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Review

A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges

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A B S T R A C T

In the backdrop of prompt advancement, information and communication technology (ICT) has become an inevitable part to plan and design of modern solid waste management (SWM) systems. This study presents a critical review of the existing ICTs and their usage in SWM systems to unfold the issues and challenges towards using integrated technologies based system. To plan, monitor, collect and manage solid waste, the ICTs are divided into four categories such as spatial technologies, identification technologies, data acquisition technologies and data communication technologies. The ICT based SWM systems classified in this paper are based on the first three technologies while the forth one is employed by almost every systems. This review may guide the reader about the basics of available ICTs and their application in SWM to facilitate the search for planning and design of a sustainable new system.

Contents

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1. Introduction

With the rapid footsteps toward urban future by the modern world, the volume of municipal solid waste (MSW), major by-products of urban lifestyle, is mounting even faster than the degree of urbanization. The global production of MSW is about 1.3 billion tonnes/year i.e. 1.2 kg/capita/day. Ten years ago, waste generation rate was about 0.64 kg/capita/day i.e. 0.68 billion tonnes/year. The solid waste generation will be 1.42 kg/capita/day i.e. 2.2 billion tonnes/year from 4.3 billion of urban residents by the year 2025 (The World Bank, 2012). Table 1 shows the urban population and MSW generation rate for the year 2012 and 2025 (estimated data) of 161 countries of different 7 regions in the world (The World Bank, 2012).

Solid waste management (SWM), is the one thing just about each municipality delivers for its habitants which is perhaps the most significant municipal service and a prerequisite for other complicated municipal services like health, transportation or education (Rajendran et al., 2013). For the municipalities, the difficulties as well as challenges of SWM are continuously increasing due to this urbanization (Cheng and Hu, 2010). Now it becomes an urgent priority for the authorities responsible for SWM to improve their services, particularly in low and middle income countries (The World Bank, 2012). The overall target of SWM is to monitor, collect, treat, and dispose solid wastes generated by the population groups, in a cost effectively, environmentally and socially satisfactory manner. Municipalities are facing problem with solid waste route optimization for collection that has various effects on collection efficiency, cost and pollutant emissions. There are many researches on optimization problems such as vehicle routing problem, capacitated vehicle routing problem and vehicle routing problem with time windows have been studied to reduce cost, less emission, serve customers and depot through optimized route (Johansson, 2006; Nuortio et al., 2006; Faccio et al., 2011). However, most of the researches considered static data rather than real time dynamic data for optimization. To address the above problems, local governments are usually authorized to manage MSW and their laws give them exclusive rights over waste once it has been placed outside. To handle the increasing problems in SWM, ICTs are becoming more significant due to the growing necessities for automated data acquisition, identification, communication, storage and analysis in connection with swift and parallel computing. But, systems that are not using ICTs pose various limitations in terms of site selection, collection monitoring, intelligent recycling, inefficient waste disposal etc. ICTs can help to overcome these challenges to make a sound SWM system (Johansson, 2006; Mcleod et al., 2013; The World Bank, 2012).

Information and communication technologies (ICT) are generally known as technologies that facilitate capturing, processing and communication of information (OECD, 2003). ICTs provide an innovative way to address SWM issues because of their unrivalled capacity to offer the access to information instantly from remote location at a comparatively low cost (Lu et al., 2013). An obvious motivation on using ICTs in accomplishment of comprehensive SWM goals could allow municipalities to attain more sustainable cities. To encounter the aims of automated and intelligent SWM system, ICTs are becoming more vital due to the growing requirements of acquiring, transmission as well as analysis of huge data along with speedy computational capability. Advancement in MEMS technologies boost the development of modern ICTs during the last few decades (Lyshevski, 2013), that contributes to design and establishment of more and more efficient system for SWM. Though ICTs can face with various environmental problems by combining hardware and software applications (Vassilas et al., 2001), there are some challenges that the developing world is facing and these make the 'Digital Divide' continue. The barriers of adopting ICT based systems are mainly the lack of financial resources, poor access to the internet, shortage of skilled human capital and lack of proper policy (Aleke et al., 2011; Ndou, 2004).

So far, various researches have been showed that ICTs can help handle different types of SWM related issues with a more efficient manner in terms of cost, time, risk and environment (Lu et al. 2013). In the past, the overall SWM system was manual, hence there was no exact information about waste generation and collection which led to an unplanned management. As a result site selection for trash bins, collection point, disposal point or recycling station were accomplished without proper planning. In addition, waste collection was conducted without perceiving or analyzing demand and the drivers were responsible to construct travelling routes for waste collection (Beliën et al., 2012). It cause inefficient collection as trash bins may be empty or overflow. Sometimes the resulting disturbed waste become apparent as more costly in terms

Table 1
Urban population and MSW generation rate of different regions of the globe for 2012 and 2025 (estimated).

Region	No. of countries included	2012		2025 (Projections)	
		Urban population (millions)	Urban MSW generation (kg/capita/day)	Urban population (millions)	Urban MSW generation (kg/capita/day)
Africa	42	261	0.65	518	0.85
East Asia and Pacific	17	777	0.95	1,230	1.52
Europe and Central Asia	19	227	1.12	240	1.48
Latin America and the Caribbean	33	400	1.09	466	1.56
Middle East and North Africa	16	162	1.07	257	1.43
Organization for Economic Co-operation and Development (OECD)	27	729	2.15	842	2.07
South Asia	7	426	0.45	734	0.77

of re-collection effort and environmental threat (The World Bank, 2012). Urban areas, however, continue to expand and the significance of efficient SWM system is increasing. ICTs are tools that tries to exhaust the possibilities of developing accepted solution. However, this is tough to comprehend, which combination of technologies will provide the best solution for an efficient SWM system.

Till now many systems have been proposed to settle associated issues and maximize waste management efficiency. In this study, the systems that are widely used can be categorized in three groups such as, (i) spatial technologies based systems which are founded by using graphical information system (GIS) and/or global position system (GPS) or remote sensing (RS) as main technology. SWM operators adopt this systems to monitor the location of trash bins and collection vehicles during collection (Wilson et al., 2007; Yang et al., 2008; Zamorano et al., 2009). (ii) Identification technologies based systems where barcode or radio frequency identification (RFID) tags are installed with trash bins for tracking identification to determine their location and to acquire the time of collection (Chowdhury and Chowdhury, 2007; Friedlos, 2005; Greengard, 2010; Kietzmann, 2008). (iii) Data acquisition technologies based systems that contain several sensory elements installed inside trash bins such as image sensor, distance sensor, volumetric sensor etc. to observer its status (Rovetta et al., 2009; Johansson, 2006). And (iv) data communication technologies that are normally used in all previous three kinds of system to facilitate the transmission of captured or analyzed data.

There are some intelligent systems also studied based on fuzzy parametric modeling, fuzzy stochastic programming and fuzzy chance-constrained mixed-integer programming to demonstrate the applicability, tackle uncertainty and provide decision to the waste manager on trade-offs between system economy, reliability and constraint violation under complex uncertainty (Srivastava and Nema, 2012; Wang et al., 2012; Xu et al., 2014). Thus, an automated and intelligent SWM system can reduce the management costs, time, effort and emissions (Rada et al., 2013; Shahmoradi, 2013; Tavares et al., 2009). With the advancements in sensing and communication technologies, real time monitoring of trash bin has become more viable and accessible (Nuortio et al., 2006). The motivation for using various sensors and wireless sensor network (WSN) with combination of short range and long range communication technologies lies in the ability of these technologies to provide municipalities with information about bin status.

The purpose of this study is to give direction to the reader by presenting an in-depth discussion of available ICTs applied to municipal SWM along with the available literature where the ICTs are used to solve SWM problems. The classifications in this review make it possible to select the proper ICTs or combination of ICTs for a particular problem specific solution. If one is, for example, interested in a solution for site selection, collection vehicle monitoring or planning waste collection vehicle routing, an ICT or combination of ICTs that fit those requirement can be easily chosen. Finally, the challenges and issues are mentioned to guide for future system development.

2. ICTs and their usage in SWM systems

ICTs have experienced remarkably rapid improvement in the past few decades. To handle the increasing problems in SWM, ICTs are becoming more significant due to the growing necessities for automated data acquisition, identification, communication, storage and analysis in connection with swift and parallel computing. The relevant ICTs and techniques differ depending on the research aims and in many cases, the roles of these ICTs have been limited to stand-alone applications without cooperative effects.

With regard to monitoring, collecting, transporting, treating and managing, the spectrum of ICTs for SWM can be classified into four categories: spatial technologies, identification technologies, data acquisition technologies and data communication technologies as shown in Table 2. The SWM systems that are fabricated by using technology are mainly implemented based on the first three categories such as systems based on spatial technologies, systems based on identification technologies and systems based on data acquisition technologies. The data communication technologies are used in all three types of systems. Although most of the existing systems were developed by combining two or more categories, the classification made in this study is mainly based on the technology that focused more on that system. Brief descriptions about the ICTs and their usage in solid waste monitoring, collection and overall management are discussed in the following sections.

3. Spatial technologies for SWM system

Spatial technologies are the most widely used ICTs in environmental modeling, as spatial analysis is very important for many environmental studies. These technologies are effective to handle complex spatial information and to provide platforms for the integration of various models, interfaces and sub-systems as well. Spatial technologies are classified in three main types such as geographic information systems (GIS), global positioning system (GPS) and remote sensing (RS) (Milla et al., 2005). The major functions of this type of technology include the capturing, storing, analyzing and mapping of spatial data. The contents of a spatial dataset may contains attribute data, spatial topology, raster, features and even network datasets. With the development of modern spatial technologies in current years, new tools and possibilities has aroused to use this technique in many areas. The following

Table 2
Various ICTs and their application in SWM.

ICT classification	ICT Sub-Class	Applications
Spatial Technologies	GIS	Site selection; planning; management; estimation; optimization
	GPS	Route and collection optimization; vehicle tracking; planning; scheduling; billing
	RS	Site selection; environmental impact assessment; features monitoring
Identification Technologies	Barcode	Intelligent recycling; waste disposal; reduce landfill space; risk management
	RFID	Bin and driver tracking; optimization; sorting and recycling
Data Acquisition Technologies	Sensors	Sorting; optimization; moisture; energy and odor measurement; scheduling
	Imaging	Waste sorting; route and collection optimization; monitoring
Data Communication Technologies	GSM/GPRS	Long range communication
	ZigBee	Short range communication
	Wi-Fi	Short range communication
	Bluetooth	Short range communication
	VHFR	Long range communication

sub-sections briefly describe the three types of spatial technologies, their applications in SWM systems and their deficiencies.

3.1. Geographical information system (GIS)

GIS, one of the most sophisticated spatial technology, is a computer based information system that is able to collect, store, manage, integrate, manipulate, analyze and display of spatial data known as geospatial or geographically referenced data. Usually, these data are arranged into thematic layers by forming digital maps, where the power of GIS systems lies. Analyzing data visually helps in identifying patterns, trends, and relationships that might not be visible in tabular or written form (Basagaoglu et al., 1997).

