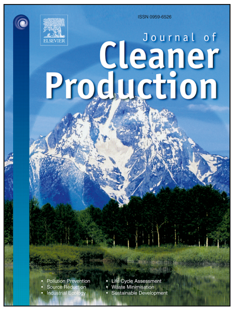

A sustainable circular economy approach for smart waste management system to achieve sustainable development goals: Case study in Indonesia

Yun Arifatul Fatimah, Kannan Govindan, Rochiyati Murniningsih, Agus Setiawan

PII: S0959-6526(20)32310-6

DOI: https://doi.org/10.1016/j.jclepro.2020.122263

Reference: JCLP 122263

To appear in: *Journal of Cleaner Production*

Received Date: 25 November 2019

Revised Date: 13 May 2020

Accepted Date: 14 May 2020

Author Contribution Statement

Equally contributed by all authors

A Sustainable Circular Economy Approach for Smart Waste Management System to achieve sustainable development goals: Case Study in Indonesia

Yun Arifatul Fatimah[a] Kannan Govindan[b, c,1] Rochiyati Murniningsih[a]
Agus Setiawan[a]

[a]Universitas Muhammadiyah Magelang, Engineering Faculty, Magelang, Indonesia
[b]China Institute of FTZ Supply Chain, Shanghai Maritime University, Shanghai, 201306, China
[c]Center for Sustainable Supply Chain Engineering, Department of Technology and Innovation, Danish Institute for Advanced Study, University of Southern Denmark, Campusvej 55, Odense M, Denmark

Abstract

Indonesia is facing a number of independently managed challenges related to the collection, transportation, processing (composting, recycling), and landfill dependence on waste management. An intervention is needed to bring stakeholders together to solve these waste challenges. The objectives of this study are to investigate the fundamental issues and opportunities and to develop a sustainable and smart country-wide waste management system. The system should provide a multi-dimensional approach, determine the maturity level of the waste management system in a technical method, and pursue the goal of designing a new strategy to minimise waste management problems. A comprehensive systematic literature review, intensive focus group discussions, and direct observation in Indonesian cities were approaches used to develop waste management business processes and their system design. Waste business processes consist of mixed-collecting, sorting, transporting, varied-treatment, and chained-disposal. The design of the proposed waste management system presents circular economy processes that can separate municipal waste, identify waste characteristics, and determine sustainable waste treatment technologies through the use of Internet of Thing (IoT) as the integrator. This study contributes to the sustainable development goals (SDG's) such as Good health, and wellbeing (SDG 3); Clean water and sanitation (SDG 6); Decent Work and Economic Growth (SDG 8); Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13). The study proposes a new design of smart and sustainable waste management which could achieve satisfactory economic, social, and environmental waste management performances.

Keywords: Sustainability; Sustainable circular economy; Smart waste management;

[1] Corresponding author. China Institute of FTZ Supply Chain, Shanghai Maritime University, Shanghai, 201306, China. kgov@iti.sdu.dk

Maturity model; Internet of Thing (IoT); Sustainable development goals (SDG's)

.

1 Introduction

Indonesia's waste problem creates a critical threat to the sustainability of the nation's economy, society, and our environment. The nation's enormous waste production demands even more space dedicated to landfills, which competes with the community's need for more sustainable sites. When landfills become overburdened, excess waste is then burned in open and uncontrolled ways or it is spilled into waterways. Both methods increase the risk of disease, pollution, and hazardous emissions for Indonesian citizens. Further, the landfills themselves, called Waste Mountains, are dangerous areas because they attract scavengers, trash collectors, and informal workers. Based on research conducted in Jakarta, Semarang, Yogyakarta, and Magelang in 2018, the mainstream of municipal waste is collected from households and traditional markets. Municipal waste is initially collected at a temporary collection point (TPS). The TPS is divided into several different area functions: 3R (reduce, reuse, recycle), TPS with multi-compartments, and TPS with waste type-based schedule. These divisions are enacted before waste is sent to its final disposal centre (TPA). The majority of waste collection activities are still conducted manually by both formal and informal sectors (Kannan et al., 2016). A regular schedule is observed, but there is a limited use of facilities or infrastructure. Most collected waste is still mixed and unsorted, because most residents do not properly separate waste.

Based on their characteristics, most collected waste is processed through composting, recycling, gasification, anaerobic digestion, or waste-to-energy systems. However, this approach has not optimally touched the economic, social, and environmental aspects of the waste management system. Regulations for waste management in Indonesia are obvious and sufficient. For instance, Law No. 18/2008 concerns solid waste management, Government Regulation No. 81/2012 addresses economic-oriented household waste management, and the ministerial decree of environmental department Act No. 13/2012 focuses on reduce, reuse, recycle actions through the waste bank. Further, the Ministerial decree of the Interior No. 33/2010 about waste management concerns the involvement of the community as waste producers in the waste management system, Ministerial decree public work No. 03/2013 governs household waste management, and Presidential regulation No. 97/2017 is concerned with household waste national policy and strategy. Despite these decrees, most waste management systems in Indonesia are still traditional and conventional. Open dumping, transferring, collecting, and landfill are the most common methods of disposal in some urban cities. A sustainable waste management system is far from standard. In short, current waste management systems are not yet integrated, participation from corporations is rare, social awareness about environmental cleanliness is limited, and government policies are not yet optimally applied.

The current waste management system is not able to identify specific characteristics, types, and amounts of municipal waste collected in the final collection centre, nor is that system able to provide sufficient, accessible, reliable, accurate, or timely information for applying appropriate treatment technologies to manage the waste in economically, socially, and environmentally beneficial ways. A comprehensive system intervention is needed to bring stakeholders together to solve these waste problems.

The use of Information and Communication Technology (ICT) and the Internet of Things (IoT) offer a new generation approach to improve the global waste management system effectively and efficiently in developed countries. The ICT-IoT integration consists of the use of local sensing, data integration, analytics of things, and cognitive action in the area of waste management. Waste activity could be real-time tracked and monitored to enable an efficient and effective waste management and to transform large and complex waste characteristics to become valuable resource, materials, and energy (Adam, Okasha, Tawfeeq, Margan, & Nasreldeen, 2018; Anagnostopoulos et al., 2017; Gutiérrez et al., 2014).

The research questions we plan to explore include:

What is the current waste management system in Indonesia?,

At what level of maturity is the current system?, and

What appropriate approaches and strategies are needed to achieve the expected level?.

This research has developed an innovative assessment to measure the existing performance of the waste management system, and we have developed a sustainable and smart waste management system based on the maturity level of the current system. The sustainable and smart waste management system provides a better decision-making process and policy supports, appropriate treatment technologies, optimal waste, and resource recovery methods, which helps to achieve sustainable development goals (SDG's). It uses minimal virgin materials and low energy consumption, low environmental degradation and pollution, and it supports highly skilled workers as it enhances social values.

The remainder of this paper continues as follows: Section 2 presents the materials and methods. Section 3 outlines the results. Section 4 analyses and discusses these results through our case study. Section 5 summarises the conclusions.

2. Materials and Methods

The objectives of this study are to investigate the issues and opportunities of developing a country-wide waste management system in the industrial revolution 4.0 era. We also seek to design a sustainable and smart waste management system with a multidimensional approach, to present the maturity level of the waste management system in its technical method, and to design a new approach of sustainable and smart waste management for Indonesian urban cities. Partially, the IOT and ICT development and implementation in the waste management value change is concerned. The study consists of the following steps:

a. Case study in four urban cities of Indonesia (i.e., Jakarta, Magelang, Semarang, Yogyakarta). These cities were selected on the basis that they have applied the smart city program through the implementation of smart environment, which also is concern with waste management; they have also agreed to participate in the study.
b. Direct observation of both final and temporary disposal centres and landfill areas of the four cities, and the waste management value chain, including collection, selection, transportation, processing, and landfilling.
c. Direct communication with and semi-structured questionnaires sent to government personnel from municipality and environmental departments, collection centre agents, scavengers, recycling industries, and the general community. The semi-structured questionnaire was a mix of questions related to waste management requirements, real case performance, challenges, and expectations to achieve better economic, social, and environmental performance. The respondents were characterised on their level of expertise and their job structure. Government personnel were selected at head of department levels and field supervisors, and collection centre agents and industry respondents were selected at the level of operation manager. The community respondents were selected at the level of community leaders.
d. Intensive discussion with circular economy and ICT practitioners and experts about relevant topics in the waste management value chain. More than 40 articles are used as reference in the study.
e. An in-depth analysis of the current situation was completed, to determine the maturity level of the current waste management, and state-of-the-art and future expectations for sustainable and smart waste management.
f. Framework development of a sustainable waste management system is performed, followed by the proposed system.

Direct observation was conducted at the municipalities of the four cities to deliver the semi-structured questionnaire. Questions focused on these central issues:

a. What – regulation (i.e., legal policy), waste type (i.e., physical, chemical, biological), waste characteristics (i.e., organic, non-organic), facility capacity (i.e., year, month, day), waste transportation vehicles (i.e., truck), treatment technology (i.e., composting, recycling), ICT and IOT adoption, future development.

b. Where – sources, location of collection centre, final disposal centre, temporary disposal centre, and landfill area, distance from civilization, transportation route.
c. Who – recyclers, city municipality, scavengers, community, government, NGO, recycling industry, direct and non-direct labourers, private company, investors.
d. When – waste management schedule, facility maintenance, established date.
e. How – volume, route, selection method, distance, number of scavengers, waste management promotion, managed waste volume, unmanaged waste volume, processed waste volume, supply chain, waste level, GHG level, automation.

Some examples of questionnaires are presented as follows:

a. Where is the site location of the temporary and final disposal centres? Are they near to the community? How far is the distance between the temporary site to the final or to the landfill centre?
b. What are the treatment processes conducted in the centre? Are there specific selection or segregation methods applied before the waste is transported to the next step?
c. What are the transportation tools and vehicles used to transfer the waste from centre to centre? Please include the tools used and the vehicle capacity and type.
d. How many labourers are involved in the waste management process in the city? Are these labourers formal (i.e., government staff in waste collection centres) or are they non-formal labourers (i.e., scavengers or waste pickers)?
e. What are the types, volume, characteristics of the waste (i.e., physical, biological, chemicals, non-organic and organic wastes) found in the waste management area?
f. What are the sources of the waste (i.e., community, markets, industry, and schools)?
g. What are the treatment technologies and infrastructure applied in the area? Include recycling, reuse, recondition, ICT, and IoT usages.
h. What are the regulations, policies, community commitment, and local wisdom available in the cities?

In total, there were 78 respondents willing to answer the questions. The results were analysed to identify the current issues and opportunities of the industrial revolution 4.0 waste management.

The state-of-the-art of the waste management system in the industrial revolution 4.0 (i.e., digitalization, environmentally conscious, socially aware) gathered from the experts' contributions and publications were used as the fundamental ideas to develop the framework of sustainable and smart waste management. The literature review relevant with waste management topics, including digitalization in industrial revolution 4.0, IoT for waste management, smart waste collection system, circular economy, and IoT were evaluated and identified to understand the contributions of previous research.

