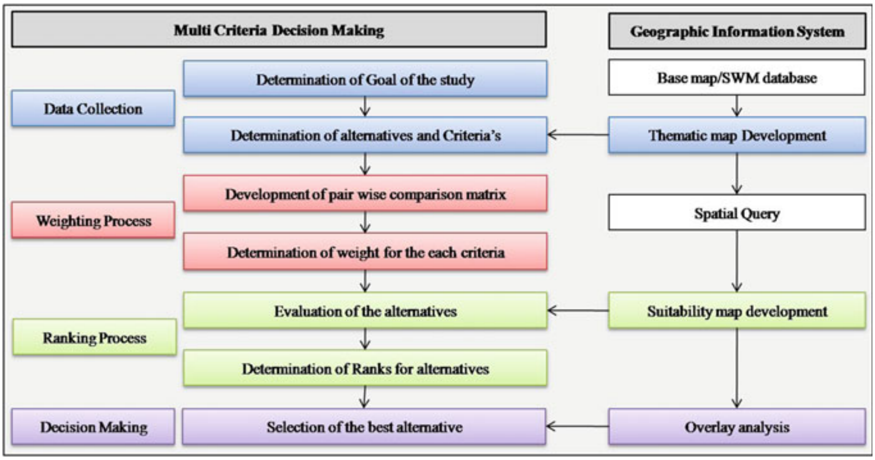

Fig. 3 Model frameworks for integration of GIS with MCDM

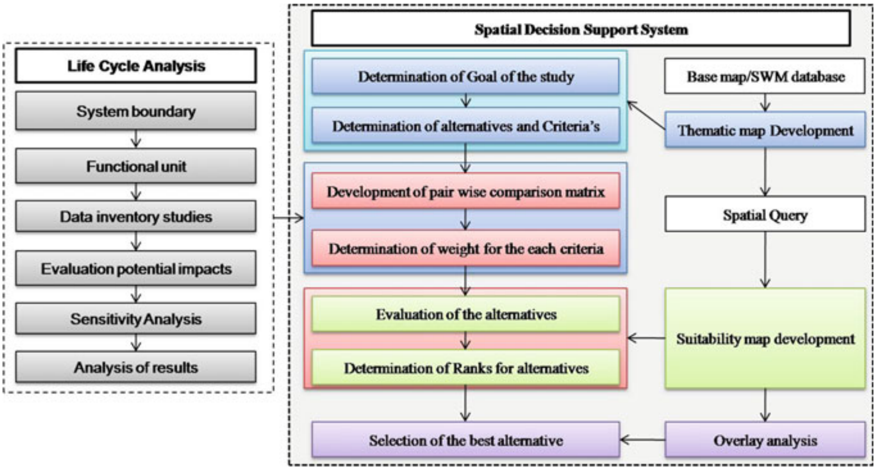

Fig. 4 Model frameworks for integration of LCA and SDSS

materials, and emissions across the system boundary. Material and energy mass balance are developed to understand the environmental interventions. The potential impacts and an environmental burden are determined and assessed using systematic analysis of the inventory data.

In Fig. 4, model framework for integration of LCA with SDSS is represented. The environmental burdens determined using LCA study are inputted in the SDSS for the development of the pair-wise matrices and weighting criteria. During the evaluation of alternatives in SDSS, alternatives with minimum environmental impact can be assessed using the weights developed from LCA study. The combination of different scenarios can be performed, and the cumulative weight factor can be assessed. The sensitivity analysis component in LCA process enables us to assess the impacts of site-specific data.

LCA is being widely applied in decision-making and strategy planning of integrated solid waste management systems. Computer-aided tool following a hybrid approach by combining equations for inventory analysis and expert inputs in assessment and characterization of impacts is being applied by the authors in their studies. The components of the solid waste management design varied from location to location in characteristics of the waste, disposal options, treatment methods, and market for derived products. Potential management plans and improvements are identified by assessing the alternative options including economic, technical aspects. The LCA methodology provided a scope for an involvement of public and private actors in determining the best solution. Table 3 presents the applications of LCA in solid waste management systems. It presents the geographical location, functional unit, number of scenarios considered, impacts studied, and sensitivity analysis application. The impacts studies are classified into non-toxic, toxic, resources, and energy classes.

7 Summary and Conclusion

In a smart city, the waste management systems should be designed to reduce the stress on the environment. The systems should be planned, designed, optimized, and implemented to ensure the development of sustainable waste management systems. These include a holistic, comprehensive, and interdisciplinary framework synergizing technical, economic, and social components, stakeholders, and timescales. Collaborative planning, infrastructure development, capacity building, database management, and implementation play a vital role in building an integrated waste management system. A systems engineering framework combining SDSS and LCA provides a multidisciplinary approach for the urban planners. The development of the systems based on the site-specific process including spatial and temporal components will enhance sustainability. The integration of this framework and information and communication technologies (ICTs) provides a rationale for the policy- and decision-makers and urban local bodies to develop a smart waste management system. Figure 5 presents a framework for developing ISWM in a smart city by integrating SDSS, LCA, ICT and IoT components.

The evaluation of digital applications and application of a wide range of ICT tools provided a scope for advancements in database management and information transfer systems. The Internet of things (IoT) applications increased the managerial and behavioral potential in developing effective management systems in urban areas. Interactive communication and information exchange are an added advantage for effective planning. The applications of ICT in solid waste management can be enhanced by combining decision support systems, expert, and knowledge-based systems. The performance of the waste management systems can be evaluated by the

Table 3 Applications of life-cycle analysis in solid waste management systems

Geographical features	Functional unit	Scenarios studied	Sensitivity analysis	Studied impacts				Ref.
				Non-toxic	Toxic	Resources	Energy	
Hangzhou, China	Waste produced in a year	5	Yes	PC	PC	CC	NC	[66]
Naples, Italy		6	Yes	PC	PC	CC	NC	[67]
UK		4	No	PC	PC	NC	NC	[68]
London		10	Yes	PC	NC	CC	NC	[11]
Asturias, Spain		6	No	PC	PC	CC	NC	[69]
Tianjin City, Beijing		7	Yes	PC	PC	CC	CC	[70]
Sakarya, Turkey	1 t of MSW	5	No	CC	CC	CC	NC	[71]
Italy		4	Yes	Only GW	NC	CC	CC	[72]
Iran		5	Yes	PC	PC	CC		[73]
Thailand		5	No	CC	PC	CC	NC	[74]
Indonesia		5	Yes	PC	NC	NC	NC	[75]

(continued)

Table 3 (continued)

Geographical features	Functional unit	Scenarios studied	Sensitivity analysis	Studied impacts				Ref.
				Non-toxic	Toxic	Resources	Energy	
South Korea		4	No	CC	PC	CC	NC	[76]
China		4	Yes	CC	PC	CC	CC	[77]
Turkey		5	Yes	PC	PC	PC	NC	[78]
Denmark	1 t of wet household waste	7	No	CC	PC	NC	NC	[79]
Italy	1 t of OF	2	Yes	PC	PC	CC	NC	[80]
UK	101 kt of MSW	4	No	PC	NC	NC	CC	[81]

Non-toxic impact categories: global warming; ozone layer depletion; acidification; eutrophication
Toxic impact categories: ototoxicity; human toxicity; particulate matters; aquatic toxicity; terrestrial eco toxicity
Resources: Abiotic depletion potential
CC complete coverage; *PC* partial coverage; *NC* no coverage

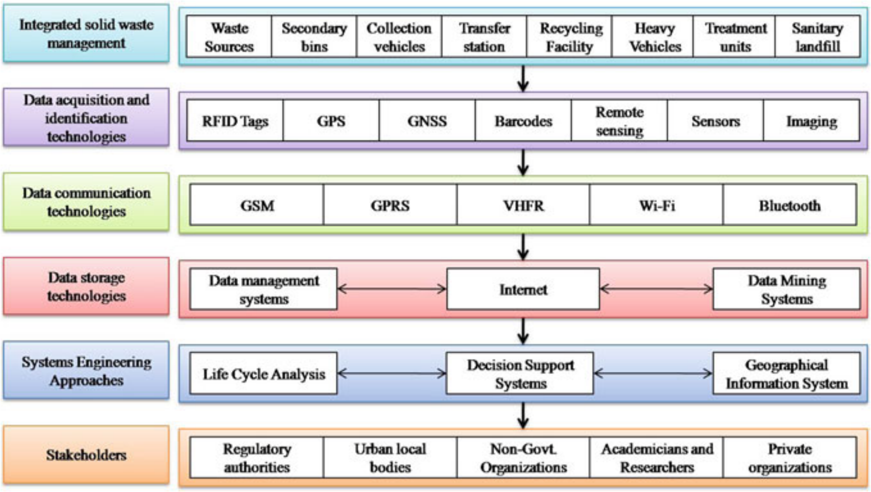

Fig. 5 Framework for developing ISWM in a smart city

local authorities through scientific analysis of the outcomes achieved by the application of these systems.

The mobility behavior of the vehicles plays a vital role in the design of the collection and transport systems. Dynamic interactive pattern modeling and prediction of the vehicle movements explore new dimensions for developing smart, sustainable, efficient, and effective waste collection and transport systems. Vehicle space–time interactions are developed from the trajectories of data acquisition and navigation instruments. The application of spatial and non-spatial technologies for data acquisition and identification generates digital information. Development of space–time database for the waste management enables the urban local bodies to design, optimize, and implement an effective waste management services.

Data communication systems development provided scope for quick transmission of data instantly to the remote areas. Rapid developments in the area of communication technologies developed opportunities to share and explore new dimensions in waste management. Communication protocols and wide area network (WAN) based on the leased line, switching logic, and cell relay are being handled by the Internet. The remote communications are being performed by the Internet using wireless, copper wire and fiber-optic access technologies. Short-range communication system is being applied for automatic data acquisition and interchange of instruction. Global system for mobile communication (GSM), general packet radio service (GPRS), and very high-frequency radio (VHFR) for long-range applications and wireless fidelity (Wi-Fi), Zigbee, and Bluetooth for short-range communication are being applied in SWM applications. The integration of SDSS and LCA with applications of ICT and Internet of things (IoT) for developing a smart city presents an overall structure for the decision-making, executing, and operation of the SWM systems.

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