Normally, a GIS has four classes of components such as production of spatial data, management of data, cartography and display, and analysis of data (Lu et al., 2013). The production of spatial data includes data capture, quality inspection, input data and format conversion. In GIS, the spatial data may take two formats such as vector data or raster data. In vector data format, all vector characteristics are referenced to the same coordinate and maps are made of points, lines or polygons (Sanchez-Hernandez et al., 2007). In raster data format, the maps are made of as group of grid cells with each cell having a color value for presenting what lies where that cell is (Bishop et al., 2000).

The use of GIS in combination with other spatial and communication technologies assists to capture, communicate and analyze spatial data for planning and designing various applications. It is successfully used in applications, such as SWM, urban utilities planning, natural resources management, transportation, forestry, natural disasters prevention, geology and in many aspects of environmental modelling (Clarke, 1997). In (Zsigraiova et al., 2013), the authors have proposed a novel dynamic scheduling and routing model incorporating GIS which reduce the operation costs and pollutant emissions of MSW collection in Barreiro, Portugal. The paper presents an innovative methodology for the reduction of the operational costs and pollutant emissions involved in the waste collection and transportation. It is combined dynamic scheduling and routing for efficient waste collection. The optimization process of the traversed routes incorporates a GIS and uses total spend time and covered distance as optimization criteria. The model also considers variables related to fuel consumption, pollutant emissions, truck speed and capacity transported as part of the optimization process. Experimental evaluation is performed for the case of glass waste collection and transportation. The strengths of the system is the incorporation of GIS and the advanced dynamic scheduling and routing models. However, the system exploits data only from limited data acquisition devices. Moreover, it was usable only for the specific type of glass waste bin.

Table 3 presents a summary of SWM systems that are based on GIS technology. The table is organized in chronological order that highlights GIS technology is used widely in various aspects of SWM systems. As presented in the table, the most widespread use of GIS on SWM lies in the areas of site selection for landfill, trash bin and transfer stations (Chang and Lin, 1997; Kao, 1996; Kao and Lin, 2002; Lotfi et al., 2007; Sener et al., 2011; Tralhão et al., 2010; Vijay et al., 2008) and routing and scheduling optimization based on historical or predicted data (Fan et al., 2010; Ghose et al., 2006; Jovičić et al., 2010; Kanchanabhan et al., 2011; Ozkan et al., 2006; Tavares et al., 2009). Others applications of GIS in SWM includes waste generation estimation by using socioeconomic data and local demographic (Ahmed et al., 2006; Karadimas and Loumos, 2008; Marah and Novotny, 2011), local management planning (Hrebicek and Soukopova, 2010; Macdonald, 1996), integrated SWM establishment (Karadimas et al., 2004; Tao, 2010) and risk assessment (Lo Porto et al., 1997; Rajkumar et al., 2010).

3.2. Geographical positioning system (GPS)

GPS is a global navigation and localization system based on a constellation of multiple satellites and ground stations that are placed by the United States' Defense department into the orbit. Although the intention to develop the GPS was for military use, later the U.S. government opened it for civilian also. From that time, GPS has been used widely for numerous civilian applications on the land, sea and in air. The GPS system is divided into three sub-systems like space sub-system (the satellites), control sub-system (the ground stations) and user sub-system (GPS receivers). The space sub-system contains 24 satellites that are functioning from 12,000 miles upon the Earth's surface (Kumar and Moore, 2002). These satellites are organized such a way, so that, GPS receiver from any place on earth can receive signals at any given time form as a minimum of four satellites. The satellites transmit radio signals with low power and require line-of-sight (Elena et al., 2002). The satellites are controlled by the control sub-system and provides accurate orbital and time information (Zhao, 2002). There have five stations, situated around the world. The user sub-system is every individual user with GPS who can make queries about his/her spatial information (Arvanitis et al., 2000).

The use of GPS in combination with other spatial and communication technologies especially with GIS assists to track collection vehicles and trash bins for observing location and collection time. It is effectively used with numerous SWM systems to confirm activities run smoothly while decrease costs and successfully manage vehicles and employees. In (Faccio et al., 2011), the authors have developed a framework that focuses on GPS and other traceability technology for the optimization of solid waste collection in terms of route and cost. Bins installed with sensing technologies and vehicle installed with GPS receiver, RFID receiver, weighing system, GPRS module and a mobile laptop with vehicle traceability software application. Remote server contains DB and GUI. Data from bins and truck location are collected by the control server parses from GPRS/GPS network. The central DB contains bin position and local map that are accessed by the GIS subsystem and the routing sub-modules. The strengths of the system are the well-defined framework for enabling traceability and monitoring as well as the proposed dynamic scheduling and routing models. However, it does not support a wireless sensor network for further fusion of the sensor data and GPRS in every bins which increase the operation costs.

Table 4 presents a summary of SWM systems in chronological order that are mainly focused on GPS technology. As shown in the table, GPS based SWM system is primarily used in collection vehicle tracking to measure the time, delayed by the vehicles in waste transfer stations (Lee and Thomas, 2004; O'connor, 2008; Wilson et al., 2007). Others applications of GPS in SWM focused on route optimization based on static data (Alam Flora, 2009; Minghua et al., 2009; Nielsen et al., 2010), collection monitoring (Arebey et al., 2011; Purohit and Bothale, 2011) and implementation of efficient billing (Swedberg, 2009).

3.3. Remote sensing (RS)

RS normally denotes to the modernized use of aerial sensing technologies for detecting and classifying objects on earth surface from a remote platform via signal propagation like electromagnetic radiation from satellites or aircraft (Schowengerdt, 2007). In RS, the collected electromagnetic radiation is processed into a digital image which can be overlaid with another spatial data. Usually, a bundle of RS devices contains sensors, data communication tools, image processing tools along with a working platform.

Table 3
Summary of SWM systems based on GIS technology.

References	Target application	Methodology	Functional domain
(Muttiah et al., 1996)	Site selection	Simulated annealing based on Markov-chain	Execution time reduction for disposal site selection
(Kao, 1996)	Site selection	GIS Spatial analysis and raster-based branch-bound algorithm	Landfill site location selection by considering land compactness
(Macdonald, 1996)	Local planning for SWM	GIS spatial analysis and development with multi-criteria	Decision making for local SWM planning
(Basagaoglu et al., 1997)	Site selection	GIS based on 3D analysis and investigation	Waste disposal sites screening considering their storage capacity
(Mcleod et al., 1997)	Decentralized management	Elementary GIS analysis	Selection of locations for in-vessel composting arrangement
(Chang and Lin, 1997)	Transfer station's location selection	GIS based spatial analysis with MIP optimization model	Selection of appropriate location for the placement of waste pickup stations
(Lo Porto et al., 1997)	Risk assessment	GIS based spatial analysis with GLEAMS model	Environmental assessment of landscape disposal for animal waste
(Basnet et al. 2001)	Composting site selection	Weighted linear combination and analytical hierarchy process	Site selection for safe application to compost animal waste
(Kao and Lin, 2002)	Transfer station's location selection	GIS analysis with customized model for shortest service	Selection of appropriate location for the placement of waste pickup stations
(Karadimas et al., 2004)	Integrated SWM establishment	GIS with fleet depot tracking using spatio-temporal analysis	SWM framework creation to calculate total cost and feasible alternative
(Karadimas et al., 2005)	Waste generation estimation	GIS based spatial analysis with clustering	Identification of the ideal number and placement of location for the trash bins
(Ghose et al., 2006)	Routing and scheduling	GIS based network analysis with ant colony system	Waste collection route optimization and collection scheduling
(Ahmed et al., 2006)	Waste generation estimation	GIS based spatial analysis	Relocation and identification of the ideal number of trash bins
(Ozkan et al., 2006)	Route optimization	GIS based network analysis	Solid waste collection route optimization
(Karadimas et al., 2006)	Waste generation estimation	GIS with fuzzy logic	Estimation of the amount of solid waste productivity
(Lotfi et al., 2007)	Site selection	GIS based analysis with fuzzy logic	Solid waste landfill site selection
(Vijay et al., 2008)	Trash bin's location selection	GIS based spatial analysis with *p*-median constrained model	Finding appropriate location for trash bins and corresponding command area
(Karadimas and Loumos, 2008)	Waste generation estimation	GIS based spatial analysis with clustering	Estimation of solid waste produced by commercial activities
(Tavares et al., 2009)	Route optimization	3D analysis of GIS based spatial and network information	Fuel consumption reduction by collection route optimization
(Bastin and Longden, 2009)	Risk assessment	GIS based spatial analysis	Assessment of environmental impact caused by solid waste transportation
(Sfakianaki and Kasis, 2010)	Site selection	GIS based analysis with multi-criteria evaluation	Selection of suitable sites for solid waste landfill
(Tralhão et al., 2010)	Trash bin's location selection	GIS based spatial analysis with multi-objective MIP	Selection of location for multi-compartment trash bins
(Jovičić et al., 2010)	Route optimization	GIS network analysis with objective and location tracking	Fuel consumption and CO_2 emission reduction by route optimization
(Fan et al., 2010)	Routing and scheduling	GIS decision support system with genetic algorithm	Route optimization and scheduling for municipal solid waste collection
(Hrebicek and Soukopova, 2010)	Local planning for SWM	GIS based network analysis	Construct of a complete graph of solid waste distribution in Czech
(Tao, 2010)	Integrated SWM establishment	Spatial analysis with WebGIS	Internet-based monitoring of reverse logistics for electronic waste
(Rajkumar et al., 2010)	Risk assessment	GIS based spatial analysis with field sampling and statistics	Assessment of groundwater contamination
(Sener et al., 2011)	Site selection	GIS based spatial analysis with analytical hierarchy process	Appropriate site selection for disposal of solid waste
(Kanchanabhan et al., 2011)	Routing and scheduling	GIS based spatial analysis with vehicle tracking system	Route optimization for collection and transportation
(Marah and Novotny, 2011)	Waste generation estimation	GIS based spatial with weighted overlay analysis model	Estimation of cigarette butt waste generated in urban environment
(Senthil et al., 2012)	Trash bin's location selection	Bin location calculation based on GIS data and collected by GPS	Selections of optimum location and disposal to maximize utilization

In (Yang et al., 2008), the authors have developed a system for landfill site selection by analyzing the leachate and gas emissions from landfills used for domestic waste disposal. The system investigate remotely-sensed environmental features in close proximity to landfills and evaluate compliance of their location and leachate quality with the relevant national regulations in a metropolitan area of Jiangsu province, China. The research focus on remote sensing technology along with a GIS database for selected five landfills in the metropolitan areas of Wuxi and Suzhou city, Jiangsu province, to examine whether data were in compliance with national environmental and public health regulations. The strength of the system is the development of a remote monitoring framework for selecting landfill site that considers man-made environmental threats to overcome potential health risks. However it is unable to provide real time information and deliver a partial service for SWM. Table 5 presents a summary of SWM systems in chronological order that are based on RS technology. Applications of RS based systems in SWM includes disposal site selection (Adeofun et al., 2011; Jensen and Christensen, 1986), environmental features and impact monitoring for solid waste disposal site (Folkard et al., 1998; Yang et al., 2008; Zhao et al., 2005) and environmental impact assessment of buried waste (Irvine et al., 1997; Oluic et al., 2006).