Furthermore, an in-depth research on current waste management and its treatment technology in Indonesia was conducted for 2 years (2018 to date). The results gained from this research were collected to determine the current maturity position of the sustainable waste management in Indonesian cities. A number of regulations, policies, and strategies applied by the local and national governments were intensively discussed for better future approach.

3. Results

3.1 Research method implementation

This research consists of several stages, including determining the research questionnaire, developing case studies, determining the maturity level, developing multi-dimensions of sustainable and smart waste management, and analysing the gap to determine the current maturity level of each city we investigated. The maturity levels of the current waste management are ultimately used to develop a newly designed smart waste management system.

3.2 Case study on urban cities

As mentioned in the previous section, we interviewed in four urban cities (Semarang, Magelang, Yogyakarta, Jakarta) and to various stakeholders (scavengers, waste collection agencies, community, recycling industry). Individuals were interviewed regarding the existing performance of their waste management and future opportunities. From these five main question areas, specific open-ended questions were formulated. The questions were given to respondents at the four cities through direct interview, mails, and communication. The results of the direct interview and communication are presented as follows.

Semarang waste management

Semarang is the capital city of Central Java. Jatibarang is the centre of waste disposal area of Semarang City. To reduce the amount of waste, the Semarang Government uses a 3R strategy under the national regulation number 18/2008 about waste management. Integrated waste management is located in the centre of Semarang City and is controlled by the Environmental Department. There are two waste management facilities that belong to Semarang City: a final disposal centre (TPA) at Jatibarang, Kedungpane, and Mijen, and a temporary disposal centre (TPST) at Jatisari, Mijen. The TPA was built in 1993 and still has 9 years to be used. The area of TPA is about 46.44ha and the usable area is about 23.22ha. Sanitary landfill is the operation system conducted in the TPA. To manage the liquid waste created, the TPA is facilitated with leachate IPAL, disposal zone, drainage and operation line gate, and the development of methane (CH4) for household gas and electricity energy. The distance from the community area is about 2 km away, the distance to the nearest water body is 2 km, and the distance to the beach is 10 km away. The waste management operation in the TPA is under the DELH environment regulation, and it is managed by the Environment and Life Department. On the other side, the TPST was built in 2010 under the Analysis of Environment Management protection. To manage the waste, the operation system segregates the waste and runs composting. The total area of the TPST is about 2ha and the use of the area is about 2ha. The distance from TPST to community area is about 2 km, the distance from TPST to water body is 2 km, and the distance from TPST to beach is 10 km. Instead of a governmental department as overseer, the waste collector industry and scavengers are two main informal elements involved in the waste management system in Semarang. It is found that the average waste collector is able to collect about 50kg waste per day, while scavengers collect 5kg per day. Waste management is conducted by Government Environmental Agency by the help of PT Narpati, which changes the organic waste into granule compost and, secondly, changes the organic waste into refuse-derived fuel. The final collection centre is at Jatibarang with the area size of 46,0183ha. Methane gas created from the waste is distributed to the community as cooking gas. Through cooperation with Denmark, it is expected to generate about 1.2MW of electricity. Non-valuable waste is dumped and managed using sanitary landfill; the waste is covered with land. The waste generated in Semarang is 62% organic and 36% inorganic. Waste volume is about 900 tons/day, and the capacity of the waste management in the TPA is 1200 tons/day. The flow of waste starts from community level waste collection, then is sent to TPS using community vehicles, and finally sent to TPA by the environmental agency trucks. There are about 268 TPS located in the Semarang area. The type of waste consists of plastic, steel, rubber, paper, food waste, garden greens, and dry branches.

Magelang waste management

The waste management system is still a big problem for Greater Magelang including Magelang City and Magelang Regency. Waste generation in Magelang City reaches 0.4 kg per person per day, while Magelang Regency generates 0.47 kg per person per day in 2017. This creates a significant amount of waste: 19,000 tons per year for Magelang City and 236,000 tons of waste per year for Magelang Regency. Organic waste in Magelang City is about 74% of the total waste, while organic waste for Magelang Regency is about 54% of the total waste. Waste management (servicing, management, collection, processing) is regularly conducted by the city’s and regency’s Environmental Agency every day. The City of Magelang has no waste disposal centre due to its limited area. Currently, waste from the city municipal is sent to a final disposal centre that belongs to Regency of Magelang. TPS is the temporary collection centre (transfer station) in which waste is separated into recycled waste (TPS 3R) and non-recycled waste. The city has 5 TPS 3R and 13 transfer stations. The environmental agency of the city has 200 employees for managing the waste, while the environmental agency of the regency has 194 employees. Three-wheeled motors, pick-up cars, and trucks are transportation vehicles used in both cities. The waste treatment technologies applied in the city consist of composting, leachate treatment, landfill gas collection. However, limited technology, human resources, and financial support to provide appropriate treatment technology are a big challenge for Magelang City to manage their waste sustainably. In addition, many informal sectors, including scavengers and private waste collectors, work independently in unhealthy and dangerous workplaces.

Yogyakarta waste management

The waste management system in Yogyakarta or called Jogja is conducted by two Agencies, including the Provincial Environmental Agency and the Regional Development Agency. Regulations stem from local government decree number 10, 2012 about waste management. The waste is collected from the community and then sent to a temporary collection centre before it is sent to a final collection centre. The contributions of waste generation in Yogyakarta come from municipal, hospital, hotel, and tourism areas; other city waste collected and managed by the Environment Service Agency is about 200 tons/day or about 10-15 trucks daily. The number of labourers involved in the waste management is about 430 individuals, consisting of 170 technicians, 160 government labourers, 80 segregators, and 20 non-government labourers. There are also about 500 scavengers and 500 cows at the final waste collection centre (TPA). The primary challenge faced by Yogyakarta waste management system is a lack of community awareness on waste management. The final disposal centre is a regional TPA in which waste comes from Sleman (30%), Yogyakarta City (50%), and Bantul (20%). The TPS is not fairly distributed to Yogyakarta area. A lot of waste comes from Sleman and its surrounding area. Waste is mounting steadily in the Yogyakarta TPA. Technically, the waste sent to TPA from TPS uses 6 truck deliveries, and the labour is 24 hours standing by to clean the TPS. The waste in TPS is not 100% non-organic; the most waste is residue. The number of depots is about 11 units. Cow farming in the waste area belongs to the community. Disposal waste costs about 200 million per month for 25 thousand tons. The city's budget per year is 20 billion. Total expenditures of 20 billion consider about 16 billion for waste, and 4 billion for fuels. The benefit retribution is about 3.3 billion and it is returned to community at a rate of about 25%. The community is charged for waste collection activity with a current rate of about 200 thousand to 1 million rupiah/family.

Jakarta waste management

Waste management in Jakarta is conducted by the Provincial Environmental Service Agency with large areas landfilled without a treatment facility. In Jakarta, sanitary landfilling takes place. The landfill area known as “Pyramid” has developed simple water treatment installation (IPAS) technology through water filtering from waste. Powerhouse/electricity booths that convert methane to electricity are available. Composting from traditional market waste produces 40 tons of compost/day. Bantar Gebang is the integrated waste processing site for Jakarta city. Jakarta produces nearly more than 10 million tons of waste annually, and this amount increases 2-4% annually; it is expected to exceed the waste management capacity by 2019. The main waste in Jakarta is organic waste, which comprises about 74% of the total waste. It is predicted that by 2019, the volume of waste in Jakarta will reach 7.8 thousand tons/day. Household (municipal waste) is the largest waste source, followed by traditional markets. To improve waste management, Jakarta’s government has introduced some eco-technology through TPST, TPST 3R, and intermediate waste facilities, composting, and waste banks. Waste to Energy is one potential treatment technology project planned to reduce Jakarta’s waste.

3.3. State-of-the-art sustainable and smart waste management

A literature review of current organic waste management and treatment technology for developed countries, including US, Canada, Mexico, Australia, NZ, Japan, and the European Union, found that the waste management and treatment technology is rapidly improving with more efficiency and greater environmentally sound practices. Developed countries place greater emphasis on the advantages of modern engineered landfills, recycling technology, incineration, mechanical biological treatment (MBT), and anaerobic digestion. Other emerging countries, such as China, India, and Asian countries (Indonesia, Malaysia, Philippines), emphasise composting, limited incineration, MBT, and anaerobic digestion (Artiola, 2019; Damanhuri et al., 2014; IA. Jereme, Siwar, & Alam, 2014; Islam, Hannan, Arebey, & Basri, 2012; Jouhara et al., 2017; Tchobanoglous, Theisen, & Vigil, 1993; Woodard & Curran, Inc., 2007). Those waste management and treatment technologies offer some benefits, including economic (affordable), social (new job, safety), and environmental (low GHG emission) to manage the waste. Waste management is a complex activity that not only concerns disposal activity, but also focuses on collection systems, transportation, temporary storage, processing, and disposal. Instead of strictly implementing 6R strategy, developed nations like US, UK, Australia, and Japan have applied advanced methods of waste collection such as underground waste collection systems, Geographic information system (GIS) technology, solid waste bin monitoring system using GSM technology, and indoor/outdoor waste compactors (Wajeeha, Ayesha, Muneeba, Fatima, & Ghazala, 2016; Yoshida & Yoshida, 2012). Underground waste collection system is a new technology of waste storage that replaces technologies such as waste bins with underground collection points for collecting recyclables, organic wastes, and oils. The technology is suitable for extremely hot climates, requires less maintenance, and is more aesthetically acceptable. GIS technology is an integrated application dedicated to individual or association municipalities to manage optimally and automatically each phase of the waste entire chain/cycle from waste production point to recycling/treatment point or final disposal point (landfill). The latest technology for waste collection and monitoring is Global System of Mobile (GSM) (Hannan, Arebey, Basri, & Begum, 2010). This technology uses sensors that are placed in public garbage bins to assess the optimal level of waste inside of the bin (Misra, Das, Chakrabortty, & Das, 2018). When the garbage touches the threshold level, through SMS using GSM, the sensor will send an indication to controller, and further sends an indication to the collection truck driver to collect garbage immediately. Compact garbage collection trucks are the latest technology used by many developing countries in order to increase the collection capacity of vehicles. Due to narrow roads, some waste compactors are designed in small collection trucks using lightweight materials for optimising the load capacity.

Along with the development and implementation of smart city technologies and platforms, new solutions for intelligent waste collection and sorting are being developed. While an intelligent garbage collection system using information technology and computers is still in its initial phase, Smart Bins have begun to be used to collect garbage. Smart Bins are trash bins equipped with ultrasonic sensors with the function of measuring the space of the trash can. A sensor gateway uses the WLAN protocol, and the collection, analysis, and visualization of junk data uses the cloud platform. Some literature presents IoT platforms for waste management, such as Zanella and Vangelista who present IoT platform solutions for the smart city, with a case study on the city of Padova (Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014). In Romania, the garbage collection system for the historic city centre of Sibiu was developed based on several parameters: garbage volume (which is variable due to seasonal events), composition of waste, source concentration, current infrastructure, distance from the source, and the level of public attention (Ciudin et al., 2014). In Sweden, the automatic waste collection system is limited to four types of waste: general waste, organic waste, recycled paper, and cardboard. This system cannot collect WEEE, batteries, light bulbs and fluorescent lamps, hard sheets, glass receivers, etc. (Bernstad, La Cour Jansen, & Aspegren, 2011).

The further step, one that is very important in waste management, is known as waste processing. Autoclaving, fluffing, and melting technology are the latest technologies for waste processing (Gao

& Li, 2011). Autoclaving technology applies steam treatment to the waste at 140-160 degrees C for 30-40 minutes in order to sterilize the waste, and then the residue can be screened. In this process, waste is separated on the basis of weight, while glass and dirt are removed from organic fibres, and metals and plastics are sent to the recycle process. The organic fibre is used for land applications and Refuse-Derived Fuel (RDF) production (Sarc & Lorber, 2013). Fluffing is a waste processing technology in which the solid waste is separated and sterilized, and the organic portion is processed to become pulp material known as fluff. This technology produces fluff rich with organic base and high nitrogen. A lot of western countries adopt this technology with some recycling rates achieving 95% of total waste. The next current technology examined by both developed and developing countries is melting technology, which can melt the waste through fuel and electricity combustion to reduce the waste volume. This technology is better than incineration, as it solves the fly ash problem and stabilises metal portions. Incineration technology is a thermal waste treatment in which untreated waste is burned at a high temperature. Some European countries (UK) have applied this technology to process their waste. The Japanese have introduced a new incineration technology which is pollutant free by recycling ash and removing the acidic gases through a control technology. Vermi composting is the latest common technology used by Japan and UK, in which animal, pharmaceutical, food, and sewage wastes are transformed through earthworms into vermi wash which contains high nitrogen, phosphate, and potassium contents. Energy recovery technology is the last phase before disposal process, in which all waste residues are inaugurated for a renewable energy alternative. This technology consists of bio and thermal conversion technologies. Thermal conversion is water/heat pressure utilised technology that converts organic and inorganic waste (plastics, computer, tires) into useful chemicals and compounds through a thermal processing system. The next technology is advanced thermal treatment technologies, which include pyrolysis, gasification, and excluded incineration. Pyrolysis converts waste to liquid or gaseous fuels together with the residue, which is a combination of non-combustible material and carbon. Gasification presents partial oxidation of a substance, which occurs between combustion and pyrolysis. Gasification products are similar to pyrolysis, and include syngas and low C ash. Gasification is economically and environmentally sound technology to maintain landfill sustainability. Biofuel can also be produced from food waste through a variety of fermentation processes. Currently, hydrogen, ethanol, biodiesel and biogas are produced by using valorization, which is a thermopile process without biogas recirculation involved (Artiola, 2019; Millard, 2017; Ministry of the Environment, 2012; Srivastava, 2016; Tisserant et al., 2017; Wajeeha et al., 2016).

The last step of waste management system is the disposal process, in which the invaluable waste that comes from residue of trash, recycling, and other treatment technology is disposed. As disposal is the most technical step, some advanced technologies are urgently required to be developed. Most disposal sites in developing countries are still open dumps, without appropriate leachate treatment and landfill gas utilization; therefore, they cause many aesthetic and other environmental issues. Landfill is an efficiently engineered depression in low population area for final disposal. In this depression, the waste is buried to avoid any hydraulic relation between trash and environment (air and water). Bioreactor is one of the latest technologies to process waste disposed. The objective of bioreactor is to improve the decomposition rate, leachate circulation, and microbial growth. The conventional landfill technology is used to dry the waste. The latest technology is to generate electricity from waste through micro turbines, which are optimally applied to small scale projects. The technology can reduce the issue of pollution and emissions of landfill gas air. The Indonesian sanitary landfill, a major disposal activity, is designed as monitored landfill. However, the waste source is operated under an open dumping system which creates serious environmental problems (Bronson, 2017; Pariatamby, A. & Tanaka, 2015; Rawlins, Beyer, Lampreia, & Tumiwa, 2014; H. Sudibyo et al., 2017)

3.3 Developing Multi-dimensions of Sustainable and Smart Waste Management

Sustainability has become a topic of debate and it is a target achievement for many countries (Govindan et al., 2020a). Also, sustainability turn into a fundamental part of waste management, Sustainable waste management is a circular feedback system which concerns process activities, adaptability, and the diversity of waste from manufacturing to disposal phase (Seadon, 2010). Industrial Revolution 4.0 has brought significant changes in global waste management and value changes (Chen, Wang, Huang, Huang, & Tsai, 2018). That framework consists of five aspects, including governance, economy, social, environmental, and technological.

Through the implementation of IOT, digitalization, and ICT, achieving sustainability in waste management is becoming more possible, reliable, transparent, efficient, and optimum in the industrial revolution 4.0 era. IOT and ICT applications can help reduce the time and resources required to provide better performance of waste management toward sustainable and smart systems (Abdullah, Alwesabi, & Abdullah, 2019). Therefore, the use of IOT, digitalization, and ICT in waste management is an interesting pursuit because it brings more economic, social, and environmental opportunities for waste businesses. Smart waste management presents an automatic, integrated, and connected system and provides great economic opportunities for municipalities, waste industries, and the community in the fields of collection (e.g., route optimization), segregation (e.g., waste identification), and treatments (e.g., recycling, remanufacturing, reconditioning) (Abdullah et al., 2019; Antikainen, Uusitalo, & Kivikytö-Reponen, 2018).

However, there are several challenges faced by Indonesia in achieving sustainable and smart waste management. Those challenges include financial supports, technical capabilities, political conditions, institutional capacities, and social issues (Aprilia, Tezuka, & Spaargaren, 2013;

Damanhuri, Handoko, & Padmi, 2014; Hanifrahmawan Sudibyo et al., 2017). In these cities, waste management cost is high, while the revenue or income/profit gathered from the waste management process is low. An ideal framework should provide a better solution that represents higher economic value by optimising waste management and treatment technology and facilities. The other challenge is a lack of information and data about real waste management cost requirements as they apply to their processes and technologies. Furthermore, the amount of waste sent to landfills increases the cost of waste management. A secondary challenge is the lack of technically-skilled local people and government staff who can practice effective and efficient waste management and treatment. The quality of the waste itself, because it is mostly mixed dirty, is another challenge for Indonesian waste management. If the waste is mixed and dirty, it requires special treatment to separate the various components and to make them ready to be processed.

Therefore, it is important to apply waste collection activities in the beginning process of waste, at the source. In addition, the availability of an integrated, clear, and transparent waste management process and sufficient information are both critical elements to achieve ultimate value and to minimise the cost of the waste management system. Another objective of the waste management system is to improve the population's social performance and the community by reducing the impacts of waste. Social impacts include the desire to minimise the decline of the environment, and to improve the cleanliness and health of the community, to augment conservation efforts, and to provide labour opportunities for employment. The huge amount of waste sent to landfills shows that community awareness of the importance of waste reduction is still low. In addition, the work opportunity given to scavengers (waste pickers) often risks the health and safety of that individual due to lack of waste facilities. Greater attention to health and safety issues, and more informed participation and cooperation from citizens and the public is needed to make waste management socially viable. Good governance plays a key role in smart waste management. However, implementing sustainable waste management requires participation from both political and other official stakeholders. Appropriate regulations, technology selections, ICT and infrastructure development, and effective waste management operations need local and national government participation and coordination.

A fundamental framework of the circular, sustainable, and smart waste management is developed through the value chain process of waste management. That circular process (use, selection, sorting, technical recovery, biological recovery, energy recovery, and landfill) (Kannan et al., 2020; Govindan et al., 2020b) is illustrated in Fig. 1. The four dimensions of governance, economic, social, and environment become the drivers in the framework. Information and data management through IOT and ICT intervention is located at the centre of the system. Internet of things (IoT), a new generation technology, is applied in this system for information and data integration, sharing, and connection in the waste management value chain. The concept of IoT consists of local sensing, data integration, analytics of things, and cognitive action. In the area of waste management, the IoT could provide track waste identification in real time. Connected devices allow for the tracking of products, components, and materials, and that promotes efficiency in recovery and reuse of the waste.

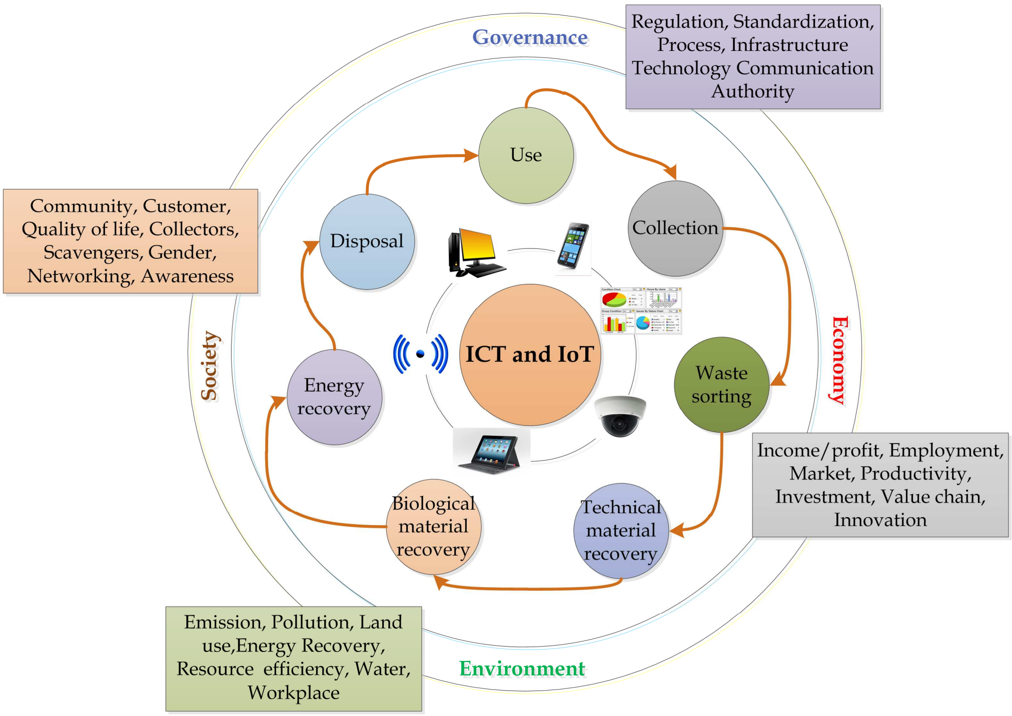

Fig. 1. Fundamental framework of Sustainable and Smart Waste Management System

Fig. 1 shows how the ICT and IOT are designed as the core of the waste management system. The waste management system is integrated through the establishment of appropriate IOT and IOT infrastructures, in which some automatic technologies are adopted to improve the productivity and efficiency of the waste system. The ICT and IOT solutions should be uniquely aligned with social, economic, and environmental aspects and they should maximise the benefits of the system.

Details of the framework and each aspect are elaborated below. Also explained is how these aspects relate to each other, and a categorization of the levels of their sub-aspect. Each dimension has several subdimensions that has different characteristics as presented in Table 1.