Table 4
Summary of SWM systems based on GPS technology.

References	Target application	Methodology	Functional domain
(Karadimas et al., 2004)	Integrated SWM system	GIS database and fleet depot tracking by GPS with spatio-temporal analysis	Framework creation for SWM to find cost-effective and feasibility
(Lee and Thomas, 2004)	Vehicle tracking	GPS data collection and transmission using personal communications services (PCS)	Tracking of collection vehicle along with solid waste
(Apaydin and Gonullu, 2007)	Route optimization	Analysis of GPS and GIS data with present SWM data along with recorded video	Waste collection route optimization
(Wilson et al., 2007)	Vehicle tracking	GPS installed in five waste collection vehicles to replace traditional data collection	Collection of various information to help SWM planning
(Wilson and Vincent, 2008)	Vehicle tracking	On-board GPS receiver to collect spatial data of vehicles, GPRS module and geofences	Collection of waste information during vehicles movements to transfer stations
(O'connor, 2008)	Driver's tracking	GPS and onboard computer in vehicle along with others ICTs for capturing and transmitting data to remote web server	Offers better visibility of drivers' pickup activities
(Rovetta et al., 2009)	Collection optimization	GPS receiver on the collection vehicle and GIS based spatial analysis	Spatial data collection for tracking, mapping and planning
(Alam Flora, 2009)	Vehicle tracking	Collection vehicle installed with GPS receiver, GPRS and server to visualize on Google Map	Tracking of waste collection vehicles
(Hiramatsu et al., 2009)	Planning for SWM	Data collection by meeting with waste related parties and GPS/GIS spatial analysis	Development of policies to enhance MSW recycling
(Minghua et al., 2009)	Routing and scheduling	GPS installed in collection vehicles and collected data is integrated with GIS	Implement dynamic scheduling of collection vehicles
(Swedberg, 2009)	Efficient billing	Vehicles equipped with GPS receiver along with others ICTs and remote server	Keeps track on bins and vehicles toidentify irregular customer
(Nielsen et al., 2010)	Route optimization	GPS enable RFID reader on vehicles, tag in bins and decision support system at backend	Optimization of waste collection vehicles and automated billing
(Purohit and Bothale, 2011)	Collection monitoring	GPS and GSM for capturing and transmitting spatial information to a control server	Automated system for monitoring vehicles and bins collection
(Arebey et al., 2011)	Collection monitoring	Vehicles equipped with GPS receiver and others ICTs with remote server	Monitoring of collection vehicles and solid waste bin

Table 5
Summary of SWM systems based on RS technology.

References	Target application	Methodology	Functional domain
(Jensen and Christensen, 1986)	Site selection	Spatial analysis based on RS and industrial location constraint criteria	Selection of disposal site for MSW and hazardous waste
(Irvine et al., 1997)	Environmental assessment	Historical aerial image and RS thermal image comparison analysis	Site remediation planning by detecting of buried waste
(Folkard et al., 1998)	Environmental monitoring	Remote sensing based analysis of imaging spectroscopy	Examination and differentiation of the reason for stress in vegetation
(Zhao et al., 2005)	Environmental monitoring	Environmental analysis using data, collected from NASA's Terra and Aqua satellites and on-site sensors	Contamination and recovery status observation for environmental assessment of solid waste disposal
(Oluic et al., 2006)	Environmental assessment	Spatial analysis using Landsat ETM satellite and aerial images	Investigation of suitable disposal site for waste in underground galleries
(Yang et al., 2008)	Environmental features monitoring	Image analysis acquired from Landsat 7 ETM + satellite and study of slopes obtained from digital elevation model	Analysis of leachate and gas and investigation of environmental conditions near to the landfills
(Adeofun et al., 2011)	Site selection	Spatial elements analysis from geo-referenced high resolution image collected by satellite	Selection of disposal sites and waste transportation route in the city of Abeokuta

4. Identification technologies for SWM system

In recent decades, researchers and organizations involved in SWM have investigated different kinds of technology to enhance the efficiency of waste management and automate the collection of bins (Gnoni et al., 2013). To solve the problems in manual data collection, many researchers have studied the possibility of implementing advanced SWM systems that are based on identification technologies. The proliferation of identification technologies, such as barcode and RFID technologies, brought a new strength to SWM systems (Lu et al., 2013). A brief description of identification technologies and their contribution to SWM systems are given as follows.

4.1. Barcode

Barcode is an electronic data interchange medium that contains machine readable dichromatic mark that encodes information for objects labeling using an arrangement of geometric symbols (Lu et al., 2013). Normally, barcode is recognized as an alternating combination of black and white lines. It provides a very simple and low-cost method for recording information in numerous applications. The working principal of barcode technology is called symbology that defines the barcode and determines the interpretation and mapping of the encoded data (Gao et al., 2007). This type of encoding permits a scanning device to distinguish the starts and stops of a character. In the barcode technology, the symbologies may be organized in various ways such as characters starting with a black line and stopping with a space or white line called continuous symbology and characters beginning with a black line, next a space and then another black line is called discreet symbologies.

In (Saar et al., 2004), the authors developed a system that links existing bar codes on mobile phones to web sites containing disassembly information for European cell phones. The paper presents, the recycler can determine the exact make and model of the product and automatically be shown correct dismantlement information by reading a bar code. The strengths of this research is the development of a framework for intelligent recycling at source.

However, it is a partial system and provides very few data for SWM and did not consider environmental effects. Table 6 presents a summary of MSWM systems that are developed based on barcode technology. As presented in the table, barcode based SWM system is developed to implement intelligent recycling by performing source separation during the production, collection or treatment and by providing exact dismantlement information to the recyclers (Ogawa, 2003; Saar et al., 2004; Stutz et al., 2004). This technology has also used to build SWM systems with target to minimize avoidable waste (Li et al., 2003), reduce landfill space (Greengard, 2010), risk management (Cronin et al., 2011) and facilitate advanced waste disposal (Hata, 2004).

4.2. Radio frequency identification (RFID)

RFID is an automated data collection technology that uses radio frequency signals by inductive and backscatter coupling for transferring information between transceiver and transponder to identify object uniquely. It is a generic terminology using for technologies which are based on radio waves and used for automatic identification or tracking of objects or assets and people. The most usual method to for identification involves storing a specific serial number for a particular object and other information on an RFID tag. An RFID reader can scan and read the tag to get the identification information. Actually, the RFID tag and reader transfer information using radio waves and the reader converts the reflected waves into digital information which is then send to computers to process the data. An RFID system consists of three main components such as transponder named as RFID tag, interrogator which is termed as RFID reader and host that is a data collection application in a device (such as computer). An RFID tag is the component that is attached with the object to be identified. A tag is basically contains an integrated chip, an antenna and covering. The integrated chip is composed of a micro control unit, a modulation–demodulation unit and memory. A reader is device that can be fixed or mobile to read data from the RFID tag. It can also writes data onto the tag via RF communication when the tag comes within its range. The read range of a reader varies and the RFID technology works from one inch to 100 feet or more (Finkenzeller, 2003).

Table 6
Summary of SWM systems based on barcode technology.

References	Target application	Methodology	Functional domain
(Li et al., 2003)	Minimize avoidable waste	Keeps track and status of materials and combined with incentive for waste reduction	Reduction and management of construction waste
(Ogawa, 2003)	Intelligent recycling	Information scanned from two-dimensional barcode label, cargo bill and satellite data to SWM system for waste treatment	Facilitating for source separation during the production, collection or treatment of solid waste
(Saar et al., 2004)	Intelligent recycling	Relates existing barcodes on waste material with websites through mobile phones to get disassembly information	Provides exact dismantlement information to the recyclers for automated recycling
(Stutz et al., 2004)	Intelligent recycling	Web links connection by scanning the barcode label using GSM mobile to get corresponding disassembly information	Offers exact dismantlement information to the recyclers for automated recycling
(Hata, 2004)	Advanced waste disposal	Discrimination disposal cost by attaching required information in barcode of products to deposit the cost by the manufacturer	Provides information regarding deposit point and disposal cost of goods for advanced waste disposal
(Greengard, 2010)	Reduce landfill space	Deployment of barcodes on waste objects	Real time observation of the waste's path
(Cronin et al., 2011)	Risk management	Scanning data from a identifiers attached to waste objects and comparison with reference data to match predetermined safety criteria	Identification and separation of banned waste materials

Table 7
Summary of SWM systems based on RFID technology.

References	Target application	Methodology	Functional domain
(Friedlos, 2005)	Bin tracking	RFID tag attached in bin, RFID reader in collection truck, local MS SQLCE database and remote server	Provides tag information to the central server for bin tracking and collection time monitoring
(O'connor, 2007)	SWM performance improvement	RFID tag attached on the base of the bin, RFID reader mounted on the truck, PDA with Bluetooth, GPRS connectivity and remote server	Collection and transmission of tag information after trash bins were emptied.
(Chowdhury and Chowdhury, 2007)	Bin monitoring	Smart RFID tag in trash bin and Wi-Fi enabled personal digital assistant (PDA) with RFID reader	Automatic capturing of identity and weight of trash bins and facilitating stolen bins identification system
(Kietzmann, 2008)	Supervising waste collection process	Trash bins and drivers were equipped with RFID tag and mobile RFID reader scan the tags to get data for control server	SWM operators were able to check accurate information about bin collection and delivery time, and estimate the location of the driver
(O'connor, 2008; Pratheep and Hannan, 2011)	Driver's activity tracking	RFID tag installed on bins and the RFID reader with antenna mounted on vehicles	Offers better visibility of drivers' pickup activities, and to monitor large trash receptacles
(Gnoni et al., 2013; Swedberg 2009; Wyld, 2010)	Efficient billing	Trash bins and collection vehicles were equipped with RFID tag and RFID reader in vehicle	Facilitate the growth of Pay as You Throw based billing for SWM services
(Nielsen et al., 2010)	Route optimization	RFID reader with GPS receiver in vehicles, tag in trash bins and decision support system at backend	Optimization of waste collection vehicles and in some case weight measurement for billing purpose
(Ali et al., 2012; Arebey et al., 2010; Hannan et al., 2011)	Collection monitoring	RFID tag installed in bin, black box installed in vehicles containing RFID receiver, camera, GPS receiver, GSM/GPRS module and remote server	Monitoring of collection vehicles and solid waste bin to automate SWM system
(Glouche and Couderc, 2013; Sinha and Couderc, 2012)	Sorting and recycling	Smart bins equipped with RFID reader, RFID tag with recyclable material information for each waste item	Bin level efficient processing of waste item for selective sorting and recycling

Payment and waste collection are still manual, and are thus subject to possible errors and mistakes common in manual operation. Asking the drivers to handle all the tasks in collection make the process more risky. The RFID system automates the process and reduces the driver's responsibility. Waste management efficiency is thus improved by applying RFID (Abdoli, 2009). The RFID system can overcome the problems of barcode. In recent years, the RFID system has been successfully applied in numerous areas, such as hospitals, animal tracking, supply chain management, environmental management, and SWM (Wyld, 2010). In (Hannan et al., 2011), the authors have proposed a waste bin and truck monitoring system for Malaysia that enabled with RFID and ICTs. The paper presents an integrated system that focused on RFID technology with GPS, GIS and camera for designing an intelligent monitoring system for bins and trucks. A novel integrated theoretical framework, a hardware architecture and an inference algorithm has been introduced in the proposed research. The model incorporate database which stores bin and truck information related with the bin and truck identity. In addition, it processes the date and time of waste collection, the bin status, the amount of waste transported and the truck GPS coordinates. Experimental results proved that the proposed monitoring system is stable and has high performance. The strengths of the system are the intelligent system incorporated for bins and trucks monitoring as well as the enhanced communication technologies. However, the model exploits data produced only from a specific type of data acquisition device and not consider real time bin information for collection scheduling and routing.