Table 1: Sustainable / Smart Waste Management Dimensions

Dimension	No	Features – sub dimension	Infrastructure, facility
Governance	1	Use of information and communication technology for collecting, sharing, and receiving waste data	Radio, telephone, newspapers, mobile phone, website portal system, forum, apps - local to local, local to national government
	2	Community participation through a	Suggestion boxes, community feedback website

		system which collect community voices	portal, interactive discussions between government and citizens
	3	Easy access to government funding, and transparency and accountable investment	Available open and free data online
	4	Regulation, guidelines and standard operational procedure to follow on waste management	Waste collection, selection, disposal regulation, guideline, standard operational procedure
	5	Availability of interaction channel between community, government and industry	Online waste management report, waste transaction online, funding scheme
Economy	1	Affordable cost of waste management and service	Minimum Service cost per month
	2	High productivity of waste treatment process cost	Potential Material and labour productivity
	3	Low cost resource consumption	Opportunity cost earned from landfill reduction
	4	Job opportunities	Employment gains through waste management activities
	5	Affordable infrastructure and technology investment	Low maintenance and operation cost
	6	Availability of purchasing, marketing and promotion division	Financial benefits through smart, intelligent purchasing, market identification
	7	Potential reduction cost from green campaign and initiative	Clean up community activities and behaviour changes
Social	1	Level of safety and healthy life of people in the area of waste management	Health and safety insurance and facilities, life expectation of waste worker
	2	Skilled labour and knowledge of the employee in the area of waste management	Certification, salary improvement, carrier opportunities, human resource development
	3	Solid coordination between employee and employer.	Routine and scheduled meetings
	4	Improvement of community's living capacity	Freedom of organisation and association participation
	5	Education to community, industry to reduce waste, and to increase resource efficiency	Availability of formal and non-formal education to community and industry
	6	Informal sectors participation through Government supervision	Supervision programs from local government to voluntary scavengers, waste private collectors
Environment	1	Ultimate amount of wastes collected	Maximum amount of waste collected
	2	Ultimate amount of wastes processed, recycled, composted etc.	Maximum amount of waste processed
	3	Appropriate waste management value	Efficient collection, sorting, transportation, disposal

		chain	
	4	Low carbon emission of waste management process	Potential CO_2 and methane emission reduction through landfill minimisation
	5	Efficient resource consumption and production	Energy recovery and material savings from waste treatment process
	6	Environmental protection and hazardous reduction activities	Minimum effects on environment and humans
	7	Contamination hazard to ground water, air	Amount of waste water, dust and litter in the waste area
Technology	1	Use appropriate technology to transform waste into valuable materials/energy in the cities	Waste treatment technologies
	2	Wide application of digitalization, ICT and IOT from collection to treatment	Appropriate sensors, GPS, mobile application, cloud system used in waste management
	3	Wide implementation of automatic technology from collection to treatment	Suitable automatic system, robotic, automatic conveyor
	4	Availability of transportation vehicles	Number of trucks, cranes, excavators
	5	Efficient Energy consumption technology	Number of Green or renewable tchnologies

3.2. Determining Maturity levels

In this section, a maturity level is a set of structured levels from the lowest level to the highest level which describes how good the government, organisation, business, community and technology manage waste from five points of view including governance, social, economy, technological, and environmental dimensions. Each dimension has several components as illustrated in the following section. **Governance dimension -** There are three maturity levels differentiated in the Governance perspective: low, mediocre, and advanced. Low governance refers to a basic governance performance which is characterized by an unforced legal waste management system, and the society is not involved in the public waste management system. Mediocre governance is considered adequate or average performance; generally, one finds contemporary values and practices of public waste management in existence. Advanced governance is the way waste management is managed in the highest-level organizations. Advanced governance works coherently, with discipline and accountability, and it involves participation from all stakeholders. **Social dimension -** Social dimension is strongly related to people, their life and interactions which are an essential part of the sustainability of waste management. The social dimension considers five maturity levels: legal, organizational, technological, management and procedure, and human competency. Legal waste management is operated under institutional and legal processes by the local government and it is based on national regulations and policies. The organizational level demonstrates that waste management is operated by an organization with a formal structure, which has goals at the level strategic to be achieved. The technological level refers to the implementation of technology to boost labour productivity of waste management. Management and procedure shows how the workflow in the waste management process operates. The fifth maturity level in the social dimension consists of human competencies. Waste management occurs due to the work of a set of labourers or skilled people with specific characteristics; their skills enable the efficiency of the system's job performance. **Economic dimension –** Three maturity levels, including slow, fast, and advanced, are present in the economic dimension. A slow economy prevents or hinders the receipt of economic value or benefits from the waste management business process. When economic values decrease or stagnate, business processes tend to be unprofitable. A fast maturity level refers to a real, verifiable growth in the waste business which can be measured. An increase in investments in the waste management business contributes to a healthy economic development, and an increase in the labour force, technology, and human capital are reasonable expectations. The advanced maturity level refers to highest level of economy performance available in the system. This waste management is more developed and features advanced technologies, infrastructure, and facilities. Importantly, an advanced economy waste management system is able to significantly transform waste into valuable money. **Technological dimension –** Technology has three maturity levels: common, variety, and diverse. Common technology is known, easily available and commonly used in waste management. Variety means that the technology or system applied in the waste management has different types, categories of collection, transportation and treatment technologies. A diverse technological level is the highest level of sustainability and it shows a great deal of variety; these technologies are different, specific, and unique in some certain process. **Environmental dimension –** Environmental has three maturity levels: low, medium, and high. A low maturity level means the environmental impacts are seriously affecting human and environmental performance. Medium means there are environmental impacts but also that some preventive and curative actions have been taken. High maturity means there are few or zero human and environmental impacts. Fig. 2 presents the multi-dimensional sustainable smart waste management.

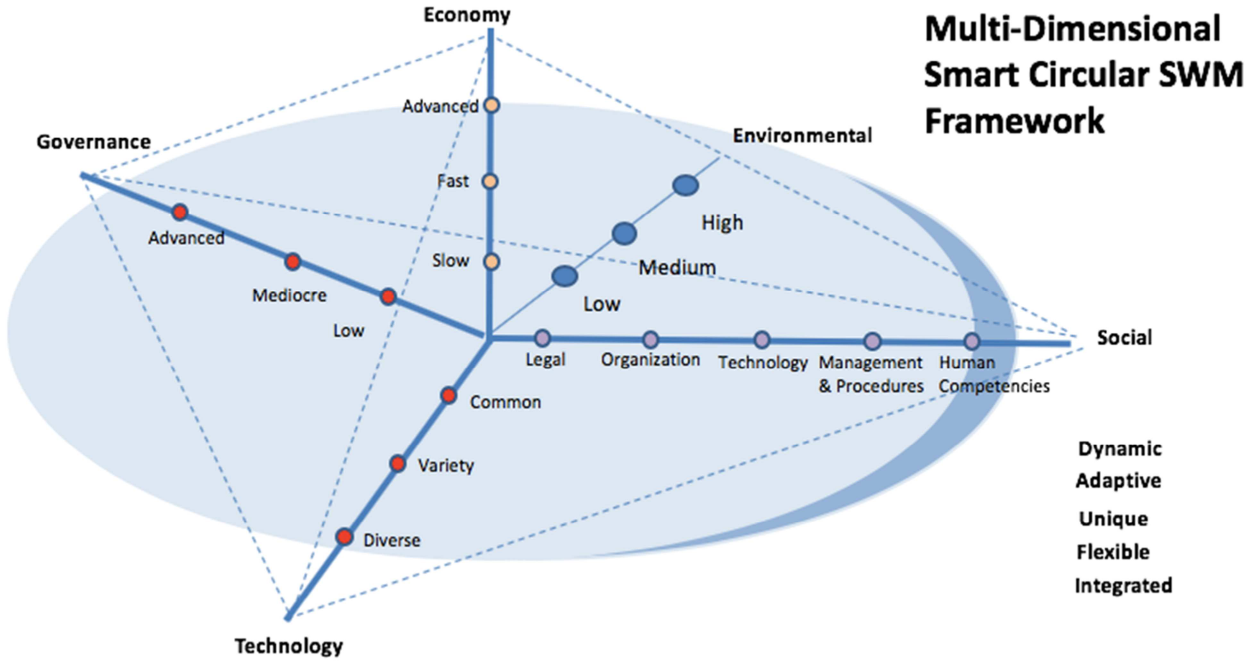

Fig. 2. Multidimensional Sustainable and Smart Waste Management Framework

In addition, we identified five maturity stages of waste management including traditional, common, organised, integrated, and smart, all of which are scored in Table 2. The maturity level of the waste management will depend on the score assessment which was adjusted for relevant intervals based on the scale linkers used in this study. A waste management will be categorised or ranked as traditional if it scores 30-42; common if the system scores 43-57, organised if it ranks 58-72, integrated with a score between 73-85, and smart for ranking 86-102.

Table 2: Score card of the maturity levels

Score/Dimension	Traditional	Common	Organised	Integrated	Smart
Governance	5 - 7	7 – 8	9 – 10	11 – 12	13 – 15
Economic	7 – 9	10 – 12	13 – 15	16 – 18	19 – 21
Social	6 – 10	11 – 14	15 – 19	20 – 24	25 – 30
Environmental	7 - 9	10 – 12	13 - 15	16 – 18	19 – 21
Technological	5 - 7	8 – 9	10 – 11	12 – 13	14 – 15
Total	**30 – 42**	**43 – 57**	**58 – 72**	**73 - 85**	**86 – 102**

The stages are determined based on the performance of the governance, economic, social, environment, and technological aspects of the system. These five maturity stages are outlined in the following section.

Level 1 – Traditional: The traditional waste management system involves limited facilities and technology with minimum machinery and automation. It is mostly manually operated, and no standard process and procedure exists. Regulations are applied at the very basic standard to meet government requirements, and there is little participation from the community and citizens. Further, there is a lack of communication between municipal departments. The ICT investment is limited to the use of SMS alerts for waste data confirmation; there is a lack of skilled workers, a lack of regulation compliance, and no communication channels between departments. Key approaches for reaching a higher level include stakeholder identification and involvement, management improvements that focus on technology applications, and building a citizen and community base.

Level 2 – Common: The waste management is addressed to meet waste regulations with a primary focus on accessibility to the collection process; waste management is set to be semi-automatically operated. There is communication between departments to handle the waste; however, there is still a lack of coordination between stakeholders. ICT applications are used for basic communication, and regulations drive the waste management process. A minimum number of skilled workers are employed. Key directives for achieving a better waste management system are grounded on changing community behaviour and cultures, implementing basic automatic machinery and technology, complying with minimum regulations, improving basic communication channels and augmenting environmental awareness. Finally, improving awareness of policies and regulations, and adding relevant information on waste management system, processes, and procedures is needed.

Level 3 – Organised: The waste management has an efficient, streamlined, effective waste process, with average skilled workers, total regulation compliance, established communication channels between department, some community participation, and some participant/management levels demonstrated in the environmental awareness of employees. Key approaches to augment an organised system should focus on improvements in community behaviour, knowledge and skills of waste workers through both formal and informal education, promoting worker productivity through automation and improved monitoring, ICT investments, a website to disseminate and to promote waste management activities and to share pertinent information such as pick up services and new regulations. The expected level of the current waste management performance in the four cities is organised, since smart cities, including those with smart environments, have achieved the integrated level.

Level 4 – Integrated: This waste management system is modern and is aligned with the behaviour of the people; this system is comprehensively and intensively integrated to reduce global waste. This system employs standard skilled workers, operates beyond regulatory compliance, presents a high level of communication and transparency, and involves all management levels in a culture that values environmental awareness. Key approaches here rest on collaborating or contracting with the recycling industry, changing management structure, data integration, and boosting community engagement and participation.

Level 5 – Smart: The smart waste management system is globally connected through the entire system. Waste treatment values are considered in decision making, automatic technology and systems are employed to achieve efficiency, waste data and information are integrated in big data centres using IoT systems, workers are highly skilled, the community is naturally involved, insurance or other initiatives are available for health, hygiene, and safety occupations, the system's compliance style is founded on self-regulation, all information is available real time, and all personnel are committed to a culture of environmental awareness.

Instead of multiple dimensions, the waste management system has several different characteristics including dynamic, unique, adaptive, flexible, and integrated:

a. Dynamic - waste management constantly changes in terms of its content, volume and location; however, they have capacity to dynamically manage the changes.
b. Unique - Even though the waste management system has many things in common, but SWM may have uniqueness and creativity in managing the waste from one place to another.
c. Adaptive - The degree of technology applied to SWM may differ, but it remains adaptive to change.
d. Flexible - The waste management can be easily modified to respond to altered circumstances and sustainability requirements. Technology and IOT are partially used as the inter-operability communication tool.
e. Integrated - The maturity level of all aspects reaches the highest level, integrated waste management systems, automatic and high-tech technology, IOT and big data are used to integrate the system.

The following Table 3 interprets waste management characteristics based on their maturity level.

Table 3: Interpretation of waste management characteristics based on maturity levels

Characteristic	Features	Traditional	Common	Organised	Integrated	Smart
Dynamic	Waste management constantly changes in terms of its content, volume and location; however, they have capability to dynamically manage the changes.	Y	Y	Y	Y	Y
Unique	Even though the waste management system has many things in common, but SWM may have uniqueness and creativity in managing the waste from one place to another.	N	Y	Y	Y	Y
Adaptive	The degree of technology applied to SWM may differ, but remains adaptive to change.	N	N	Y	Y	Y
Flexible	The waste management can be easily modified to respond to altered circumstances and	N	N	N	Y	Y

	sustainability requirements. Technology and IOT are partially used as the inter-operability communication tool.					
Integrated	The maturity level of all aspects reaches the highest level, integrated waste management systems, automatic and high-tech technology, IOT and big data are used to integrate the system.	N	N	N	N	Y

.

3.4 Gap analysis through direct assessment

Table 4 represents all data related to waste management in Indonesian urban cities gathered from the questionnaire and interviews of government staff and stakeholders. The waste management dimension of the Indonesian urban cities shows different performance levels. Governance aspects present good performance of the regulations, guidelines, and standard operational procedures to follow on waste management and of the availability of interaction channel between community, government, and industry. However, negative performance is found on the use of information and communication technology for collecting, sharing, and receiving waste data, community participation through a system which collects community voices, easy access to government funding, and transparency and accountable investments for waste management. Table 4 presents the assessment analysis of the sustainable and waste maturity level.

Table 4: Assessment analysis based on maturity score of Indonesian cities

Dimension	**Features**	Maturity score				
		Threshold	Jakarta	Magelang	Semarang	Yogyakarta
Governance	1. Use of information and communication technology for collecting, sharing, and receiving waste data	3	2	1	1	1
	2. Community participation through a system which collect community voices	3	2	1	1	1
	3. Easy access to government funding, and transparency and accountable investments for waste management	3	1	1	1	1
	4. Regulations, guidelines, and standard operational procedures to follow on waste management	3	2	2	2	2
	5. Availability of interaction channel between community, government, and industry	3	2	1	2	1
	Total score	15	9	6	7	6
Economy	1. Affordable cost of waste management and service	3	1	1	1	1
	2. High productivity of waste treatment process	3	2	1	2	1
	3. Low cost resource consumption	3	1	1	1	1

	4. Job opportunities	3	3	3	3	3
	5. Affordable infrastructure and technology investment	3	2	1	1	1
	6. Availability of purchasing, marketing, and promotion division	3	2	2	2	2
	7. Potential reduction cost from green campaigns and initiatives	3	1	1	1	1
	Total Score	21	12	10	11	10
Social	1. Level of safety and healthy life of people in the area of waste management	5	3	2	2	2
	2. Skilled labour and knowledge of the employees in the area of waste management	5	3	2	2	2
	3. Solid coordination between employee, industry and government	5	2	2	2	2
	4. Improvement of community living capacity	5	3	3	3	3
	5. Education to community, industry to reduce waste and to increase resource efficiency	5	3	3	3	3
	6. Informal sectors participation through Government supervision	5	2	2	2	2
	Total score	30	14	12	12	12
Environment	1. Ultimate amount of wastes collected	3	2	2	2	2
	2. Ultimate amount of wastes processed, recycled, composted etc.	3	1	1	1	1
	3. Appropriate waste management value chain	3	1	1	1	1
	4. Low carbon emission of waste management process	3	1	1	1	1
	5. Efficient resource consumption and production	3	2	1	2	1
	6. Environmental protection and hazardous reduction activities	3	2	2	2	2
	7. Contamination hazard to ground water, air	3	2	1	1	1
	Total score	21	11	10	11	10
Technology	1. Use of appropriate technology to transform waste into valuable materials/energy in the cities	3	1	1	1	1
	2. Wide application of digitalization, ICT and IoT from collection to treatment	3	1	1	1	1
	3. Implementation of automatic technology from collection to treatment	3	1	1	1	1
	4. Availability of transportation vehicles	3	2	2	2	2
	5. Efficient energy consumption technology	3	1	1	1	1
	Total score	15	6	6	6	6

4. Discussion

4.1. Maturity level of current waste management system

Despite positive maturity levels that exist in the governance, social, and economy dimensions of waste management, the maturity levels in the environment and technology dimensions are still at a low position. Fig. 3 shows the data gathered from the survey conducted in the urban cities which assesses the environmental aspects of the waste management. Ultimate amount of wastes processed recycled and composted is far from the threshold value. The other aspects including waste management value change and carbon emission of process still have low level. These issues cause the waste management to produce high environmental impacts which negatively degrade not only the ecosystem but also risk human health and life. Therefore, the waste management stakeholders and Indonesian government need to take an innovative approach to improve environmental conditions. They need to work effectively and efficiently on the waste process, recycling, and treatment at the onsite waste operations and waste supply chains. The investment into infrastructure and facilities is also critical to be improved in order to optimize waste treatment and to reduce hazardous emissions.

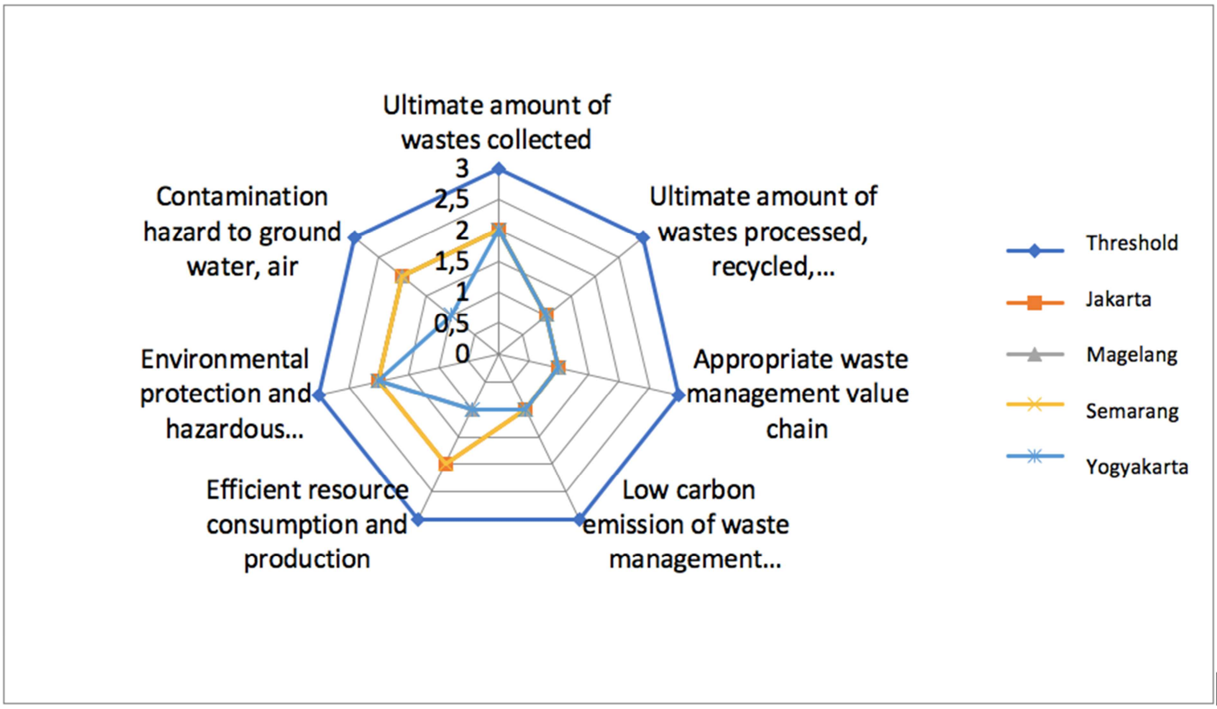

Fig. 3 Maturity level of the waste management system for environmental aspects

Fig. 4 illustrates the technological maturity levels of the current waste management. The maturity level that use appropriate technology, apply ICT and IOT, implement automated technologies and efficient energy consumption are still at a low level. Essentially, the use of automation and ICT plays a critical role in achieving sustainability of economic, social, and environmental aspects of the waste management. Therefore, the Indonesian Government needs to invest more in innovative technologies to improve waste management practices in Indonesia. In addition, improvement of knowledge and skills of the labour force in order to maximise the use of technologies is urgently required.