Table 7 presents a summary of MSWM systems that are developed based on RFID technology. As shown in the table, RFID based SWM systems were extensively used for tracking of collection vehicles, driver activities and bins by storing required data about drivers, vehicles and bins in database and compare with captured data (Chowdhury and Chowdhury, 2007; Friedlos, 2005; O'connor, 2008; Pratheep and Hannan, 2011), facilitating the growth of Pay as You Throw based billing for SWM services as well as promote incentive based recycling programs (Gnoni et al., 2013; Nielsen et al., 2010; Swedberg, 2009) and sorting and recycling by capturing bin level data for early identification of waste (Glouche and Couderc, 2013; Sinha and Couderc, 2012). Beside these, by combining RFID with other ICTs can help the SWM operators by providing information related to ID, collecting time and area to ensure the service done well (Ali et al., 2012; Arebey et al., 2010; Hannan et al., 2011; Kietzmann, 2008; Purohit and Bothale, 2011).

5. Data acquisition technologies for SWM system

With the emergence and rapid development of data acquisition technologies, manual acquisition of data has been substituted by automatic data acquisition because of its high efficiency, cheaper long-term operational costs and less manpower requirement (Lu et al., 2013). By using the advanced data acquisition technologies, the acquisition of data can be accelerated by tracking and perceiving the targeted objects effectively and quantitatively. These ICTs are crucial for applications where real-time acquisition of data is a key requirement (Faccio et al., 2011). Based on the type of activities in SWM applications, the data acquisition technologies are classified into two categories such as sensors and imaging. A brief description of the data acquisition technologies and their contribution to SWM systems are given as follows.

5.1. Sensors

Conventional practices that involve acquiring a sample and sending it to laboratory for experiment are very time consuming. To expedite the grasping of sample, especially from remote distance, the use of sensors are the best option. A sensor is a device that perceives and measures real-world features, such as physical quantities or chemical properties, and converts them into signals that can be directly observed or adopted by another device (Fraden, 2004). A sensor is mainly composed by two elements such as sensing element and transducer element. The sensing element actively perceives or passively responds to a measured quantity. The transduction element converts that measured quantity of physical phenomena to an equivalent signal suitable for processing (e.g. electrical, mechanical or optical) though at present common sensors convert measured quantity into an electrical signal. Power supply is essential to the transduction element. If handling the weak signal, a component for signal conditioning and transformation is needed (Fraden, 2004).

Sensors are pervasive and at present, without the use of sensors, there would be no automation. They are embedded in our bodies, automobiles, airplanes, cellular telephones, radios, chemical plants, industrial plants and countless other applications. Sensors are extensively used in SWM applications. In (Vicentini et al., 2009), the authors have implemented a sensorized waste collection bin for content estimation and collection optimization. The proposed bin is prepared and tested in the Pudong New Area, Shanghai. The research presents the design and implementation of a suitable urban solid waste system which can predict the quantity and diversity of solid waste. The bin monitoring system uses capacity, weight, temperature, humidity and pressure sensors for solid waste collection. The system have used measures to correlate the capacity of solid waste with residential population and consumer index at different seasons of the year. The strengths of this system are the enhancement of the bins with a variety of sensors and cameras. However, it does not support a wireless sensor network for further fusion of the sensor data neither supports RFIDs for bin tagging and identification and GPRS in every bins increase the operation costs.

Table 8 presents a summary of SWM systems that used various kinds of sensors for rapid detection and capturing of data and ambient monitoring. As shown in Table 8, a good number of sensors have been used in SWM systems for the measurement of bin fill level to implement routing and scheduling optimization as well as collection monitoring. Such sensors includes infrared (Johansson, 2006; Mcleod et al., 2013; Patrícia and Marques, 2009), ultrasonic (Rovetta et al., 2009), volumetric (Faccio et al., 2011), proximity (Catania and Ventura, 2014) and capacitive (Reverter et al., 2003). To measure the weight of waste inside trash bin, load cell sensor (Chowdhury and Chowdhury, 2007) and strain gauge sensor (Vicentini et al., 2009) have been used. For ambient condition monitoring, resistive and capacitive sensors (Fuchs et al., 2008; Gawande et al., 2003) and tin oxide sensor (Micone and Guy, 2007) have been used to measure moisture and odor correspondingly. For sorting of glass waste and others solid waste, optical sensor (Huang et al., 2010; Lewis and Newell 1992) and infrared sensor (Serranti et al., 2006) have been employed. Besides these, calorific value sensor (Van Kessel et al., 2002) have been used for combustion monitoring in incineration plant.

5.2. Imaging technology

Imaging is the activities of sensing, capturing, storing, manipulating and displaying of digital image by synthesizing image sensors and post digital processing. Imaging is the capture, storage, manipulation, and display of images. Imaging is used to extract targets or detect events from digital images (Arebey et al., 2012). The image data can resort to different forms, such as video surveillance, camera, or scanner. The processing of digital images that captured by cameras or other image sensing devices is an important part of

Table 8
Summary of SWM systems based on sensor technologies.

References	Used sensor	Target application	Methodology	Functional domain
(Lewis and Newell, 1992)	Optical sensor, photovoltaic sensor	Glass container sorting	Five perpendicular chutes with sensors, separate both the clear and color containers followed by another sorting aid for three others color sorting.	Automated sorting system for recyclable glass containers
(Van Kessel et al., 2002)	Calorific value sensor	Optimization of incineration	Calorific value sensor and combustion optimization using a dynamic model	Optimization of MSW combustion processes
(Gawande et al., 2003)	Resistive sensor	Moisture content measurement	Simultaneous measurement of electrical resistance using resistive sensor and a thermocouple with tubing	In situ measurement of moisture content for MSW
(Reverter et al., 2003)	Capacitive sensor	Container's filling status measurement	Level estimation using the properties of existence of any nearby conductive substances by two electrodes	Fill level measurement of wastebasket collecting paper waste for recycling
(Isoaho and Peltoniemi, 2004)	Hydraulic pressure sensor	Collection scheduling	Bin equipped with hydraulic pressure and telematics along with remote control station	Improvement of traditional collection scheduling by bin monitoring
(Serranti et al., 2006)	Mid-infrared sensor	Ceramic glass waste sorting system	Addressing the spectral feature of waste glass and ceramic by spectral signature from the mid-infrared field	Detection of contaminants, presented in the recycling streams of waste glass
(Johansson, 2006)	Infrared light emitting diode	Dynamic Routing and scheduling	Four LEDs are attached under container's lid to assess fill level and sends an alarm to a control station and an email to the collecting operator if three out of the four beams are broken	Provides containers filling status in every one hour to help for implementation of dynamic scheduling and routing
(Micone and Guy, 2007)	Tin oxide sensor	Landfill odor measurement	Odor quantification by using an array of tin oxide sensor with multilayer perceptron and radial basis function	Measurement of landfill gas odor
(Chowdhury and Chowdhury, 2007)	Load cell	Bin status monitoring	RFID tag in trash bin, Wi-Fi enable personal digital assistant (PDA) and load cell in vehicle to capture and transmit ID and weight data to remote server	Automatic capturing of identity and weight of trash bins and facilitating stolen bins identification system
(Fuchs et al., 2008)	Capacitive sensor	Energy recovery	Two-channel in-phase and quadrature measurement of solid waste	Measurement of moisture content for MSW
(Cox, 2008)	Linear displacement transducers	Quick and efficient waste collection	Feedback of continuous cylinder position using magnetostrictive Linear displacement transducers	High productivity, accuracy control and versatility in MSW collection
(Patrícia and Marques, 2009)	Optical sensor	Container's filling status measurement	An emitter emits modulated infrared beam on one side which is sensed by a photodiode	Measurement of fill status of recycling point trash bins
(Sanaee and Bakker, 2009)	Ultrasound sensor	Plastic waste recycling	3D acoustic modelling for material identification and 2D medical imaging method for monitoring amagnetic density separator	Monitoring and quality checking of plastic waste recycling system
(Huang et al., 2010)	Optical sensor	Solid waste sorting	Indirect sorting from solid waste mixture by using optical sensor	Sorts waste from mixture of solid waste
(Faccio et al., 2011)	Volumetric sensor	Collection optimization	Bin installed with volumetric sensor, microprocessor, and others identification and communication modules	Framework for the optimization of solid waste collection
(Mcleod et al., 2013)	Infrared sensor	Collection scheduling	Infrared sensors with bin's lid, communication module and remote server	Implementation of dynamic collection schedule
(Catania and Ventura, 2014)	Proximity and weight sensors	Bin status monitoring	Trash bins equipped with sensors and ZigBee module with Raspberry PI and GPRS connectivity	Provides opportunity to smart waste collection

imaging. Image processing has two main parts such as feature extraction and classification. Feature extraction is a broad part of the image processing research area. Many image processing techniques are used in image feature extraction. Images have various features, entropy, energy, power etc. The features are selected based on the output of the features how they keep differences within various images (Islam et al., 2014). There have many methods for feature extraction like subtraction, gray level co-occurrence matrix (GLCM), Gabor filter, Hough transform, basic gray level aura matrix (BGLAM) etc. though the use and selection of image processing techniques depend on the application area.

In (Arebey et al., 2012), the authors developed a bin level detection model based on gray level co-occurrence matrix feature extraction approach and tested in Bangi, Malaysia. The research presents a set of GLCM displacement and quantization parameters along with the number of textural features which are tuned to determine the best parameter values of the bin images. Parameter values and number of textural features are incorporated in the GLCM database used for reasoning. Image classification and grading is based on training and testing of MLPs and KNN classifiers. The proposed model can be used in bin level classification and grading thus providing a solution for bin detection, monitoring

Table 9
Summary of SWM systems based on imaging technologies.

References	Used technology	Target application	Methodology	Functional domain
(Scott, 1995)	Spectrometer	Plastic waste sorting	Simple 2-color fixed filter near infrared spectrometer along with a ratio circuit	Efficient and quick sorting of waste plastic
(Van Den Broek et al., 1997)	Spectroscopic imaging system	Plastic waste sorting	Image acquired using near-infrared imaging followed by supervised classification and linear discriminant analysis	Remote monitoring of post-consumer plastic waste from MSW
(Apaydin and Gonullu, 2007)	Video camera	Route optimization	Video camera to capture waste collection and analysis of data from GPS and GIS	Waste collection route optimization
(Rovetta et al., 2009; Vicentini et al., 2009)	Ultrasonic, camera, LED, pressure and strain gauge sensors	Collection optimization	A small camera, an ultrasonic sensor and LEDs are installed on the top of bin, and strain gauge and pressure sensor are placed in the bottom followed telematics	Bin status data collection for monitoring, mapping and planning of MSW collection activities
(Wagland et al., 2012)	Digital camera	Solid waste sorting	Image acquired by a camera followed by analysis	Estimation of waste composition
(Arebey et al., 2012; Hannan et al., 2012)	Camera	Collection monitoring	Vehicles equipped with camera, others ICTs and remote server with image processing application	Solid waste bin status monitoring to improve waste collection system

and management. The strengths of the system are the incorporation of novel classification models for bin level detection, monitoring and management. However, the model exploits data produced only from a specific type of data acquisition device and not consider real time bin information for collection scheduling and routing. Table 9 presents a summary of SWM systems that used imaging as automatic data acquisition technology. As presented in table, among the imaging technologies in SWM applications, bin fill level measurement have been done by analyzing digital images acquired by camera (Arebey et al., 2012; Hannan et al., 2013, 2012; Rovetta et al., 2009; Vicentini et al., 2009). For sorting of plastic waste and other solid waste spectrometer sensor (Scott, 1995; Van Den Broek et al., 1997) and digital camera (Wagland et al., 2012) have been employed.

6. Data communication technologies for SWM systems

Before the advent of modern communication technologies and beforehand internet became widely spread, the communications of data were usually performed by using floppy disks, CD-ROMs or any local Supervisory Control and Data Acquisition (SCADA) systems (Lu et al., 2013). Rapid development of communication technologies with widely spread of the internet open the opportunities to transmit data instantly from remote place. The internet can handle different types of communication protocols, including TCP/IP, DECnet, IPX/SPX, XNS, and AppleTalk (Chang et al., 1997) and link different types of Wide Area Network (WAN) based on leased line, circuit switching, packet switching, and cell relay. Copper wire access, fiber optic access, and wireless access are the three kinds of technologies used for remote communication via Internet. On the other hand, short-range communication becomes necessary to interchange instruction or data among nodes of automatic acquisition. Wireless communication technologies are mainly used in SWM applications including GSM, GPRS and VHFR for long range communication and Wi-Fi, ZigBee and Bluetooth for short range communication. An overview of the communication technologies are presented in the following sub-sections.

6.1. GSM/GPRS

Global System for Mobile communications (GSM) is considered a 2G type of network which got its start in 1982 at Europe. Now it is globally accepted standard for digital cellular communication technology mainly used for transmitting mobile voice. In addition GSM facilitate with data transmission service where the data transmission rates are restricted to 9.6 Kbps and it takes several seconds for the connection setup. General Packet Radio Service (GPRS) is considered a 2.5G type of network which is a bearer service for GSM that significantly improves and abridges wireless access to packet data networks, e.g., to the Internet. To transfer data packets, GPRS uses packet switching principle that can route the packets directly from the GPRS mobile stations to packet switched networks. GPRS supports the networks based on the Internet Protocol (IP) and X.25 (Bettstetter et al., 1999).

6.2. ZigBee

The ZigBee technology developed by the ZigBee Alliance, an association of companies that are working together to develop standards for reliable, cost-effective, low-power wireless networking (Zigbee, 2008). ZigBee builds upon the IEEE 802.15.4 standard that defines the physical layer (PHY) and medium access control sublayer (MAC) specifications for low data rate wireless connectivity that consume minimal power and costs low (Howitt and Gutierrez, 2003). An 802.15.4 network can simply be a one-hop or a multi-hop network. Wireless links under 802.15.4 can operate in three license free industrial scientific medical (ISM) frequency bands. These accommodate over air data rates of 250 kb/s. Total 27 channels are allocated in 802.15.4 for the three different frequency band.

6.3. Wi-Fi

Wireless fidelity termed as Wi-Fi is a short range wireless communication technology that is broadly used in the mobile connection of home and small office network because of its flexibility and mobility. In recent years, the number of Wi-Fi access point (AP) is increased rapidly. This makes the applications of wireless network more convenient and efficient. The official name for its specification is IEEE 802.11, which is consists of more than 20 different standards, each of which is represented by a letter added to the end of the name. The most well-known standards are 802.11b and 802.11g that operate in the 2.4 GHz band and has a maximum data rate of 54 Mbps while coverage area within 250 m. Some consumer electronics use 802.11a which operates in 5 GHz band having a maximum data rate of 11 Mbps and same coverage limitation (Guo et al., 2012).

6.4. Bluetooth

Bluetooth is a wireless peer-to-peer communication technology that eliminate the requirement for cable connections between

Table 10
Summary of common data communication technologies used in SWM systems.

Communication technology	Communication type	Bandwidth	Data rate	Coverage limitation (m)	Reference (example SWM systems that used)
GSM	Long range communication	200 kHz	9.6 kbps	35,000	(Boustani et al., 2011; Isoaho and Peltoniemi, 2004; Johansson, 2006; Mcleod et al., 2013; Purohit and Bothale, 2011)
GPRS	Long range communication	200 kHz	76–172 kbps	25,000	(Ali et al., 2012; Faccio et al., 2011; Friedlos, 2005; O'connor, 2007; Rovetta et al., 2009; Vicentini et al., 2009; Wilson and Vincent, 2008)
VHFR	Long range communication	30–300 MHz	16–64 kbps	10,000	(Lee and Thomas, 2004)
Wi-Fi	Short range communication	22 MHz	54 Mbps	250	(Chowdhury and Chowdhury, 2007; Hong et al., 2014)
Bluetooth	Short range communication	1 MHz	1 Mbps	8–30	(Friedlos, 2005; O'connor, 2007)
ZigBee	Short range communication	0.3/0.6 MHz, 2 MHz	250 kbps	100–400	(Catania and Ventura, 2014; Longhi et al., 2012)

devices such as cell phones, PDAs or notebook PCs. Its standard is IEEE 802.15 and operates in 2.4–2.5 GHz ISM bands. It has a bandwidth of 1 MHz and covers a maximum distance of 30 m without the line-of-sight requirement (Bisdikian, 2001).

6.5. VHFR

Very high frequency radio (VHFR) is an ITU-8 designated communication technology that has a bandwidth of 30–300 MHz, within wavelengths of 10–1 m. It has a maximum data rate of 64 kbps while covers a maximum distance of 10,000 m. Common applications of VHFR are in FM radio broadcasting, long range data communication, marine communication, television broadcasting and private, business or military communication (Seybold, 2005).

6.6. Usage of data communication technologies in SWM systems

Most of the SWM systems are based on the three types of technologies i.e. spatial, identification or data acquisition and need to transmit data form end device to control station or vice versa. Data that are acquired automatically or artificially, required to be transmitted to the control station for further processing, analyzing, utilization and display. Conversely, various commands for controlling or diagnosis, need to be transmitted to the end devices responsible for data acquisition. For SWM applications, wireless communication technologies are mainly used for data communication.

Table 10 presents some important features of communication technologies used in SWM systems with example references. As shown in the table, long range communication technologies like GSM (Boustani et al., 2011; Isoaho and Peltoniemi, 2004; Johansson, 2006; Mcleod et al., 2013; Purohit and Bothale, 2011), GPRS (Ali et al., 2012; Faccio et al., 2011; Friedlos, 2005; O'connor, 2007; Vicentini et al., 2009; Wilson and Vincent, 2008) and VHFR (Lee and Thomas, 2004) were adopted by several solid waste collection and monitoring systems. The short-range communications technologies such as Wi-Fi (Chowdhury and Chowdhury, 2007; Hong et al., 2014), ZigBee (Catania and Ventura, 2014; Longhi et al., 2012) and Bluetooth (Friedlos, 2005; O'connor, 2007) were used among data acquisition nodes and sink nodes.

7. Issues and challenges

So far, various kinds of ICTs have been employed to develop many systems for the improvement of municipal SWM. Though the of research publications have been increasing quickly in this field but the limited number of book publications and conference proceedings indicates that technology based system for SWM is still a developing field and the future development of this field is still a vital need. Finding and understanding the benefits and limitations of different systems would help to investigate the optimum solutions boundaries for efficient SWM system that is significant for further planning and improvement towards a robust systems. Although existing ICT based SWM systems improve different sectors in SWM activities, there have some issues. The issues and challenges to overcome that issues are mentioned in the followings.

7.1. Partial system design

None of the existing researches have focused on every aspect for a complete SWM system by utilizing different types of ICTs (Arebey et al., 2012; Faccio et al., 2011; Hannan et al., 2011; Saar et al., 2004; Vicentini et al., 2009; Yang et al., 2008; Zsigraiova et al., 2013). Studies on spatial technologies based systems mainly focused on the collection, storing, analyzing and displaying of spatial information about bins, vehicles, sites, routes and collection and unable to monitor trash bin status. Literature based on identification technologies based systems concentrate on achieving ID and facilitate to track and monitor the activities of drivers and vehicles but unable to solve bin status monitoring as well as spatial information related issues. Research on data acquisition based systems focused on data acquisition along with bin status monitoring but incapable of resolving the identification or spatial information related problems. The integration of these three types of technologies along with communication technologies may produce a system that can serve to solve every aspect of an efficient SWM system. The main challenge for this issue is to find the proper combination of ICTs by considering complexity, cost, robustness and environmental impacts.

7.2. Lacking of enough data

Lacking of enough information is the main barrier to do efficient planning and design for SWM system (Arebey et al., 2012; Hannan et al., 2011; Yang et al., 2008; Zsigraiova et al., 2013). Existing research mainly focused on the statistical and survey related partial data on waste generation, collection or recycling. Bin fill level data is unknown and for some system, weight of waste is measured using some sort of weight measuring tools during the entry of disposal site but measurement at source site is little known. The challenges to solve this issue are to design and development of smart bin for waste that can acquire physical status information such as bin fill level, weight, volume, ambience condition for every bins on daily basis. This requires appropriate integration of data acquisition technologies like ultrasonic sensor, load cell sensor, temperature sensor, humidity sensor, volumetric sensor and/or camera. There also need to incorporate RFID to track the identification for every bin. The smart bin should be developed in such a way that bin status information can be collected for every waste throwing operation.

7.3. Expensive network structure

The data communication network for most of the systems in the existing literatures are using GSM/GPRS technology for long range data communication which increase the system operation costs. Some of the systems have GSM/GPRS communication module for each trash bin or each collection vehicle that impose extra operation costs (Faccio et al., 2011; Vicentini et al., 2009). This issue can be solved by designing a system using wireless sensor network (WSN). But the challenges of using effective WSN are the requirement of energy supply to sensor nodes, proper routing algorithms, problems due to signal attenuation during crossing high rise buildings, signal interference along with self-diagnosis and adaptation after node failure or new node addition as a widely spread WSN requires numerous sensor nodes.