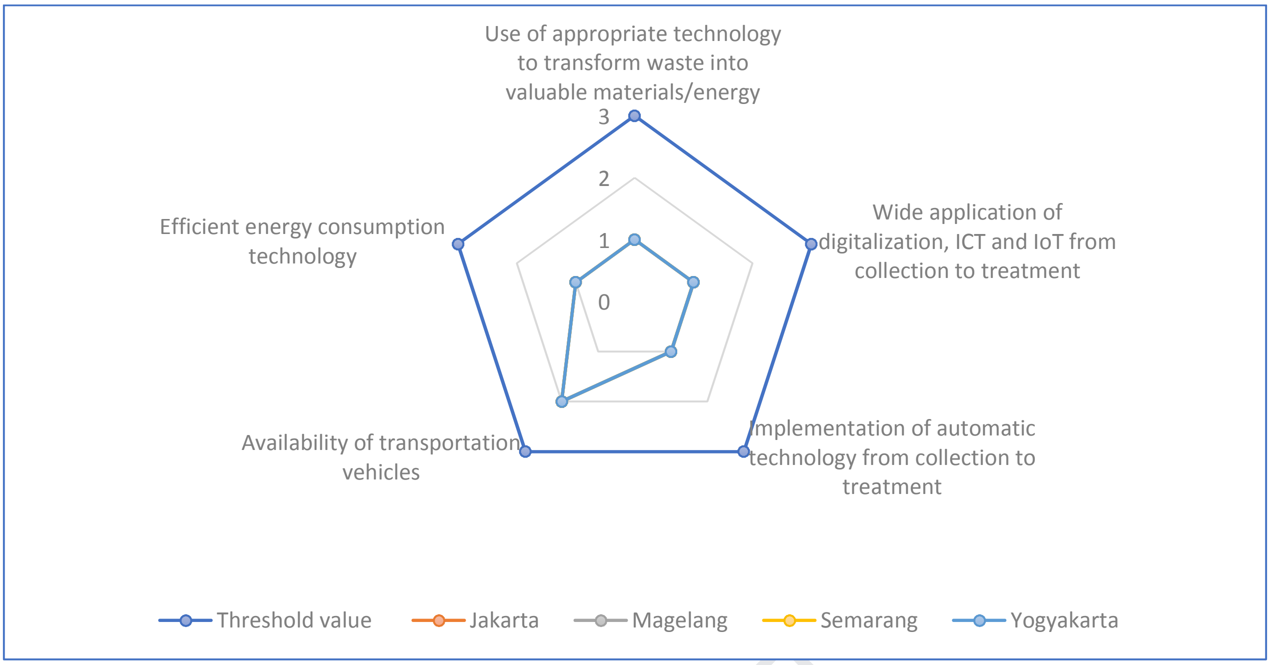

Fig. 4 Maturity level of the waste management system for technological aspects

4.2. New design of Sustainable and Smart Waste Management

According to the global assessment of the waste management, it appears Jakarta has the highest maturity level in comparison with other cities. Table 5 shows the performance of the waste management in the four cities. Threshold value is the total value in which each feature in the dimension reaches the optimal value.

Table 5. Performance of waste management

	Threshold	Jakarta	Magelang	Semarang	Yogyakarta
Governance	15	9	6	7	6
Economy	21	12	10	11	10
Social	30	14	12	12	12
Environment	21	11	9	10	9
Technology	15	6	6	6	6
Total	102	52	48	46	43

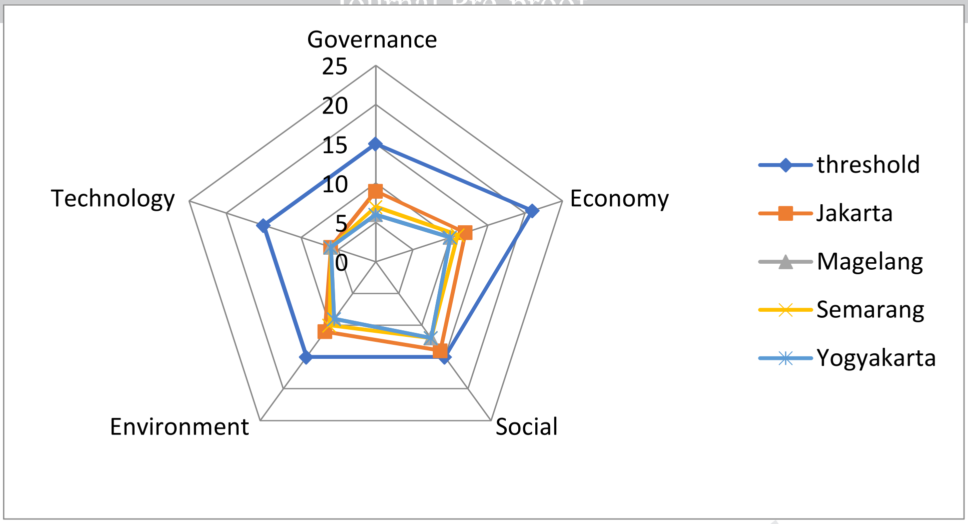

Fig. 5 Maturity level of the waste management in the four cities

Fig. 5 shows that the social aspects play a more positive impact than the other aspects. Therefore, to understand how the framework is applied in the waste management system, a sustainable and smart waste management design focusing on the business process and system workflow of the final disposal centre is developed and presented in the following section.

4.3. Business process in Final Disposal Centre

The business process is the preliminary design of the proposed waste management system, presenting a sequence of waste flow in a waste management system, separating waste based on some characteristics including size, metal/non-metal, light, inert, and combustible etc., grouping the waste material and making decisions for the appropriate treatment technology. This phase involves a preliminary design of the proposed system, by developing a waste classification system (sorting systems) based on waste type and characteristics in a sequenced waste flow. The sorting systems that consist of filters are developed via standard methods of waste classification, presented in Fig. 6.

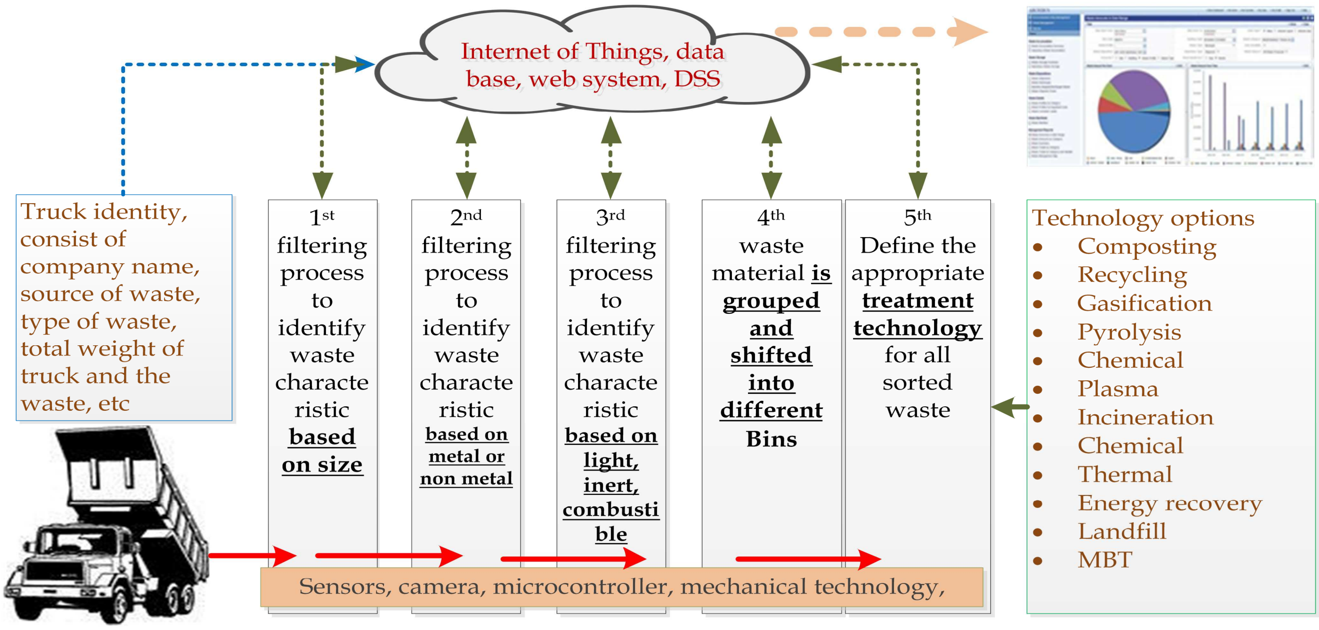

Fig. 6 Business process of the proposed system

The 1st filter is a waste sorting system that disaggregates the waste into large size materials and small size materials through a semi-manual, automatic system. The semi-manual system applies labour work and sensors to separate the dangerous materials (i.e. batteries), bottles and glass materials, and quilt and cloth materials. A rotating screening machine separates the materials into large-sized materials and small-sized materials. The 2nd filter is a waste sorting system which disaggregates the non-metal and metal materials for both large-sized materials and small-sized materials through different belt conveyors using a magnetic separator. The system uses the belt conveyors for subsequent operation from filter to filter. The 3nd filter disaggregates remaining waste material into three materials, including light materials, inert materials, and combustible materials using wind separators and belt conveyors. The 4th stage is a collection phase based on material characteristics, in which all separated waste materials are grouped and shifted into different waste compartments/bins and wait for the choice of further treatment. Following this stage, the system determines the appropriate treatment technology which is technically, economically, environmentally feasible for the specific waste material. The possible treatment technology could be recycling, composting, incineration, incineration, gasification, landfill, etc. Information communication technology (ICT) and Internet of things (IoT) components are integrated in the system to collect, analyse, and share the information system during the system processing. The IT devices such as sensors, microcontroller, equators, low-power connectivity are used to provide all waste management process, information, and performance of the waste management system. A software interface includes the embedded application that is used to support the various functions of the system, and a web server and database and a dashboard will be developed for better analysing and reporting. This system is expected to be able to measure the waste level, content, volume, characteristics and amount using sensors which are presented in the dashboard system. This system will have three main features which are sensing, monitoring, and optimising the waste management. By using this dashboard, real time monitoring, better decision making, and appropriate treatment technology can be provided by the company to achieve economically, socially, and environmentally sound waste management.

4.4. System Workflow at Final Disposal Centre

This system is addressed for municipal waste produced from household waste, shops and markets, construction areas, hotels, institutions, street sweeping, and so forth. The system will start with the flow of "invaluable" municipal waste produced by the city community and sent to final disposal centre by a compactor truck that has a barcode on it. This barcode not only identifies the truck, but also provides information such as company name, source of waste, and type of waste. Once the truck enters the arrival pit, a sensor reads the truck barcode and sends the truck identity information to a database. The truck is then scaled using a weight scale that is connected to the company database through a local area network. The weight of waste will appear on the dashboard. The truck dumps the municipal waste into a storage pit that is embedded to the system.

A mechanical machine (such as a grasp crane) will take the waste into manual sorting platform through belt conveyors for first sorting process which is conducted by labourers to sort dangerous materials, bottles, large glasses, and cotton and cloths for recycling purposes. The materials from this first stage sorting are collected in certain bins with weight sensor on it. The waste that remains on the conveyor is sent to a bag breaker (bag breaking machine) to break open the refuse bag. The broken bag waste is fed into the rotate screen (rotating screening machine) that is designed like a tub with specific dimensions. In this hole the waste is separated into different sizes (large or small sizes). Large-sized materials are expected to be mostly plastic, stone, textile, rubber, while the small-sized materials are expected to be mostly organic waste. The small size material is collected by the small collecting belt conveyor and transferred by the small transfer belt conveyor to the small material storage for further processing or landfill.