7.4. Deficiency of real time bin status information

For the existing SWM systems, in most cases the systems are unable to provide real time trash bin status information to the waste management operators (Arebey et al., 2012; Hannan et al., 2011; Zsigraiova et al., 2013). Some systems can provide semi-real type data with certain delays. But, solution for this issue is important for proper planning of waste collection schedule or route. The main challenge to solve the issue is to provide enough intelligence to a trash bin so that it can detect any waste loading or unloading related operation instantly and can respond accordingly using one or more suitable sensing elements. This issue also requires necessary sensors to collect updated bin status data as well as robust communication network to transmit the acquired data to a control station promptly.

7.5. Negligence of adding source segregation facility

The existing literatures omit the aptitude of waste segregation at source point by using various ICTs (Arebey et al., 2012; Faccio et al., 2011; Hannan et al., 2011; Vicentini et al., 2009; Zsigraiova et al., 2013). Segregating waste at source point will help to implement an efficient and easy recycling sub-system causing a huge reduction of post effort. Technology have the ability to perform such activities of discriminating and classifying solid waste using barcode or RFID. Unfortunately few researches for SWM were focused to implement in waste source segregation. The challenges to solve this issue include difficulties of universal system design that can detect and separate every type of solid waste, establishment of unique regulation for manufacturers or seller to identify every item separately, requirement of extra space for the placement of additional trash bins, time requirement related to segregation process and collection consistency after segregation.

7.6. Absence of dynamic scheduling and routing

Use of dynamic scheduling and routing for waste collection have several advantages such as collection efficiency improvement, collection cost and pollutant reduction. To implement dynamic scheduling and routing processes, real time bin status information is very important as it provides the demands of any bin to collect. This is absent in the existing SWM as that systems are mostly unable to provide real time bin status information (Arebey et al., 2012; Hannan et al., 2011). The major challenge is to use proper combination ICTs to implement a system that can facilitate with real time bin status information. Beside this challenge, robust algorithms are required to model and test using simulation prior to practical use. But for effective simulation there will be many collection point as reality that cause an exponential growth of the computational complexity. The advantages of artificial intelligence along with mathematical programming can solve this challenge of developing new robust algorithms that can produce optimal output with fast execution capability.

7.7. Negligence in environmental impacts

The issue of ICT and the environment is multifaceted and complex. It can output both positive and negative results for the environment (Berkhout and Hertin, 2001). Most of the existing research did not consider about the environmental impacts of using ICT (Saar et al., 2004). Using technology based systems have direct, indirect and systematic impacts on environment. The direct environmental cause due to the physical existence of technological goods along with their manufacturing process. The indirect impacts occur for the applications and ongoing usage of technology based system. And the systematic impacts are created because of the medium and long term usage of many technology based systems. Among these impacts, most of the negative bearings are come from the direct impacts to the environment like resources consumption and carbon emission during manufacturing and disposal of hardware. The main challenge to overcome this issue is to produce green ICT goods, services and systems by improved research and development for tackling direct environmental impacts during manufacture, usage and disposal. Beside this, ICT policies by government should be influential to aware and such life-cycle approaches.

8. Conclusion

This study reviewed the available ICTs and their applications in municipal SWM systems. The ICTs are categorized into four classes including spatial technologies, identification technologies, data acquisition technologies and data communication technologies. Among the four class, SWM systems are mainly developed based on the first three classes and the last one is used with almost every systems. The spatial technologies include GIS, GPS and RS; the identification technologies contain barcode and RFID; the data acquisition technologies include sensing and imaging technologies; and the data communication technologies comprise both the short range and long range communication technologies. The basic introduction with structure, working principal, functionalities and salient features for every technologies of each class were discussed. The SWM system for every technologies are summarized with their methodologies and functional domain. Among the overall ICTs, GIS is the mostly used technology that used to implement systems with targets of site selection, routing and scheduling optimization, waste generation estimation, local management planning, integrated SWM establishment and risk assessment. The GPS based SWM systems are primarily used in collection vehicle tracking, route optimization, collection monitoring and implementation of efficient billing. Applications of RS based systems in SWM includes disposal site selection, environmental features and impact monitoring for solid waste disposal site and environmental impact assessment. Among the identification technologies, barcode based SWM system is used to implement intelligent recycling, minimize avoidable waste and risk assessment. Later the barcode is replaced with RFID and used mainly for tracking of collection vehicles, driver activities and bins, facilitating the growth of Pay as You Throw based billing and intelligent sorting and recycling. Among data acquisition technologies, various sensors are used with SWM applications to measure bin fill level, weight of waste inside trash bin, ambient condition monitoring, waste sorting and combustion monitoring. The imaging technologies in SWM applications include bin fill level measurement and waste sorting. However, partial system design, deficiency in enough data, expensive network structure, lacking of real time information, overlooking source separation, absence of dynamic scheduling and routing and negligence in environmental impacts hamper the development of an efficient and complete SWM system. Several challenges need to face to overcome these problems successfully. Further research and development is very important to design and develop green ICT goods. With all these effort, suitable and careful government policy will extract the maximum benefits from modern ICTs for the improvement of clean and green society.

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References

Abdoli, S., 2009. RFID application in municipal solid waste management system. Int. J. Environ. Res. 3 (3), 447–454.

Adeofun, C., Achi, H., Ufoegbune, G., Gbadebo, A., Oyedepo, J., 2011. Application of remote sensing and geographic information system for selecting dumpsites and transport routes in Abeokuta, Nigeria. In: Proceedings of the Environmental Management Conference, Federal University of Agriculture, Abeokuta, Nigeria, pp. 264–278.

Ahmed, S.M., Muhammad, H., Sivertun, A., 2006. Solid waste management planning using GIS and remote sensing technologies case study Aurangabad City, India. In: Proceedings of the International Conference on Advances in Space Technologies, 2006. pp. 196–200.

Alam Flora, 2009. Towards a clean environment. Proposal on sustainable and integrated solid waste management system for University Kebangsaan Malaysia. Report from Alam Flora.

Aleke, B., Ojiako, U., Wainwright, D.W., 2011. ICT adoption in developing countries: perspectives from small-scale agribusinesses. J. Enterprise Inform. Manage. 24 (1), 68–84.

Ali, M.L., Alam, M., Rahaman, M.A.N.R., 2012. RFID based e-monitoring system for municipal solid waste management. In: Proceedings of the 7th International Conference on Electrical & Computer Engineering (ICECE'12), pp. 474–477.

Apaydin, O., Gonullu, M., 2007. Route optimization for solid waste collection: Trabzon (Turkey) case study. Global NEST J. 9 (1), 6–11.

Arebey, M., Hannan, M.A., Basri, H., Begum, R., Abdullah, H., 2010. Solid waste monitoring system integration based on RFID, GPS and camera. In: Proceedings of International Conference on Intelligent and Advanced Systems (ICIAS'10), pp. 1–5.

Arebey, M., Hannan, M.A., Basri, H., Begum, R., Abdullah, H., 2011. Integrated technologies for solid waste bin monitoring system. Environ. Monit. Assess. 177 (1–4), 399–408.

Arebey, M., Hannan, M.A., Begum, R., Basri, H., 2012. Solid waste bin level detection using gray level co-occurrence matrix feature extraction approach. J. Environ. Manage. 104, 9–18.

Arvanitis, L.G., Ramachandran, B., Brackett, D.P., Abd-El Rasol, H., Du, X., 2000. Multiresource inventories incorporating GIS, GPS and database management systems: a conceptual model. Comput. Electron. Agr. 28 (2), 89–100.

Basagaoglu, H., Celenk, E., Marino, M.A., Usul, N., 1997. Selection of waste disposal sites using GIS. Water Resour. Bull. 33 (2), 455–464.

Basnet, B.B., Apan, A.A., Raine, S.R., 2001. Selecting suitable sites for animal waste application using a raster GIS. Environ. Manage. 28 (4), 519–531.

Bastin, L., Longden, D.M., 2009. Comparing transport emissions and impacts for energy recovery from domestic waste (EfW): centralised and distributed disposal options for two UK Counties. Comput. Environ. Urban Syst. 33 (6), 492–503.

Beliën, J., De Boeck, L., Van Ackere, J., 2012. Municipal solid waste collection and management problems: a literature review. Transport. Sci. 48 (1), 78–102.

Berkhout, F., Hertin, J., 2001. Impacts of information and communication technologies on environmental sustainability: Speculations and evidence. Report to the OECD, Brighton.

Bettstetter, C., Vogel, H.-J., Eberspacher, J., 1999. GSM phase 2+ general packet radio service GPRS: architecture, protocols, and air interface. IEEE Commun. Surv. Tutorials 2 (3), 2–14.

Bisdikian, C., 2001. An overview of the Bluetooth wireless technology. IEEE Commun. Mag. 39 (12), 86–94.

Bishop, I.D., Escobar, F.J., Karuppannan, S., Suwarnarat, K., Williamson, I.P., Yates, P.M., Yaqub, H.W., 2000. Spatial data infrastructures for cities in developing countries: lessons from the Bangkok experience. Cities 17 (2), 85–96.

Boustani, A., Girod, L., Offenhuber, D., Britter, R., Wolf, M.I., Lee, D., Miles, S., Biderman, A., Ratti, C., 2011. Investigation of the waste-removal chain through pervasive computing. IBM J. Res. Dev. 55 (1.2), 1–11.

Catania, V., Ventura, D., 2014. An approach for monitoring and smart planning of urban solid waste management using smart-M3 platform. In: Proceedings of the 15th Conference of Fruct Association, pp. 24–31.

Chang, N.B., Lin, Y., 1997. Optimal siting of transfer station locations in a metropolitan solid waste management system. J. Environ. Sci. Health Part A 32 (8), 2379–2401.

Chang, N.-B., Lu, H., Wei, Y., 1997. GIS technology for vehicle routing and scheduling in solid waste collection systems. J. Environ. Eng. 123 (9), 901–910.

Cheng, H., Hu, Y., 2010. Municipal solid waste (MSW) as a renewable source of energy: current and future practices in China. Bioresour. Technol. 101 (11), 3816–3824.

Chowdhury, B., Chowdhury, M.U., 2007. RFID-based real-time smart waste management system. In: Proceedings of the Australasian Telecommunication Networks and Applications Conference, ATNAC 2007, pp. 175–180.

Clarke, K.C., 1997. Getting Started with Geographic Information Systems. Prentice Hall, Upper Saddle River, NJ.

Cox, B., 2008. Sensor helps speed waste collection. Hydraulic Pneum. 61 (6), 20.

Cronin, N.E., Leone, J., Maruca, D., 2011. Systems and methods for identifying banned waste in a municipal solid waste environment, U.S. Patent 7,870,042, issued January 11, 2011.

Elena, M., Quero, J.M., Toral, S.L., Tarrida, C.L., Segovia, J.A., Franquelo, L.G., 2002. CARDIOSMART: Intelligent cardiology monitoring system using GPS/GPRS networks. In: Proceedings of the 28th IEEE Annual Conference of the Industrial Electronics Society, pp. 3419–3424.