During this process, the magnetic separator has separated the iron/metal materials in the small materials. The large-sized material has the same process with small-sized materials process on different belt conveyors. After separating the iron/metal by the magnetic separator, the large materials (bigger than the dimension standard) are sorted out, and the remaining waste is transferred into the wind separator by belt conveyor. The wind separator will be designed by a combination of positive and negative pressures which can efficiently separate the waste into three materials, including light materials (plastic, paper), inert materials (brick, stone, ceramic, chip, glass) and combustible materials (hard plastic, textile, rubber materials, wet paper matters). The inert materials and combustible materials will be transferred by belt conveyor to the inert materials and combustible materials storage that are utilised with a weight level sensor. Useful elements will be identified through a sensor in the sorting platform and they are then sent through a conveyor into a storage bin for further treatment. The useless material is collected in a specific bin and then sent to landfill. The light materials will be transferred to the storage bin and then packed into mass materials which are easy for storage and transportation.

Each of the storage bins includes a weight level sensor which will send information to the database. All information related to the waste flow process in the system will be sent and recorded in the database. The database will provide possible treatment technology according to the performance of the waste collected and available treatment technology. A feasibility analysis of the economic, social, and environmental benefits will be provided to help in the decision making. For example, the collected plastic is possible to be converted into carbon black, fuel oil, and combustible gas through pyrolysis, while inert materials such as muck, rubble, construction debris, ashes, brick, and stone can be used for making brick. Composting is also possible to be applied from the biomass, garden, food waste, and animal, while collected metal can be tagged for recycling. Finally, the hard plastic, textile, rubber materials, wet paper materials can be used for combustion. The following Fig. 7 presents the waste flow, data flow, and logical decision making of the proposed system.

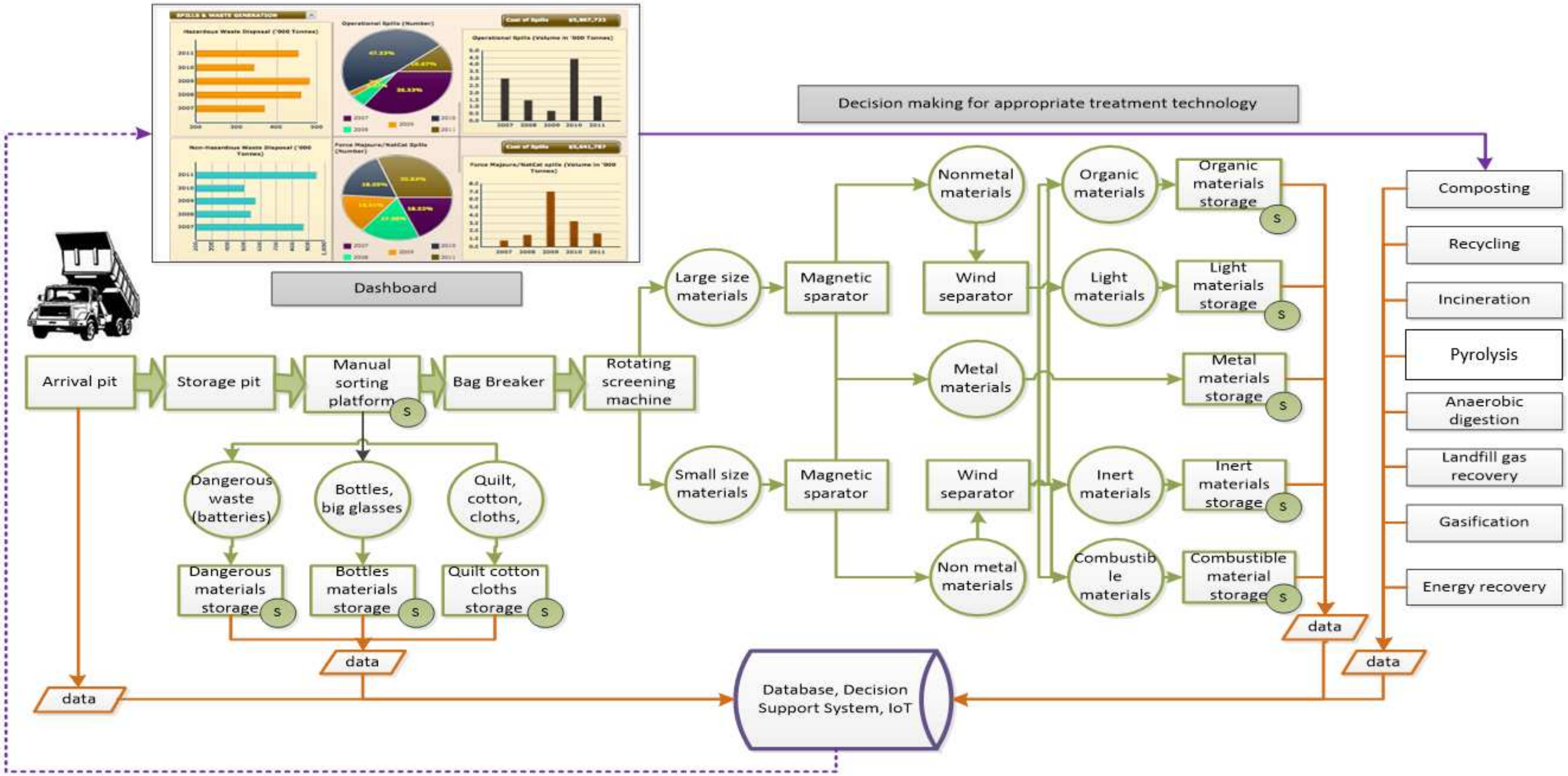

Fig. 7 Workflow Design of the Sustainable and Smart Waste Management System

The proposed system presents some fundamental agents including information on the truck, weight scale, collection and segregating room, conveyors, hazardous bins, tumbler, heavy materials compartment, light material compartment, final waste material bins accomplished with specific attributes, and procedures. The agent truck has specific capacity with a standard weight. The agent truck has a barcode identifying the company name, driver, source of waste (from-to), and waste type. The agent weight scale measures the weight of the waste truck, and a sensor placed at the entrance will help to identify the truck information from the barcode. The information is sent to the database of the waste collection centre. The agent conveyor will transfer all waste from the segregating area to next station. Manual filtering process for hazardous materials will be conducted by labourers during the transfer process. Unpacked waste is filtered and returned to segregating facility, for reprocessing/repacking. Hazardous bins are used to collect the dangerous materials. The bins have sensors which measure the level of the waste, in which the waste information will be sent to the database. The waste is then sent to agent rotating screening machine, agent bag breaking machine, agent manual platforms, agent magnet separator, and agent wind separator. The sensor will help to provide sufficient data and information of the waste to be further processed (composing, recycling, gasification, etc.).

Furthermore, a web application is used to deliver all information and data of waste flow, input, process and output from the web page to the desktop or mobile device. The illustration of web application (a dashboard system) is presented in Fig. 8. The dashboard provides the overall status of waste management including the flow process of waste, amount and weight of waste collected, the total materials collected, the compartment's status (full or empty) for each process, the facility map showing the status of the compartments, the suitable treatment technology for the waste collected, and the amount of waste residue sent to landfill.

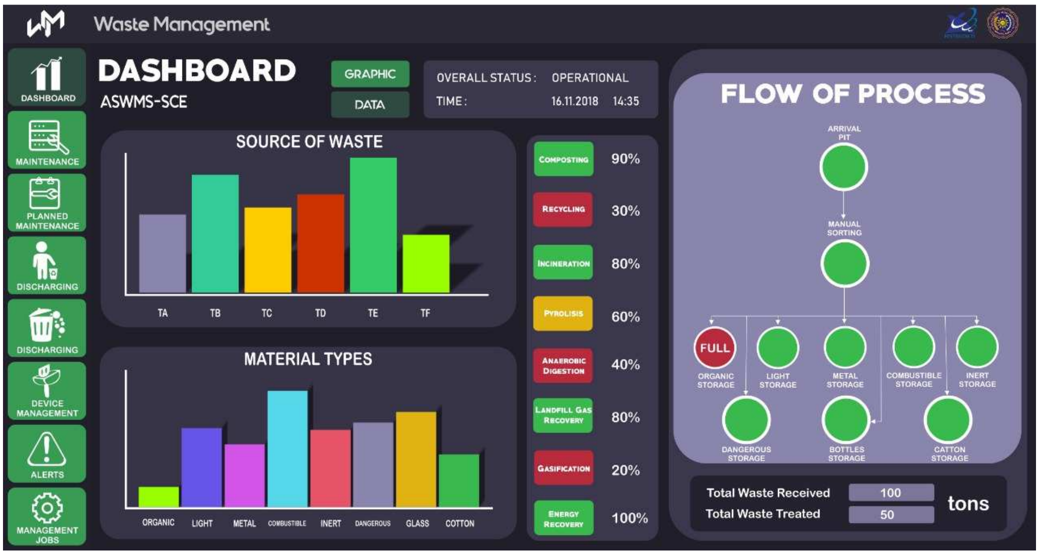

Fig. 8 Dashboard system of the waste management

4.5. SDGs Potential Achievements

This work contributes to at least five potential Sustainable Development Goals (SDGs) out of seventeen goals. Details of the achievement of those five goals created from waste management are described below.

SDG 3 - Good health, and wellbeing.

A good, clean, and healthy environment is an essential component of sustainable development globally. In recognition of this concern, SDG 3 can be achieved through the following.

- ✓ The proposed smart and sustainable waste management system is one innovation that has potential solutions to solve the issues of waste management in the community and industry. The ability to manage waste properly and to conduct waste treatment appropriately in the proposed waste management system offers direct and indirect advantages to the good, clean, and healthy environment of the global population, which would generate a significant contribution to sustainable development.

SDG 6 - Clean water and sanitation

A strong interrelation exists between waste and water in the waste management system. This new waste management system uses various treatment technologies to transform waste into valuable materials and resources, which could significantly reduce the amount of waste sent to landfill. The reduction of the toxins, residues, emissions and pollution created from waste could correspondingly reduce the water contamination in the land.

SDG 8 - Decent work and economy growth

Instead of working unofficially, a lot of waste management workers (i.e., scavengers, waste collectors) are underpaid, have little education, and are not properly protected. Such unsafe conditions seriously endanger their lives, health, and social condition. Most of them are among the poverty-stricken in Indonesia. This new system provides low-income people a better wage, more respect, and a better social life by involving them as an important contributor to a formal waste management system. Through such a system, this worker group will be designated as part-time employees of the Government, and their economic performance will be strengthened.

SDG 12 - Responsible consumption and production

One of the SDG targets is reducing pollution, emissions, waste through waste prevention, reduction, recycling, and reuse. This new system offers appropriate, automated, and integrated waste collection, separation, and treatments which could significantly reduce these environmental problems.

SDG 13 - Climate action

Optimising waste collection, segregating waste at the source, applying appropriate treatment technology, and reducing waste headed to the landfill are essential activities. These actions allow waste to be controlled and monitored, and using ICT and IOT in this system will reduce CO_2 emissions generated from the waste. This solution will help mitigate aspects of climate change.

In short, when SDGs are achieved, not only are environmental aspects improved, but economic and social aspects are also enhanced.