Faccio, M., Persona, A., Zanin, G., 2011. Waste collection multi objective model with real time traceability data. Waste Manage. 31 (12), 2391–2405.

Fan, X., Zhu, M., Zhang, X., He, Q., Rovetta, A., 2010. Solid waste collection optimization considering energy utilization for large city area. In: Proceedings of the International Conference on Logistics Systems and Intelligent Management 2010, pp. 1905–1909.

Finkenzeller, K., 2003. RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification. John Wiley and Sons, Chichester.

Folkard, A., Schaepman, M., Schlapfer, D., Itten, K., 1998. How far can imaging spectroscopy go in identifying the cause of vegetation stress around landfill sites. In: Proceedings of the 1st EARSeL Workshop on Imaging Spectroscopy, Zurich, pp. 6–8.

Fraden, J., 2004. Handbook of Modern Sensors: Physics, Designs, and Applications. Springer, San Diego.

Friedlos, D., 2005. Australian waste-collection businesses tag trash bins. RFID J., http://wwwrfidjournal.com/article/view/5145 [12 August 2014].

Fuchs, A., Zangl, H., Holler, G., Brasseur, G., 2008. Design and analysis of a capacitive moisture sensor for municipal solid waste. Meas. Sci. Technol. 19 (2), 025201.

Gao, J.Z., Prakash, L., Jagatesan, R. 2007. Understanding 2D-barcode technology and applications in m-commerce-design and implementation of a 2D barcode processing solution. In: Proceedings of the 31st Annual International Computer Software and Applications Conference (COMPSAC'07), pp. 49–56.

Gawande, N.A., Reinhart, D.R., Thomas, P.A., McCreanor, P.T., Townsend, T.G., 2003. Municipal solid waste in situ moisture content measurement using an electrical resistance sensor. Waste Manage. 23 (7), 667–674.

Ghose, M., Dikshit, A.K., Sharma, S., 2006. A GIS based transportation model for solid waste disposal–a case study on Asansol municipality. Waste Manage. 26 (11), 1287–1293.

Glouche, Y., Couderc, P., 2013. A smart waste management with self-describing objects. In: Proceeding of the 2nd International Conference on Smart Systems, Devices and Technologies (SMART'13), pp. 63–70.

Gnoni, M.G., Lettera, G., Rollo, A., 2013. A feasibility study of a RFID traceability system in municipal solid waste management. Int. J. Inf. Technol. Manage. 12 (1), 27–38.

Greengard, S., 2010. Tracking garbage. Commun. ACM 53 (3), 19–20.

Guo, Y., Zhang, S., Xiao, D., 2012. Overview of Wi-Fi Technology. In: Proceedings of the International Conference on Computer Application and System Modeling 2012, pp. 1293–1296.

Hannan, M.A., Arebey, M., Begum, R.A., Basri, H., 2011. Radio frequency identification (RFID) and communication technologies for solid waste bin and truck monitoring system. Waste Manage. 31 (12), 2406–2413.

Hannan, M.A., Arebey, M., Begum, R.A., Basri, H., 2012. An automated solid waste bin level detection system using a gray level aura matrix. Waste Manage. 32 (12), 2229–2238.

Hannan, M.A., Arebey, M., Begum, R., Mustafa, A., Basri, H., 2013. An automated solid waste bin level detection system using Gabor wavelet filters and multi-layer perception. Resour. Conserv. Recycl. 72, 33–42.

Hata, I., 2004. Recovery method of advance waste disposal expense for streetscape, Japanese Patent JP2004062837, Kind Code: A. <http://www.sumobrain.com/patents/JP2004062837A.html> (accessed 15.09.14).

Hiramatsu, A., Hara, Y., Sekiyama, M., Honda, R., Chiemchaisri, C., 2009. Municipal solid waste flow and waste generation characteristics in an urban-rural fringe area in Thailand. Waste Manage. Res. 27 (10), 951–960.

Hong, I., Park, S., Lee, B., Lee, J., Jeong, D., Park, S., 2014. IoT-based smart garbage system for efficient food waste management. Sci. World J., <http://wwwhindawi.com/journals/tswj/2014/646953/> (accessed 27.11.14).

Howitt, I., Gutierrez, J.A., 2003. IEEE 802.15. 4 low rate-wireless personal area network coexistence issues. In: Proceedings of the 2003 IEEE Wireless Communications and Networking Conference (WCNC'03), pp. 1481–1486.

Hrebicek, J., Soukopova, J., 2010. Modelling integrated waste management system of the Czech Republic. In: Proceedings of the Latest Trends on Systems: 14th WSEAS International Conference on Systems (Part of the 14th WSEAS CSCC Multiconference), pp. 510–515.

Huang, J., Pretz, T., Bian, Z., 2010. Intelligent solid waste processing using optical sensor based sorting technology. In: Proceedings of the 3rd International Congress on Image and Signal Processing (CISP'10) pp. 1657–1661.

Irvine, J., Evers, T., Smyre, J., Huff, D., King, A., Stahl, G., Odenweller, J., 1997. The detection and mapping of buried waste. Int. J. Remote Sens. 18 (7), 1583–1595.

Islam, M.S., Hannan, M.A., Basri, H., Hussain, A., Arebey, M., 2014. Solid waste bin detection and classification using dynamic time warping and MLP classifier. Waste Manage. 34 (2), 281–290.

Isoaho, S., Peltoniemi, M., 2004. Telematics for waste collection and transport. In: Proceedings of the 2nd International Conference on Ecological Protection of the Planet Earth, pp. 109–115.

Jensen, J., Christensen, E., 1986. Solid and hazardous waste disposal site selection using digital geographic information system techniques. Sci. Total Environ. 56, 265–276.

Johansson, O.M., 2006. The effect of dynamic scheduling and routing in a solid waste management system. Waste Manage. 26 (8), 875–885.

Jovičić, N.M., Bošković, G.B., Vujić, G.V., Jovičić, G.R., Despotović, M.Z., Milovanović, D.M., Gordić, D.R., 2010. Route optimization to increase energy efficiency and reduce fuel consumption of communal vehicles. Thermal Sci. 14 (suppl.), 67–78.

Kanchanabhan, T.E., Mohaideen, J.A., Srinivasan, S., Sundaram, V.L.K., 2011. Optimum municipal solid waste collection using geographical information system (GIS) and vehicle tracking for Pallavapuram municipality. Waste Manage. Res. 29 (3), 323–339.

Kao, J.-J., 1996. A raster-based C program for siting a landfill with optimal compactness. Comput. Geosci. 22 (8), 837–847.

Kao, J.-J., Lin, T.-I., 2002. Shortest service location model for planning waste pickup locations. J. Air Waste Manag. Assoc. 52 (5), 585–592.

Karadimas, N.V., Loumos, V.G., 2008. GIS-based modelling for the estimation of municipal solid waste generation and collection. Waste Manage. Res. 26 (4), 337–346.

Karadimas, N.V., Loumos, V.G., Mavrantza, O.D., 2004. Quality of service ensuring in urban solid waste management. In: Proceedings of the 2nd International IEEE Conference on Intelligent Systems, pp. 288–292.

Karadimas, N.V., Mavrantza, O.D., Loumos, V.G., 2005. GIS integrated waste production modeling. In: Proceedings of the International Conference on Computer as a Tool (EUROCON '05), pp. 1279–1282.

Karadimas, N.V., Orsoni, A., Loumos, V., 2006. Municipal solid waste generation modelling based on fuzzy logic. In: Proceedings of the 20th European Conference on Modelling and Simulation, pp. 309–314.

Kietzmann, J., 2008. Interactive innovation of technology for mobile work. Eur. J. Inform. Syst. 17 (3), 305–320.

Kumar, S., Moore, K.B., 2002. The evolution of global positioning system (GPS) technology. J. Sci. Educ. Technol. 11 (1), 59–80.

Lee, J., Thomas, V., 2004. GPS and radio tracking of end-of-life products [recycling and waste disposal applications]. In: Proceedings of the 2004 IEEE International Symposium on Electronics and the Environment, pp. 309–312.

Lewis, M.R., Newell, T.A., 1992. Development of an automated color sorting system for recyclable glass containers. In: Proceedings of the National Waste Processing Confernce, pp. 197–207.

Li, H., Chen, Z., Wong, C.T., 2003. Barcode technology for an incentive reward program to reduce construction wastes. Comput-Aided Civil Infrastruct. Eng. 18 (4), 313–324.

Lo Porto, A., Garnier, M., Uricchio, V., Marini, R., 1997. The use of GIS in assessing the land disposal capacity for animal waste and preventing groundwater pollution. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences 243, pp. 375–384.

Longhi, S., Marzioni, D., Alidori, E., Di Buo, G., Prist, M., Grisostomi, M., Pirro, M., 2012. Solid waste management architecture using wireless sensor network technology. In: Proceedings of the 5th International Conference on New Technologies, Mobility and Security (NTMS'12), pp. 1–5.

Lotfi, S., Habibi, K., Koohsari, M., 2007. Integrating GIS and fuzzy logic for urban solid waste management (a case study of Sanandaj city, Iran). Pak. J. Biol. Sci. 10 (22), 4000–4007.

Lu, J.-W., Chang, N.-B., Liao, L., 2013. Environmental informatics for solid and hazardous waste management: advances, challenges, and perspectives. Crit. Rev. Environ. Sci. Technol. 43 (15), 1557–1656.

Lyshevski, S.E., 2013. MEMS and NEMS: Systems, Devices, and Structures. CRC Press, United States.

MacDonald, M.L., 1996. A multi-attribute spatial decision support system for solid waste planning. Comput. Environ. Urban Syst. 20 (1), 1–17.

Marah, M., Novotny, T.E., 2011. Geographic patterns of cigarette butt waste in the urban environment. Tobacco Control 20 (Suppl 1), i42–i44.

McLeod, C.A., Terazawa, M., Yamamura, E., 1997. Using geographical information systems to evaluate decentralized management of municipal food waste. Compost Sci. Util. 5 (1), 49–61.

McLeod, F., Erdogan, G., Cherrett, T., Bektas, T., Davies, N., Speed, C., Dickinson, J., Norgate, S., 2013. Dynamic collection scheduling using remote asset monitoring. Transport. Res. Record: J. Transport. Res. Board 2378 (1), 65–72.

Micone, P., Guy, C., 2007. Odour quantification by a sensor array: an application to landfill gas odours from two different municipal waste treatment works. Sens. Actuators B: Chem. 120 (2), 628–637.

Milla, K.A., Lorenzo, A., Brown, C., 2005. GIS GPS and remote sensing technologies in extension services Where to start what to know. J. Extension 43 (3), 3FEA6.

Minghua, Z., Xiumin, F., Rovetta, A., Qichang, H., Vicentini, F., Bingkai, L., Giusti, A., Yi, L., 2009. Municipal solid waste management in Pudong New Area, China. Waste Manage. 29 (3), 1227–1233.

Muttiah, R., Engel, B., Jones, D., 1996. Waste disposal site selection using GIS-based simulated annealing. Comput. Geosci. 22 (9), 1013–1017.

Ndou, V., 2004. E-government for developing countries: opportunities and challenges. Electron. J. Inform. Syst. Dev. Countries 18 (1), 1–24.

Nielsen, I., Lim, M., Nielsen, P., 2010. Optimizing supply chain waste management through the use of RFID technology. In: Proceedings of the IEEE International Conference on RFID-Technology and Applications (RFID-TA'10), pp. 296–301.

Nuortio, T., Kytöjoki, J., Niska, H., Bräysy, O., 2006. Improved route planning and scheduling of waste collection and transport. Expert Syst. Appl. 30 (2), 223–232.

O'Connor, M.C., 2007. Greek RFID pilot collects garbage. RFID J., <http://wwwrfidjournal.com/articles/view?2973> (accessed 14.08.14).

O'Connor, M.C., 2008. Routeware launches RFID solution for waste haulers. RFID J., http://wwwrfidjournal.com/articles/view/4067/ [25 May 2014].

OECD, 2003. A Proposed Classification of ICT Goods, OECD Working Party on Indicators for the Information Society. <http://stats.oecd.org/glossary/detail.asp?ID=6274> (05.01.15).

Ogawa, M., 2003. Waste treatment information management system, U.S. Patent Application 10/501,086, filed January 16, 2003.

Oluic, M., Romandic, S., Schaller, A., 2006. Remote sensing and geophysical survey in site investigations for special waste disposal: Case study Trgovska Gora (Croatia). <http://www.earsel.org/symposia/2005-symposium-Porto/pdf/025.pdf> (21.08.14).

Ozkan, A., Altan, M., Banar, M., Ayday, C., 2006. Optimization of solid waste collection and transportation routes by using GIS. WSEAS Trans. Environ. Dev. 2 (10), 1322–1327.

Patrícia, O.L., Marques, M.J.B., 2009. Reliability of a line-of-view sensor for recycling point waste containers. World Congress 2009: Turning Waste into Ideas. <http://www.iswa.org/uploads/tx_iswaknowledgebase/13-291paper_long.pdf> (27.07.14).

Pratheep, P., Hannan, M.A., 2011. Solid waste bins monitoring system using RFID technologies. J. Appl. Sci. Res. 7 (7), 1093–1101.

Purohit, S.S., Bothale, V.M., 2011. RFID based solid waste collection process. In: Proceedings of the 2011 IEEE Conference on Recent Advances in Intelligent Computational Systems (RAICS), pp. 457–460.

Rada, E.C., Ragazzi, M., Fedrizzi, P., 2013. Web-GIS oriented systems viability for municipal solid waste selective collection optimization in developed and transient economies. Waste Manage. 33 (4), 785–792.

Rajendran, K., Björk, H., Taherzadeh, M.J., 2013. Borås, a zero waste city in Sweden. J. Dev. Manage. 1 (1), 3–8.

Rajkumar, N., Subramani, T., Elango, L., 2010. Ground water contamination duet o municipal solid waste disposal–A GIS based study in Erode city. Int. J. Environ. Sci. 1 (1), 39–55.

Reverter, F., Gasulla, M., Pallas-Areny, R., 2003. Capacitive level sensing for solid-waste collection. Proc. IEEE Sensors 2003, 7–11.

Rovetta, A., Xiumin, F., Vicentini, F., Minghua, Z., Giusti, A., Qichang, H., 2009. Early detection and evaluation of waste through sensorized containers for a collection monitoring application. Waste Manage. 29 (12), 2939–2949.

Saar, S., Stutz, M., Thomas, V.M., 2004. Towards intelligent recycling: a proposal to link bar codes to recycling information. Resour. Conserv. Recycl. 41 (1), 15–22.

Sanaee, S.A., Bakker, M., 2009. Ultrasound for monitoring and quality inspection in MDS plastics recycling. World Congress 2009: Turning Waste into Ideas. <http://www.iswa.org/uploads/tx_iswaknowledgebase/15-191paper_long.pdf> (accessed 30.07.14).

Sanchez-Hernandez, C., Boyd, D.S., Foody, G.M., 2007. Mapping specific habitats from remotely sensed imagery: support vector machine and support vector data description based classification of coastal saltmarsh habitats. Ecol. Inform. 2 (2), 83–88.

Schowengerdt, R.A., 2007. Remote Sensing: Models and Methods for Image Processing. Academic press, Burlington.

Scott, D., 1995. A two-colour near-infrared sensor for sorting recycled plastic waste. Meas. Sci. Technol. 6 (2), 156.

Sener, S., Sener, E., Karagüzel, R., 2011. Solid waste disposal site selection with GIS and AHP methodology: a case study in Senirkent-Uluborlu (Isparta) Basin, Turkey. Environ. Monit. Assess. 173 (1–4), 533–554.

Senthil, J., Vadivel, S., Murugesan, J., 2012. Optimum location of dust bins using geo-spatial technology: a case study of Kumbakonam town, Tamil Nadu, India. Adv. Appl. Sci. Res. 3 (5), 2997–3003.

Serranti, S., Bonifazi, G., Pohl, R., 2006. Spectral cullet classification in the mid-infrared field for ceramic glass contaminants detection. Waste Manage. Res. 24 (1), 48–59.

Seybold, J.S., 2005. Introduction to RF Propagation. John Wiley & Sons, Chichester.

Sfakianaki, E., Kasis, G., 2010. Identification and evaluation of suitable locations for waste management sites. Int. J. Decision Sci. Risk Manage. 2 (1), 66–84.

Shahmoradi, B., 2013. Collection of municipal solid waste in developing countries. Int. J. Environ. Stud. 70 (6), 1013–1014.

Sinha, A., Couderc, P., 2012. Using owl ontologies for selective waste sorting and recycling. In: Proceedings of the 9th OWL: Experiences and Directions Workshop (OWLED 2012), pp. 1–8.

Srivastava, A.K., Nema, A.K., 2012. Fuzzy parametric programming model for multi-objective integrated solid waste management under uncertainty. Expert Syst. Appl. 39 (2012), 4657–4678.

Stutz, M., Thomas, V.M., Saar, S., 2004. Linking bar codes to recycling information for mobile phones. IEEE International Symposium on Electronics and the Environment 2004, pp. 313–316.

Swedberg, C., 2009. Mississippi county tracks waste pickup. RFID J., <http://wwwrfidjournal.com/articles/view?5263> (accessed 30.08.14).

Tao, J. 2010. Reverse logistics information system of e-waste based on internet. In: Proceedings of the 2010 International Conference on Challenges in Environmental Science and Computer Engineering (CESCE), pp. 447–450.

Tavares, G., Zsigraiova, Z., Semiao, V., Carvalho, M.D.G., 2009. Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. Waste Manage. 29 (3), 1176–1185.

The World Bank, 2012. What a waste: a global review of solid waste management. Urban Development Series Knowledge Paper No. 15. Washington DC: The World Bank.

Tralhão, L., Coutinho-Rodrigues, J., Alçada-Almeida, L., 2010. A multiobjective modeling approach to locate multi-compartment containers for urban-sorted waste. Waste Manage. 30 (12), 2418–2429.

Van den Broek, W., Wienke, D., Melssen, W., Feldhoff, R., Huth-Fehre, T., Kantimm, T., Buydens, L., 1997. Application of a spectroscopic infrared focal plane array sensor for on-line identification of plastic waste. Appl. Spectrosc. 51 (6), 856–865.

Van Kessel, L., Leskens, M., Brem, G., 2002. On-line calorific value sensor and validation of dynamic models applied to municipal solid waste combustion. Process Saf. Environ. Prot. 80 (5), 245–255.

Vassilas, N., Kalapanidas, E., Avouris, N., Perantonis, S., 2001. Intelligent techniques for spatio-temporal data analysis in environmental applications. Dlm. (pnyt.). Machine Learning and its Applications. Springer, pp. 318–324.

Vicentini, F., Giusti, A., Rovetta, A., Fan, X., He, Q., Zhu, M., Liu, B., 2009. Sensorized waste collection container for content estimation and collection optimization. Waste Manage. 29 (5), 1467–1472.

Vijay, R., Gautam, A., Kalamdhad, A., Gupta, A., Devotta, S., 2008. GIS-based locational analysis of collection bins in municipal solid waste management systems. J. Environ. Eng. Sci. 7 (1), 39–43.

Wagland, S.T., Veltre, F., Longhurst, P.J., 2012. Development of an image-based analysis method to determine the physical composition of a mixed waste material. Waste Manage. 32 (2), 245–248.

Wang, S., Huang, G.H., Yang, B.T., 2012. An interval-valued fuzzy-stochastic programming approach and its application to municipal solid waste management. Environ. Model. Software 29 (1), 24–36.

Wilson, B.G., Vincent, J.K., 2008. Estimating waste transfer station delays using GPS. Waste Manage. 28 (10), 1742–1750.

Wilson, B.G., Agar, B.J., Baetz, B.W., Winning, A., 2007. Practical applications for global positioning system data from solid waste collection vehicles. Can. J. Civ. Eng. 34 (5), 678–681.

Wyld, D.C., 2010. Taking out the trash (and the recyclables): RFID and the handling of municipal solid waste. Int. J. Software Eng. Appl. (IJSEA) 1 (1), 1–13.

Xu, Y., Huang, G.H., Cheng, G.H., Liu, Y., Li, Y.F., 2014. A two-stage fuzzy chance-constrained model for solid waste allocation planning. J. Environ. Inform. 24 (2), 101–110.

Yang, K., Zhou, X.-N., Yan, W.-A., Hang, D.-R., Steinmann, P., 2008. Landfills in Jiangsu province, China, and potential threats for public health: Leachate appraisal and spatial analysis using geographic information system and remote sensing. Waste Manage. 28 (12), 2750–2757.

Zamorano, M., Molero, E., Grindlay, A., Rodríguez, M., Hurtado, A., Calvo, F., 2009. A planning scenario for the application of geographical information systems in municipal waste collection: a case of Churriana de la Vega (Granada, Spain). Resour. Conserv. Recycl. 54 (2), 123–133.

Zhao, Y., 2002. Standardization of mobile phone positioning for 3G systems. IEEE Commun. Mag. 40 (7), 108–116.

Zhao, W., Sasaki, T., Fujita, S., Ando, H., Furudate, H., Kawamata, K., Tomabechi, N., Uchiyama, H., Tanaka, N., 2005. Environmental monitoring of industrial waste using remote sensing. Phyton 45 (4), 529–534.

ZigBee. 2008. ZigBee specification. <http://home.deib.polimi.it/cesana/teaching/IoT/papers/ZigBee/ZigBeeSpec.pdf> (accessed 07.06.14)

Zsigraiova, Z., Semiao, V., Beijoco, F., 2013. Operation costs and pollutant emissions reduction by definition of new collection scheduling and optimization of MSW collection routes using GIS. The case study of Barreiro, Portugal. Waste Manage. 33 (4), 793–806.