Conclusion

In this article, we present a new waste management system that is an essential part of our ongoing research objective, to design a smart waste management system to implement a sustainable circular economy. According to maturity level of the existing waste management system in four urban cities in Indonesia, a sustainable and waste management framework and sustainable and waste disposal system was developed. By using the ICT as the core of the system, this system finds the capability of existing performance in waste management, in which real-time, smart, flexible, and reliable waste management performance and information covering governance, economic, social, and environmental dimensions can be achieved. At last, this study contributes to the sustainable development goals such as Good health, and wellbeing (SDG 3); Clean water and sanitation (SDG 6); Decent Work and Economic Growth (SDG 8); Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13). The use of ICT and IoT improves the efficiency and effectiveness of the waste management system, despite having some technical challenges such as limited type of sensors, complexity of system, and limited mechanical technology, all of which are to be overcome before product development. Future research is to improve validity and reliability of the instruments for data gathering. The number of characteristics used in this study is only 30, so more criteria is expected to be added to strengthen the classification of waste management maturity levels, and to improve the determination of thresholds. More samples of case studies with a variety of characteristics will be applied to test the consistency of the classifications. The potential achievement of SDGs through the implementation of the waste management need more comprehensive study including industrial sharing economy (Govindan et al., 2020c).

Acknowledgement:

This research was supported by a Grant from SDU - Direktionens Strategiske Pulje for project titled "SDG- Tools".

References

Abdullah, N., Alwesabi, O. A., & Abdullah, R. (2019). IoT-based smart waste management system in a smart city. *Advances in Intelligent Systems and Computing*, *843*, 364–371. https://doi.org/10.1007/978-3-319-99007-1_35

Adam, M., Okasha, M. E., Tawfeeq, O. M., Margan, M. A., & Nasreldeen, B. (2018). Waste Management System Using IoT. *2018 International Conference on Computer, Control, Electrical, and Electronics Engineering, ICCCEEE 2018*. https://doi.org/10.1109/ICCCEEE.2018.8515871

Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J., & Hadjieftymiades, S. (2017). Challenges and Opportunities of Waste Management in IoT-Enabled Smart Cities: A Survey. *IEEE Transactions on Sustainable Computing*, *2*(3), 275–289. https://doi.org/10.1109/TSUSC.2017.2691049

Andrews, D. (2015). The circular economy, design thinking and education for sustainability. *Local Economy*. https://doi.org/10.1177/0269094215578226

Antikainen, M., Uusitalo, T., & Kivikytö-Reponen, P. (2018). Digitalisation as an Enabler of Circular Economy. *Procedia CIRP*, *73*, 45–49. https://doi.org/10.1016/j.procir.2018.04.027

Aprilia, A., Tezuka, T., & Spaargaren, G. (2013). Inorganic and Hazardous Solid Waste Management: Current Status and Challenges for Indonesia. *Procedia Environmental Sciences*, *17*, 640–647. https://doi.org/10.1016/J.PROENV.2013.02.080

Artiola, J. F. (2019). Industrial Waste and Municipal Solid Waste Treatment and Disposal. In *Environmental and Pollution Science* (pp. 377–391). https://doi.org/10.1016/b978-0-12-814719-1.00021-5

Bernstad, A., La Cour Jansen, J., & Aspegren, H. (2011). Life cycle assessment of a household solid waste source separation programme: A Swedish case study. *Waste Management and Research*. https://doi.org/10.1177/0734242X11406170

Bronson, M. C. (2017). Treatment of solid wastes. In *Separation Techniques in Nuclear Waste Management (1995)* (p. 153). https://doi.org/10.1201/9780203710388

Chen, W. E., Wang, Y. H., Huang, P. C., Huang, Y. Y., & Tsai, M. Y. (2018). A smart IoT system for waste management. *Proceedings - 2018 1st International Cognitive Cities Conference, IC3 2018*, 202–203. https://doi.org/10.1109/IC3.2018.00-24

Ciudin, R., Isarie, C., Cioca, L., Petrescu, V., Nederita, V., & Ranieri, E. (2014). Vacuum waste collection system for an historical city centre. *UPB Scientific Bulletin, Series D: Mechanical Engineering*, *76*(3), 215–222.

Damanhuri, E., Handoko, W., & Padmi, T. (2014). Municipal Solid Waste Management in Indonesia. In *Environmental Science and Engineering* (pp. 139–155). Retrieved from https://link.springer.com/chapter/10.1007/978-981-4451-73-4_8

Gao, Q. Y., & Li, S. L. (2011). Preparation and properties of resistant starch from mung bean starch. *Huanan*

Ligong Daxue Xuebao/Journal of South China University of Technology (Natural Science). https://doi.org/10.3969/j.issn.1000-565X.2011.04.016

Govindan, K., Rajeev, A., Padhi, S. S., & Pati, R. K. (2020a). Supply chain sustainability and performance of firms: A meta-analysis of the literature. *Transportation Research Part E: Logistics and Transportation Review*, *137*, 101923.

Govindan, K., Mina, H., Esmaeili, A., & Gholami-Zanjani, S. M. (2020b). An integrated hybrid approach for circular supplier selection and closed loop supply chain network design under uncertainty. *Journal of Cleaner Production*, *242*, 118317.

Govindan, K., Shankar, K. M., & Kannan, D. (2020c). Achieving sustainable development goals through identifying and analyzing barriers to industrial sharing economy: A framework development. *International Journal of Production Economics*, *227*, 107575.

Gutiérrez, V., Galache, J. A., Santana, J. R., Sotres, P., Sánchez, L., & Muñoz, L. (2014). The Smart City Innovation Ecosystem: A Practical Approach. *E-LETTER*.

Hannan, M. a, Arebey, M., Basri, H., & Begum, R. a. (2010). RFID and Integrated Technologies for Solid Waste Bin Monitoring System. *Australian Journal of Basic and Applied Sciences*, *4*(10), 5314–5319. https://doi.org/10.1007/s10661-010-1642-x

IA. Jereme, Siwar, C., & Alam, M. M. (2014). Waste Recycling in Malaysia : Transition from Developing to Developed Country Waste recycling in Malaysia : Transition from developing to developed country. *Indian Journal of Education and Information Management*, *4*(February), 1–14.

Islam, M. S., Hannan, M. A., Arebey, M., & Basri, H. (2012). An Overview for Solid Waste Bin Monitoring System. *Journal of Applied Sciences Research*, *8*(2), 879–886.

Jouhara, H., Czajczyńska, D., Ghazal, H., Krzyżyńska, R., Anguilano, L., Reynolds, A. J., & Spencer, N. (2017). Municipal waste management systems for domestic use. *Energy*. https://doi.org/10.1016/j.energy.2017.07.162

Kannan, D., Govindan, K., & Shankar, M. (2016). Formalize recycling of electronic waste. *Nature*, *530*(7590), 281-281.

Kannan, D., Mina, H., Nosrati-Abarghooee, S., & Khosrojerdi, G. (2020). Sustainable circular supplier selection: A novel hybrid approach using streaming data. *Science of The Total Environment*, 722, 137936.

Millard, E. (2017). Still brewing: Fostering sustainable coffee production. *World Development Perspectives*, *7–8*, 32–42. https://doi.org/10.1016/j.wdp.2017.11.004

Ministry of the Environment. (2012). *Solid Waste Management and Recycling Technology of Japan - Toward a Sustainable Society*. Retrieved from https://www.env.go.jp/en/recycle/smcs/attach/swmrt.pdf

Misra, D., Das, G., Chakrabortty, T., & Das, D. (2018). An IoT-based waste management system monitored by cloud. *Journal of Material Cycles and Waste Management*, *20*(3), 1574–1582. https://doi.org/10.1007/s10163-018-0720-y

Pariatamby, A. & Tanaka, M. (2015). Municipal solid waste management in Asia and the Pacific Islands: Challenges and strategic solutions. In *Springer*. https://doi.org/10.1177/139156140901000108

Prastiwi, W. D., Nada, D. F., Azizah, Y. N., & Wibowo, E. A. P. (2017). The Effect Of Waste Bagasse (Saccharum sp) Fertilizer Toward Growth Of Peanuts (Arachis hypogaea L .). *Agrotech Journal*.

Rawlins, J., Beyer, J., Lampreia, J., & Tumiwa, F. (2014). *Waste to energy in Indonesia*. Retrieved from https://www.carbontrust.com/media/512147/ctc831-waste-to-energy-in-indonesia.pdf

Sarc, R., & Lorber, K. E. (2013). Production, quality and quality assurance of Refuse Derived Fuels (RDFs). *Waste Management*. https://doi.org/10.1016/j.wasman.2013.05.004

Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., & Krausmann, F. (2014). The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010. *Global Environmental Change*, *26*, 87–97. https://doi.org/10.1016/J.GLOENVCHA.2014.03.013

Seadon, J. K. (2010). Sustainable waste management systems. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2010.07.009

Srivastava, R. (2016). Waste Management: Developed and Developing. *International Journal of Science and Research (IJSR)*, *5*(3), 202–203. https://doi.org/10.21275/v5i3.nov161825

Sudibyo, H., Majid, A. I., Pradana, Y. S., Budhijanto, W., Deendarlianto, & Budiman, A. (2017). Technological Evaluation of Municipal Solid Waste Management System in Indonesia. *Energy Procedia*, *105*. https://doi.org/10.1016/j.egypro.2017.03.312

Sudibyo, Hanifrahmawan, Pradana, Y. S., Budiman, A., & Budhijanto, W. (2017). Municipal Solid Waste Management in Indonesia - A Study about Selection of Proper Solid Waste Reduction Method in D.I. Yogyakarta Province. *Energy Procedia*. https://doi.org/10.1016/j.egypro.2017.12.716

Tchobanoglous, G., Theisen, H., & Vigil, S. A. (1993). Physical, Chemical, and Biological Properties of Municipal Solid Waste. In *Integrated solid waste management: engineering principles and management issues* (p. 978). Retrieved from https://lib.ugent.be/en/catalog/rug01:000312687

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., & Tukker, A. (2017). Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints. *Journal of Industrial Ecology*, *21*(3), 628–640. https://doi.org/10.1111/jiec.12562

UNEP. (2015). *Global Waste Management Outlook*. Retrieved from https://issuu.com/zoienvironment/docs/gwmo_report

Wajeeha, S., Ayesha, Z., Muneeba, T., Fatima, A., & Ghazala, Y. (2016). Latest technologies of municipal solid waste management in developed and developing countries: A review. *International Journal of Advanced Science and Research*, *1*(10), 1–8.

Woodard & Curran, Inc. (2007). Solid Waste Treatment and Disposal. In *Industrial Waste Treatment Handbook* (pp. 363–408). https://doi.org/10.1016/b978-075067963-3/50011-4

Yoshida, F., & Yoshida, H. (2012). WEEE management in Japan. In *Waste Electrical and Electronic Equipment (WEEE) Handbook* (pp. 576–590). https://doi.org/10.1533/9780857096333.5.576

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for Smart Cities. *IEEE Internet of Things Journal*, *1*(1), 22–32. https://doi.org/10.1109/JIOT.2014.2306328

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: