Solid Waste Management: A Review from the Supply Chain Perspective

Vinay Gonela*
Texas A&M University – Central Texas, Killeen, Texas USA

Jun Zhang
California Baptist University, Riverside, California, USA

Dalila Salazar
Texas A&M University – Central Texas, Killeen, Texas USA

Iddrisu Awudu
Quinnipiac University, Hamden, Connecticut, USA

The solid waste (SW) generation rate around the world is increasing at an unprecedented rate. The growing levels of SW have raised several environmental, ecological, and human health related issues. Therefore, it is critical to design an effective and efficient solid waste management (SWM) system that can sustainably recover, reuse, recycle, and dispose SW. In order to design a sustainable SWM system, it is important to study SWM from a supply chain perspective. Therefore, this review's purpose is twofold. The first purpose is to provide an overview of SWM from a supply chain perspective that will: (1) study and analyze different stages of SWM; and (2) propose a conceptual framework combining performance measures, decisions, and decision levels at various stages of SWM. The second purpose is to: (1) gain insights from literature by categorizing SW network structures; and 2) provide the important future research directions on SWM.

* Corresponding Author. E-mail address: vinay.gonela@tamuct.edu

I. INTRODUCTION

Solid Waste (SW) is defined as the waste generated from households, commercial establishments, institutions, industries and businesses (Eiselt & Marianov, 2015). Currently, 1.3 billion tons/year of SW is generated around the world and is expected to increase to 4 billion tons/year by the year 2100 (Hoornweg & Bhada-Tata, 2012). The management of SW is expensive and costs around 20-50% of municipal budgets (Hoornweg & Bhada-Tata, 2012). Consequently, municipalities around the world have relied heavily on Solid Waste Management (SWM) strategies that are cheap such as open burning, unregulated dumping, and landfilling depending on their economic status. For instance, 41% of the total SW that is generated is disposed of through unregulated burning every year (Atmos News, 2014). In 2014, the USA had landfilled around 52.6% of SW (Simmons, 2016). However, these SWM strategies have been ineffective in handling increasing levels of SW and have posed several sustainability related concerns. For example, open burning in China contributes to 22% of the reported large particle emissions that cause human-health issues such as decreased lung functions, neurological disorders, cancer, and heart attacks (Atmos News, 2014). The pollution from landfills in the USA not only creates a toxic atmosphere, but also contaminates water systems as pollutants from SW run into rivers and/or seep into ground water (Simmons, 2016).

In order to reduce the negative impact of SW, an effective and efficient SWM system is essential to assist societies in disposing SW in an environmentally and economically sustainable way (Beigl et al., 2008). However, designing a successful SWM system is difficult due to its complex nature. SWM systems consist of multiple stages, such as pre-collection, collection, pre-treatment, treatment, and disposal. Each stage in a SWM system requires various interrelated decisions, from a wide range of decision options, such as selection of appropriate service policy, locations, capacities, treatment, and disposal technologies. At the same time, there are many types of SW; the most common types include but are not limited to the following: food waste, gardening waste, paper, board, glass, plastic, and metal. These different types of SW can be collected, treated, or disposed of using different methods. For example, paper can be collected by a recycling channel and sent to recycling sites, collected by a regular channel and sent to a landfill, or sent to a waste-to-energy plant to generate electricity. Recycling paper might lead to environmental sustainability. However, if the geographic location of the waste is in the remote suburban area, handling and transportation costs might be too high to make recycling feasible. Therefore, an effective and efficient SWM system should be able to deal with the complexity of the problem and provide optimal strategies that maximize life cycle environmental and economic benefits by considering factors such as SW composition, geographic location, and infrastructure availability.

A wide range of SWM studies have been conducted addressing SW problems from different perspectives. However, none of the up-to-date literature has studied SWM from a supply chain perspective. Therefore, the purpose of this review is twofold. The first purpose is to provide an overview of SWM from a supply chain perspective that will: (1) study and analyze different stages of SWM; and (2) propose a conceptual framework combining performance measures, decisions, and decision levels at various stages of SWM. The second purpose is to: (1) gain insights from literature that involve categorizing SW network structures; and 2) provide the important future research directions on SWM.

The rest of the paper is organized as follows: First, we discuss different stages in SWM. Second, we discuss the solid waste categories and composition. Third, we propose a conceptual framework for SWM decision making followed by possible SW network structures. Finally, we present conclusions followed by a discussion on potential future research directions.

II. STAGES IN SWM

One of the important decisions of SWM is to design an effective SW supply chain. Identifying the stages of the SW supply chain is an essential step to design an effective SW supply chain. Figure 1 presents the possible stages of the SW supply chain. Typically, the SW supply chain consists of five stages: (1) pre-collection; (2) collection; (3) pre-treatment; (4) treatment; and (5) disposal (Bovea et al., 2010). These stages are highly interrelated and consist of several activities. The decisions made in one stage highly impact the activities and decisions in other stages. For example, SW sorted in pre-collection can reduce or completely eliminate pre-treatment costs. In addition, the decisions in each of these stages have severe implications on the SWM costs, material recovery, recycling ability, and disposal rates. Therefore, it is necessary to study and understand each of the stages of SWM in detail. It is also important to note that not all SWM systems consist of all five stages.

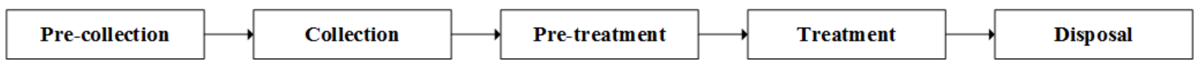

FIGURE 1. STAGES OF SW SUPPLY CHAIN.

2.1. Pre-collection

Pre-collection is the process of separating, storing and pre-processing SW at its origin (household) in order to facilitate collection. In some cases, pre-collection involves changing the physical characteristics of SW (i.e., reducing density, removing moisture, and home composting, etc.) (Gallardo et al., 2015). In the pre-collection stage, decisions are made to select the appropriate waste fractioning level, storage methods, and service policies.

2.1.1. Waste fractioning level

Waste fractioning level involves separation of SW at the source (source separation) in which the SW is divided into different SW streams to facilitate the transfer to different pre-treatment/treatment/disposal facilities (Gallardo et al., 2015). Although, sorting SW into different SW streams (e.g., organic waste, paper, glass, metal and residuals by households) is inconvenient to households, it has become a common practice as it provides environmental benefits (Ferri et al., 2015). Waste fractioning not only increases the quality of recyclables, compost, and incineration, but also diverts the amount of waste going to landfills (Mueller 2013; Elia et al., 2015). In addition, waste fractioning enables effective financing of waste management activities, while minimizing the necessity for downstream activities.

Waste fractioning can range from 0% fractioning in which SWs are not segregated (unorganized) to 100% fractioning (organized) in which all the SWs are segregated into a number of different SW streams based on the SW type (Di Maria et al., 2016). While too little SW streams lead to SW contamination resulting in reduced recyclable waste causing high environmental impact, too many SW streams can result in increased costs due to increased logistic activities (Rada and Cioca, 2017). Table 1 presents the description and application of different SW streams. The level of the SW to be segregated depends on several factors such as SW composition, available treatment methods, regulations, and user requirements (Gallardo et al., 2015).

TABLE 1. DESCRIPTION AND APPLICATION OF DIFFERENT SW STREAMS
(Shi et al., 2014)

SW stream	Description	Application
Mixed/Commingled	Both recyclables and non-recyclables are collected together.	Rural areas producing low level SW.
2 – Bin system	Dry recyclables and residual SWs are separately collected by using two bins.	Sub-urban areas producing medium level of SW.
3- Bin system	Dry recyclables, organic wastes, and residual SWs are collected separately by using three bins.	Urban areas producing high level of SW.
Presorted (more than 3-bins)	All the SWs are separately collected.	Urban areas producing high level of SW.

2.1.2. Storage methods

Once the SW are segregated into streams, different streams require storage until the collection activity takes place. Table 2 presents the different storage methods, descriptions, and applications. It should be noted that Table 2 is ordered based on the following: (1) highest to lowest convenience for household; and (2) highest to lowest cost for municipality. For example, mobile pneumatics and door-to-door are the most convenient methods for households. However, the costs are significantly higher for municipalities (Mueller, 2013). The type of storage method to be selected depends on a number of factors, including cost, population density, waste fractioning rate, and regulations (Iriarte et al. 2009). Varying storage methods can be used for different SW streams; hence, a particular municipality can have several storage methods.

2.1.3. Service policies

In the past decade, tax-based policies have been used for SW collection which are solely designed to cover the costs of the SWM activities. The *flat rates policy,* is one of the tax-based policies in which households are charged a fixed cost irrespective of the amount of SW that is generated. However, recent environmental and ecological concerns (resulting from the disposal of SW) have forced authorities to look for alternative policies that can increase recycling such that the majority of SW is diverted from landfills (Elia et al 2015; Mueller, 2013). Consequently, new policies such as *bag limits*, *pay as-you-throw* (PAYT), and *extended producer responsibility* (EPR) have emerged in recent years.

The *bag limits* policy sets a quota for the number of bags of SW that will be accepted per household. The underlying goal of this policy is to control SW generation behavior (Mueller, 2013). The PAYT policy is one in which households are charged a variable rate based on the amount or weight of SW generated (Elia et al., 2015). The EPR policy is an environmental policy that shifts the responsibility of collecting specific recyclable SW from local municipalities over to the producers of products (Agamuthu and Victor, 2011). The EPR extends the producer's responsibility to the post-consumer stage and helps not only recover or recycle the product at the end-of-life, but also enables the producers to refocus on the design phase such that sustainable products are produced (Wagner, 2013; Agamuthu and Victor, 2011). Table 3 presents the impact of different service policies on costs, volume, waste fractioning, and storage method.

TABLE 2. STORAGE METHODS AND APPLICATION
(Gallardo et al., 2015; Iriarte et al. 2009)

Storage method	Description	Application
Mobile pneumatics	Mobile pneumatics consists of inlets, underground pipes, and suction trucks. The SWs thrown into different inlet doors are transported by underground network of interconnected pipes to the suction points which are easily accessed by the trucks.	• Increases serviceability, especially to areas where trucks are not easily accessible. • Used at both privately owned houses and shared spaces. Inlet doors are assigned to each household or business entity in case of shared space. • Different inlets or time frames can be used for different SW streams to increase recycling.
Door-to-Door	Bins are located at each door.	• Increases serviceability. • Effective for individual single homes. • Source separation can be used to increase recycling.
Curbside bins	Collection points are located within a distance of 20-30 meters from households and are separated by a distance of 40-60 meters.	• Goal is to reduce cost and provide reasonable serviceability. • Can be used at shared spaces such as apartments, industrial, and commercial zones. • Source separation can be used to increase recycling.
Drop-off sites	Collection points are located within a distance of 100-300 meters from households and are separated by 200-400 meters.	• Selective collection of recyclable SWs such as packaging, paper/cardboards and glass. • Communities focusing on recycling.
Establishment	The collection points are placed within the establishments depending on the number of establishments that participate in the program.	• The onus of SW collection is on producer. • Used to collect special SWs such as batteries, medical products, and electronic devices.
Green points	The collection points are placed in facilities located at a distance less than 15 kilometers.	• Used to collect SWs such as bulky, inert, and hazardous.

TABLE 3. IMPACT OF SERVICE POLICY ON COSTS, VOLUME, WASTE FRACTIONING, AND STORAGE METHOD.

Service Policy	SW volume	SWM costs	Waste Fractioning	Storage method
Flat rates	No impact on volume. Volume can be reduced when used with bag limits policy	Used to solely cover the costs of SWM.	• As waste fractioning level increases, flat rate charges will increase to cover the increased logistic costs. • Maintaining lower flat rate cost for recyclable streams compared to non-recylable streams will increase material recovery.	• Higher flat rates for highly convenient storage methods due to increased logistic costs • lower flat rates for for inconvenient storage methods due to lower logistic costs.
Bag limits	SW volume is reduced due to bag limits.	Reduces SWM costs due to reduced SW generation rates.	As waste fractioning level increases, number of SW streams increases. However, volume for each stream reduces resulting in increased logistic costs.	Usually used for convenient storage methods such as mobile pneumatics and door-to-door.
PAYT	SW volume reduces as households are charged based on the SW volume generated.	Directly proportional to SWM costs as higher SW generation is charged with higher rates.	Maintaining lower per unit costs for recyclable streams compared to non-recyclable streams will increase material recovery.	Effective for all storage method as the primary goal of PAYT policy is to reduce SW.
EPR	Reduces reuse and recyclable product burden on muncipalities.	Reduce costs to muncipalities as producers take responsibility for collection.	Reduces waste fractioning streams for muncipalities as producers collect recyclable products.	Best storage methods are drop-off sites, establishements, and green points.

2.2. Collection

Collection is the process of picking up SW from the primary collection points using collection vehicles. The SWs collected are then transported to the pre-treatment facilities/treatment/disposal centers (Ferri et al., 2015). Typically, small-sized waste haulers are used for SW collection (Bovea et al., 2010). The collection for different SW streams can be scheduled differently. For example, residual SWs can be collected on a day-to-day basis (due to high volume), recyclable SWs can be collected on a weekly basis (due to low volume). The factors that impact SW collection are: (1) SW generation rates for each SW stream; (2) number of SW streams; (3) geographic size of the city; (4) distance between different collection points and pre-treatment/treatment facilities, and 5) number of SW collectors and vehicles available (Das and Bhattacharyya, 2015). Figure 2 presents the impact of pre-collection on collection activities. It indicates the following two trade-offs and municipalities often select appropriate storage and waste fractioning methods by considering the collection costs.

1. Serviceability (storage method) vs. Collection costs – If serviceability is high the collections costs are high and if serviceability is low collection costs are low.
2. SW stream (waste fractioning) vs. Collection costs – If SW streams are organized, the collection costs are high and if SW streams are unorganized, then the collection costs are low.

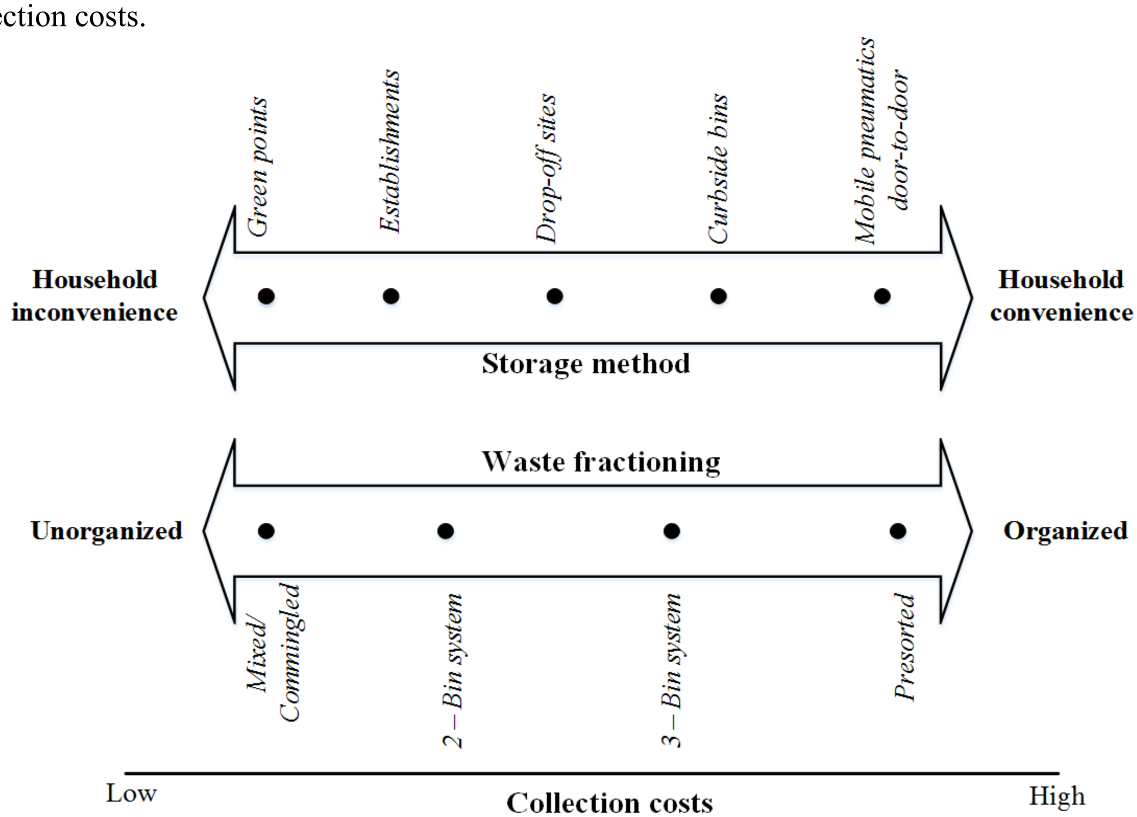

FIGURE 2. IMPACT OF PRE-COLLECTION ON COLLECTION ACTIVITIES.

2.3. Pre-treatment

The pre-treatment of SWs includes processes such as manual sorting, composting, energy recovery, mechanical treatment (e.g., crushing, grading, magnetic separation etc.), biological stabilization, thermal treatment, and aerobic/anaerobic digestion (EU EPA, 2008). Pre-treatment is used when there is minimum or low waste fractioning. The following are the two commonly used waste pre-treatment strategies: (1) transfer stations; and (2) material recovery facilities (MRFs). Other specialized pre-treatment methods include sorting of glass, paper/cardboard, packaging, and composting plants (Bovea et al., 2010). Various pre-treatment methods are designed by different municipalities based on the cost, amount of SW generated, distance from the treatment and disposal facilities, pre-collection and collection methods, and recycling goals.

Before being sent to a waste-to-energy facility or landfill, SW is temporarily held at a transfer station (LeBlanc, 2017). A transfer stations can either (1) serve as SW storage space for small cities; and/or (2) transshipment points if the distance between the SW generation location and treatment or disposal site is long. A transfer station is a point where the local SW collected by small-scale haulers are consolidated for long distance hauling to a treatment or disposal location. Transfer stations are effective in handling commingled or mixed SW which are sent to either waste-to-energy systems or landfills. In recent years, transfer stations have also been used for storage of recyclable SW. At the transfer station, typical activities include unloading of garbage trucks, pre-screening of SW, removal of inappropriate items, compacting and reloading onto larger vehicles (e.g., trucks, trains, and barges) for future transport (LeBlanc, 2017). Transfer stations can significantly reduce the transportation costs as it is cheaper to transport large loads of SW over long distance than small loads. Moreover, transfer stations can provide environmental benefits as the GHG emissions in transportation can be significantly reduced due to SW consolidation.

MRFs are usually used by municipalities whose goals are to increase material recovery and recycling. MRFs segregate and bale SW streams into saleable recyclable, organic, and non-recyclable or non-recovered SW streams, such that different SW streams are shipped to various end users. At the MRF, material that can be recycled is recovered and sold, while mixed material can be processed and converted to compost, refuse derived fuels (RDF), and biogas, depending on the available technology. Non-recoverable or non-recyclable SWs are sent to a landfill. Contrary to transfer stations, MRFs are not transshipment points; instead they are sorting, baling, and processing points that increase recycling, composting, and reduce SW contamination for incineration (Ferri et al., 2015). MRFs can be highly effective in the situations where curbside recycling proves to be unsuccessful and/or SW streams are unorganized (Ferri et al., 2015). MRFs can have different input and output technologies. Input MRF technologies are those in which incoming SW are sorted, baled, and sent to their respective destinations. Output MRF technologies not only sort, bale, and ship SW streams, but also include specific technology to convert certain SW stream to value added products. Table 4 presents MRF technology, types, descriptions, and their effectiveness for SW stream type.

2.4. Treatment

The treatment of SW spans the following process: manual – mechanical – biological – thermal (EU EPA, 2008). Unlike pre-treatment systems which involve several activities, treatment systems are highly dedicated systems that produce specific value-added products. Figure 3 presents the flow chart for the treatment of SW that include: (1) input factors; (2) treatment method; (3) conversion pathway; (4) products; and (5) applications. In order to determine effective treatment method, it is important to consider input factors such as SW characteristics, SW volume, pre-collection strategy, pre-treatment strategy, and transportation costs. For example, commingled SW stream can be used to generate compost through a composting channel or energy through a WTE systems channel depending on the moisture content, contamination level, and volume.

Furthermore, if MRF with output type (MRF with composting, RDF producing MRF, and MRF with anaerobic digestion) is used for pre-treatment, then the treatment of commingled waste can be completely eliminated.

TABLE 4. MRF TECHNOLOGY TYPES, DESCRIPTION, AND THEIR EFFECTIVENESS FOR SW STREAM TYPE
(Pressley et al., 2015).

MRF Technology	Type	Description	Effectiveness for type of SW stream
Mixed stream	Input	Mixed stream in which recyclables and non-recyclables are collected together and sorted by the MRF.	Mixed/Commingled
Dual stream	Input	Dual stream in which incoming recyclable SWs arrive as fiber and container SW streams and MRF is used to further segregate the SW streams.	Recyclable streams of 2-bin, 3 bin, and pre-sorted systems.
Pre-sorted	Input	Pre-sorted stream in which recyclable SWs arrive presorted and MRF is used to further segregate the waste streams.	Recyclable streams of 2-bin, 3- bin, and pre-sorted systems.
MRF with composting	Output	MRF with composting in which recyclable materials are recovered for sale and mixed material fraction are converted to compost through aerobic digestion.	All waste fractioning systems. However, composting market is readily available in the area.
RDF producing MRF	Output	RDF producing MRFs in which recyclable materials are recovered for sale and mixed material fraction are converted to RDF through aerobic digestion.	All waste fractioning systems. Since RDF’s can be stored and sold in the market at any time for combustion, they can be sold in any market.
MRF with anaerobic digestion	Output	MRF with anaerobic digestion in which recyclable materials are recovered for sale and mixed material fraction are converted to biogas through anaerobic digestion.	All waste fractioning systems. However, biogas market such as heat and electricity is readily available.

Recycling, composting, and waste-to-energy systems are the three most common treatment methods. A recycling channel consists of two conversion path ways: (1) closed-loop; and (2) open-loop. Closed loop recycling involves products being recycled back into themselves, thereby producing primary products, which are often used by manufacturers, sub-assembly users, and component suppliers (Pagell et al., 2007). For example, soda companies such as Coca-Cola and PepsiCo produce cans and bottles through vertical integration. Consequently, soda cans and bottles that are recovered from SW can be directly sent to the soda companies for closed-loop recycling. Open-loop recycling involves products being recycled into other types of products leading to product's property degradation. In this SW are shredded and grounded to salvage the materials, such as plastics, metal, etc., which can be used by secondary markets and raw material suppliers. For example, plastic recovered from SW through open-loop recycling can be used to produce toys through 3D-printing which can be sold in secondary markets.

Composting consists of several conversion pathways depending on the SW type, SW volume, particle size, moisture content, environment, and contamination level. Vermicomposting can be used when organic SW volume is low and Windrow composting can be used when the organic SW volume is high. Static pile composting is suitable for relatively homogenous mix of organic waste and In-vessel is suitable for any type of organic waste (Farrel and Jones, 2009). Even though, compost is produced through different conversion pathways, the quality of the compost varies depending on the SW characteristics. For example, compost consisting of plastic cannot be used for agricultural purpose and can be used for landfill caps.

There are several WTE conversion pathways, but a suitable WTE conversion pathway can be selected based on costs, input SW characteristics, and desired output products (Malinauskaite Et al., 2017). For example, organic SW that is wet or contains higher levels of moisture are typically converted to biogas that can be consequently used as fuel for different applications such as heat and electricity. If the mixed SW is dry, then an RDF conversion path-way is suitable as the generated high energy value RDF pallets can be stored and used later for energy generation purposed. It should be noted that WTE systems usually involve SW incineration operations in which high level energy is recovered.

2.5. Disposal

The final step of SWM is disposal. SW that cannot be recovered during the pre-treatment and treatment stages are disposed. There are two types of SW disposals: (1) landfill; and (2) incineration. Figure 4 represents the flow chart for disposal of SW. Disposal is usually preferred when the treatment costs are high and/or when SW cannot recovered. A conventional landfill is a typical SW dumping strategy where SW is directly dumped without any further energy recovery activities. In a landfill with an energy recovery strategy, the landfill gas that contains methane is used to generate electricity. The annual landfill gas rate increases and decreases with time and therefore, it becomes infeasible to use landfill gas after a certain time (Nixon et al., 2013). Studies have shown that a landfill with energy recovery is better than a conventional landfill in terms of energy recovery, environmental impact, and economic benefit (Jeswani and Azapagic, 2016). While different landfill strategies provide different sustainability benefits, a landfill is not a sustainable strategy as it requires significant land and contaminates the environment even with the sanitary technologies (Jeswani and Azapagic, 2016). Landfill mining has recently gained traction as it can recovers SW that can be recycled or incinerated while simultaneously freeing-up the landfill space. Landfill mining is a strategy in which old landfills are mined to recover material which can either be recycled or incinerated (Zhou et. 2015).

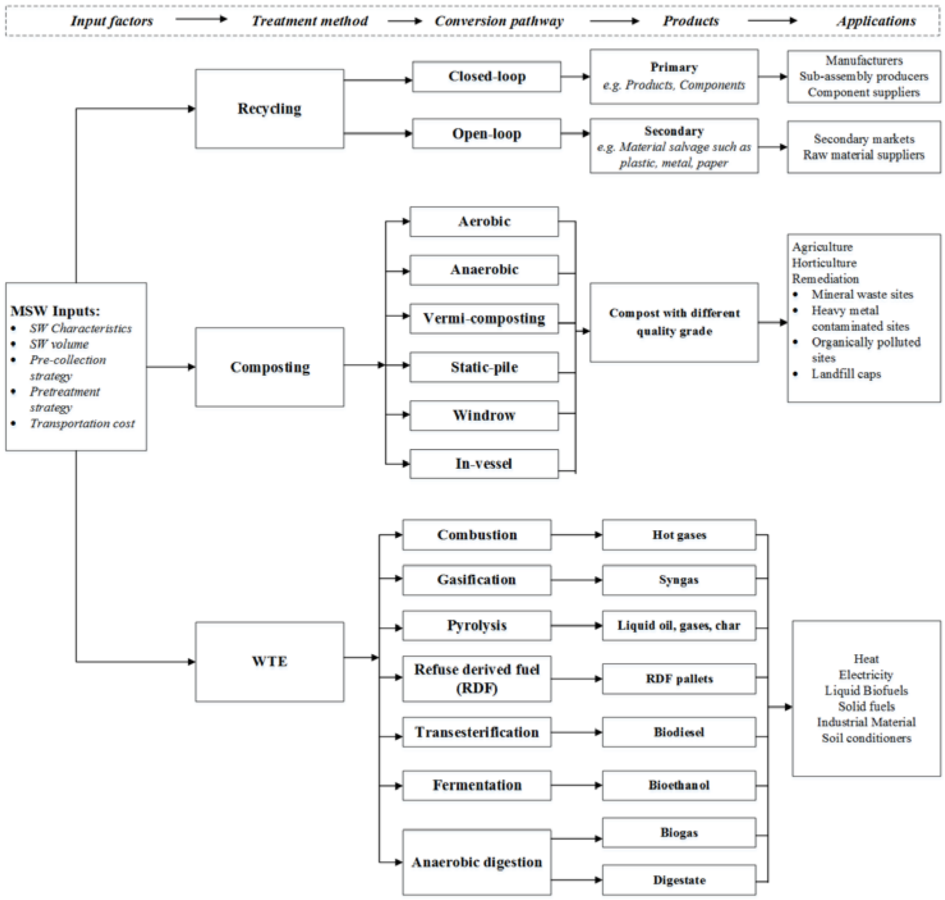

FIGURE 3. FLOWCHART FOR TREATMENT OF SW.
Source: Malinauskaite Et al., 2017; Farrel and Jones, 2009; Pagell et al., 2007.

Incineration is another disposal strategy that can be used when facing space constraints for SW disposal and when limited biogas can be recovered when landfilled (Malinauskaite te al., 2017). Unlike WTE systems (treatment methods) SW incineration is used as a disposal strategy when there is limited potential for energy recovery from SW. However, the ashes produced through incineration can be used for cement manufacturing and construction purposes.

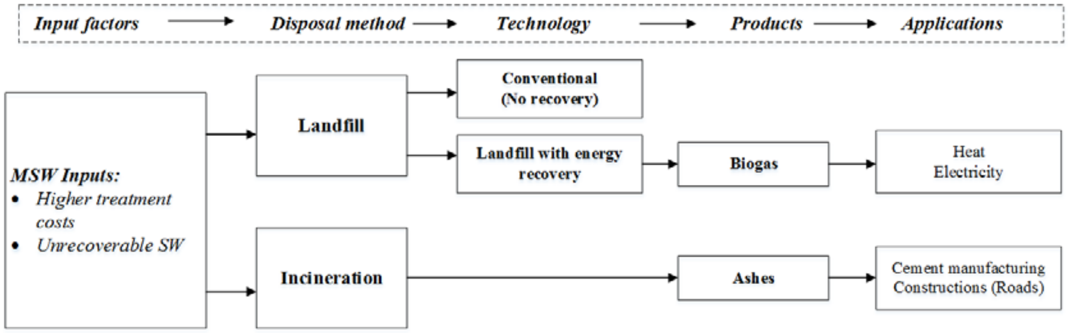

FIGURE 4. FLOWCHART FOR DISPOSAL OF SW.

III. SW CATEGORIES, COMPOSITION, AND GENERATION

It is important to understand the characteristics of SW in order to apply a sound management approach for each type. In the literature, there are different ways to categorize SW. For example, Ramachandra et al. (2018) categorize SW as organic and non-organic waste. Gundupalli et al. (2017) categorize SW as recyclable or non-recyclable. Edjabou et al. (2015) classify SW into more detailed categories: (1) food, (2) gardening, (3) paper, (4) board, (5) plastic, (6) metal, (7) glass, (8) miscellaneous combustible, (9) inert, (10) special and (11) residuals. Please refer to Edjabou et al. (2015) for more detailed definitions for each SW type.

Different categories of SW might need different collection, treatment, and disposal methods. In addition, SW composition differs from area-to-area and is influenced by factors such as geographical location, level of economic development, cultural norms, energy sources, and climate (Hoornweg & Bhada-Tata, 2012). Figure 5 contrasts the SW composition for low- and high-income countries. It indicates that the organic waste generation is high for low income countries, whereas for high income countries, paper waste is high. Information related to the composition of generated SW is needed for the planning, operation, and optimization of SWM systems (Beigle et al., 2008). For example, low-income countries can use 2-bin system consisting of organic and recyclable SW in order to collect SW. However, high-income countries can use a 3-bin system consisting of organic, paper, and other recyclable wastes. In addition, low-income countries can design SW supply chain configurations consisting of composting (as organic waste lends itself to composting), whereas high-income can design SW supply chain configurations consisting of recycling and composting (as organic and paper are two primary wastes). Table 5 presents the SW type, characteristics and their effective treatment and disposal methods. Apart from the SW composition, the SW generation rate is another important element that needs to be considered to design a long-term sustainable SWM system. This requires the development of predictive models to forecast future SW generation rate. Predictive models can be categorized as: (1) time series models, (2) data driven models, and (3) regression models. Time series models use past data and their distributions to forecast future SW generation (Kumar and Samadder, 2017). Data driven models use artificial intelligence, such as neural networks to predict future SW generation (Shahabi et al., 2012). Time series and data driven models can only be used for prediction purposes and do not help to reduce or control SW generation rates due to the lack of essential information on influencing factors. Consequently, regression models have been widely used to predict SW generation rates as they not only help to predict the SW generation rate, but also help identify the factors responsible for SW generation (Kumar and Samadder, 2017). Regression models such as multiple regression and binary logistic regression have been commonly used for identifying the factors that influence the SW generation rate. Socio-economic factors such as household size, family income, education, and occupation significantly impact the household SW generation rate (Kumar and Samadder, 2017). Other factors such as convenience to household, cost of SW collection, collection frequency, and separate curb side collection of organic waste also impact the SW generation rate (Gellynck et al. 2011).

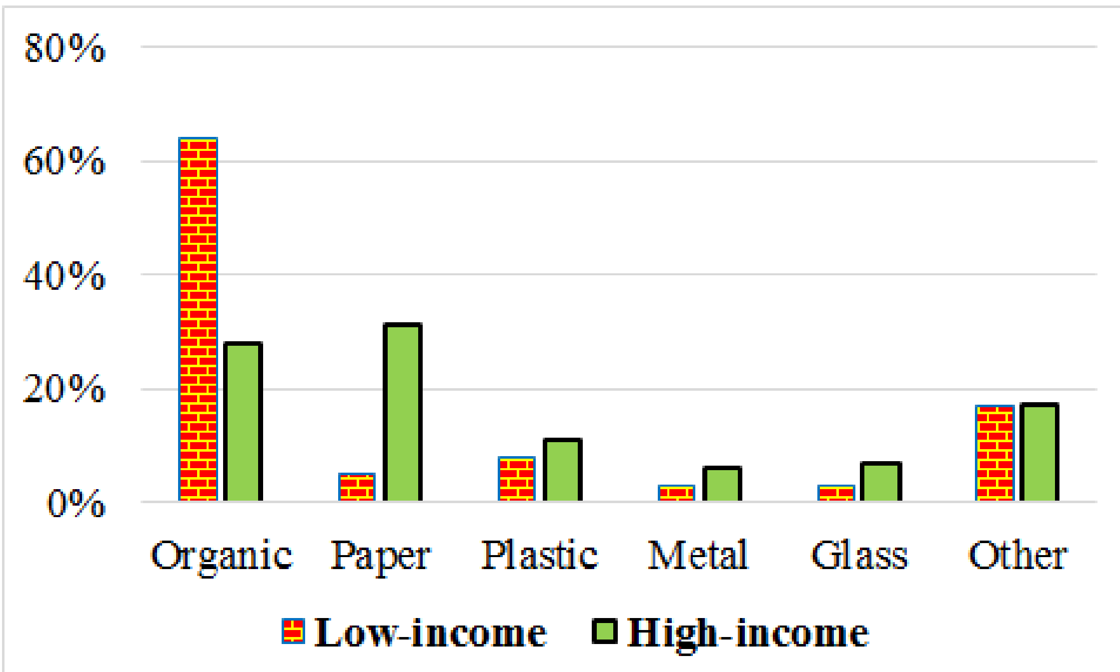

FIGURE 5. SW COMPOSITION IN LOW- AND HIGH-INCOME COUNTRIES.

TABLE 5. SW TYPE, CHARACTERICTIC AND TREATMENT AND DISPOSAL METHODS

SW type	SW characteristic		Treatment methods	Disposal methods
	Recyclable	Organic		
Food	No	Yes	• Composting • WTE	• Landfill • Incineration
Gardening	No	Yes	• Composting • WTE	• Landfill • Incineration
Paper	Yes	Yes	• Recycling • Composting • WTE	• Landfill • Incineration
Board	Yes	Yes	• Recycling	• Incineration
Plastic	Yes	No	• Recycling	• Landfill
Metal	Yes	No	• Recycling	• Landfill
Glass	Yes	No	• Recycling	• Landfill
Miscellaneous combustibles	Yes	Yes	• WTE	• Incineration
Inert	Yes		• Recycling	• Landfill
Special	Yes		• Recycling	• Landfill because of hazardousness
Residuals	No	No	NA	• Landfill, if hazardous • Incineration, if not hazardous

IV. CONCEPTUAL FRAMEWORK FOR SWM

None of the up-to-date literature on SWM has systematically and comprehensively described holistic decision making process in SWM from the perspective of SW supply chain. We address the gap in the literature by presenting a set of frameworks to be used when engaging in SWM decision making in a SW supply chain. Based on the comprehensive understanding of the literature, a conceptual framework of SWM combining performance, measures, stages and decisions are developed. Figure 6 presents performance measures that should be considered in each of the SWM stages. Figure 7 provides a framework that describes SW network structures, stages, and decisions to be made during each stage. Table 6 helps decision makers identify and plan strategic decisions, which are long-range decisions, tactical decisions, which are medium-range decisions, and operational decisions, which are short-range decisions for different decision categories. A decision maker can develop an appropriate modeling strategy to determine the optimal configuration of SWM by identifying the appropriate decisions from Figure 7 and Table 6 and by considering the performance measures as objectives from Figure 6.

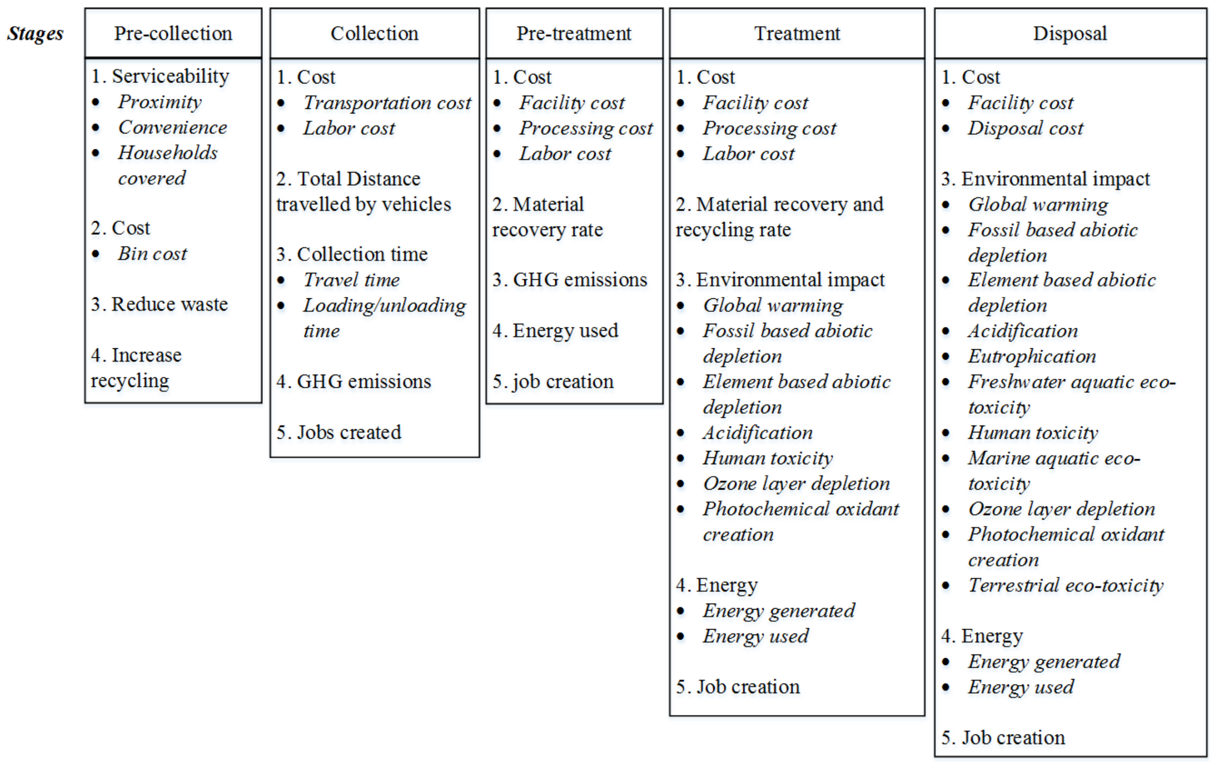

FIGURE 6. PERFORMANCE MEASURES IN EACH SWM STAGES.

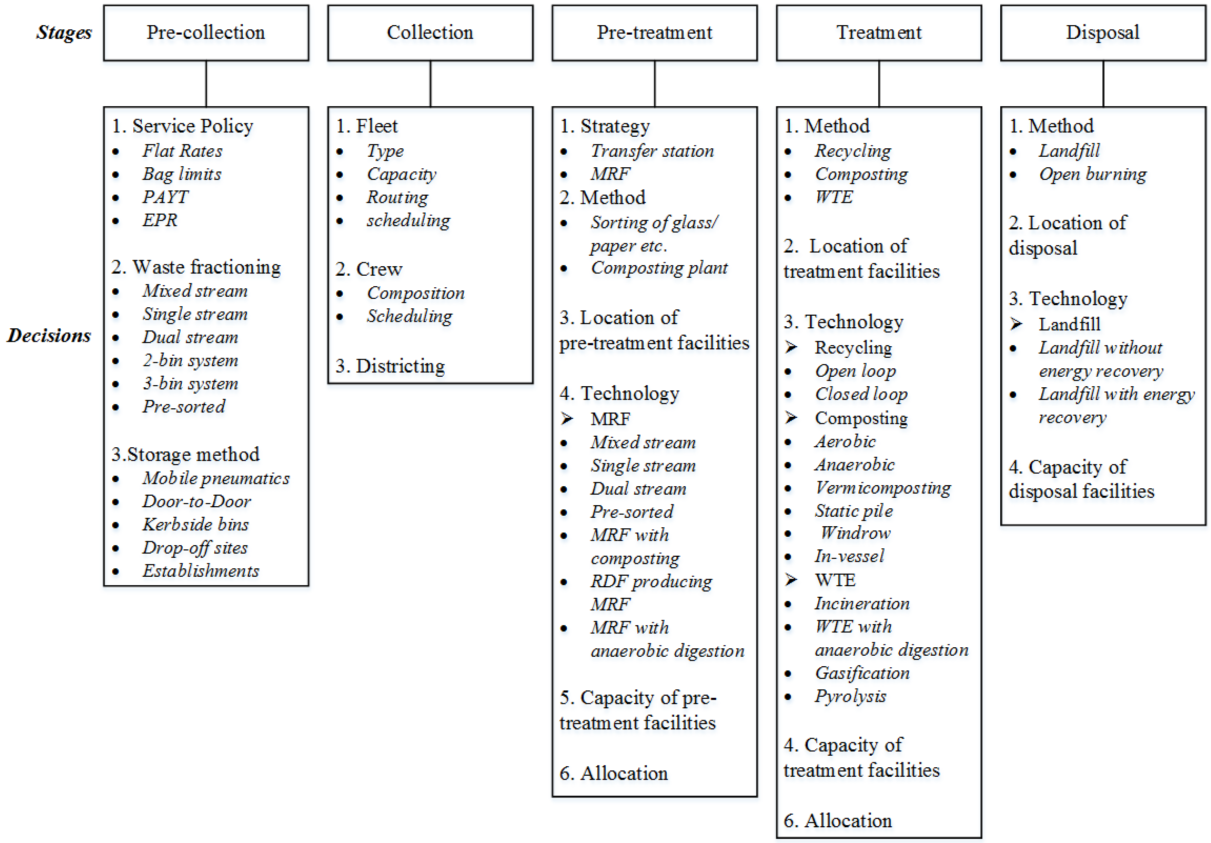

FIGURE 7. STAGES, AND DECISIONS.

TABLE 6. LITERTURE SUMMARY OF DECISION CATEGORIES, DECISIONS LEVELS, AND EFFECTIVE MODELLING STRATEGIES.

Decision Categories	Strategic decisions	Tactical decisions	Operational decisions	Effective modeling strategy	References
Methods	Pre-treatment, treatment, disposal, storage methods	Service policies, waste fractioning storage methods that include door-to-door and curbside	N/A	Simulation along with Life Cycle Assessment (LCA) can be effective to evaluate the performance of various method-based sub-systems in a SW Supply chain.	Ferri et al., (2015), Minoglou, M., & Komilis, D. (2013)
Locations	Pre-treatment facilities, treatment facilities, disposal facilities	Collection points	N/A	A Multi-objective optimization model considering the trade-off between serviceability, economic, environment, and social performances can be used to determine the optimal location of facilities in SW supply chain. Stochastic conditions such as variations in SW generation, categories, and composition can be incorporated.	Ferri et al., (2015) Eiselt & Marianov (2014)
Technology	pretreatment types, treatment types, disposal types	N/A	N/A	A decision framework combining Multi-objective optimization and LCA can be used to determine optimal technology in the SW supply chain.	Münster & Meibom, 2011

Capacity	Pre-treatment facilities, treatment facilities, disposal facilities	Collection points	N/A	A decision framework combining prediction and optimization models can be effective for long-term capacity planning.	Ferri et al., (2015), Kinobe et al. (2015)
Transportation	Fleet type, fleet capacity	Vehicle routes	Vehicle routes Crew composition	An optimization model is effective for making transportation decisions, However, heuristic algorithms are required to reduce the model complexity and solver computational time.	Nguyen-Trong et al. (2017), Louati (2016), Das & Bhattacharyya (2015)
Scheduling	N/A	Collection days, collection frequency, collection vehicle timing, fixed order or periodic order dispatch at pre-treatment facilities, SW processing and treatment scheduling	Crew scheduling for collection, pre-treatment and treatment facilities	An optimization model is effective for making scheduling decisions, However, heuristic algorithms are required to reduce the model complexity and solver computational time.	De Bruecker et al. (2017), Louati (2016)
Districting and allocation	N/A	District zoning	Allocation	An optimization model with assignment problem consideration is effective for districting and allocation decisions.	Xue et al. (2015), Coutinho-Rodrigues et al., (2012)

V. SW NETWORK STRUCTURES

Typically, SWM involves five stages: pre-collection, collection, pre-treatment, treatment, and disposal. However, not all SWM strategies involve all stages due to factors such as geographic characteristics, SW composition, and cost structures. Based on the SWM studies conducted by Ferri et al. 2015, Zhang et al. 2011, Geng et al., 2010, and Bovea et al. 2010, we categorize five SW network structures. A municipality can also use any or a combination of the basic structures depending on the geographic availability of treatment or disposal facilities, recycling requirements, budgetary constraints, and collaboration with business and industrial entities. The five basic network structures are as follows: (1) Direct Shipping (DS); (2) MRF Segregation (MS); (3) Transfer Station Merge (TSM); (4) Transfer Station Merge and MRF Segregation (TSM-MS) and (5) Urban Symbiosis Network (USN).

Figure 8 presents the DS network structure. DS involves the direct shipping of SW from the collection points to the treatment and/or disposal facilities to exploit the locally available facilities. Figure 9 presents the MS network structure in which an MRF is used for SW recovery. The MRF segregates the incoming SWs into different SW streams which are then sent to treatment and disposal facilities. Figure 10 presents the TSM network structure in which a transfer station is used for consolidating incoming SWs and shipping them to the distant treatment and/or disposal facilities by using large vehicles such as large trailers, trains, and barges. Figure 11 presents the TSM-MS network which includes a transfer station that is used for consolidating incoming SWs and shipping them to the distant MRF. The MRF then recovers the SW and sends different SW streams to treatment and disposal facilities. Figure 12 presents the USN in which municipalities and business entities develop synergistic relationships (irrespective of the distance) over time between themselves as long as the desired sustainability benefits are realized. In the USN, various business entities including municipalities collaborate through exchange of materials, energy, water and by-products, thereby creating economic, environmental, and energy intensity benefits (Geng et al., 2010). In the USN, the output products, by-products, and wastes of one entity becomes the input raw material to another entity resulting in increased resource utilization. USN strives to achieve net zero waste for the area under consideration. It is important to note that not all the SW network structures involve all the stages.

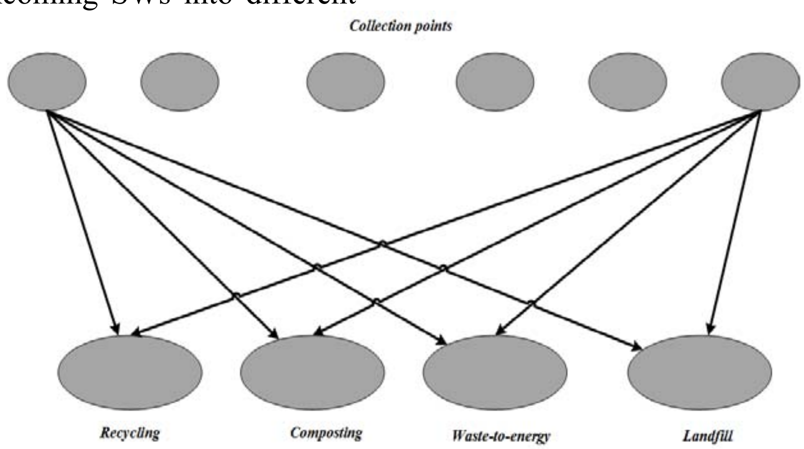

Figure 8. DS NETWORK STRUCTURE.

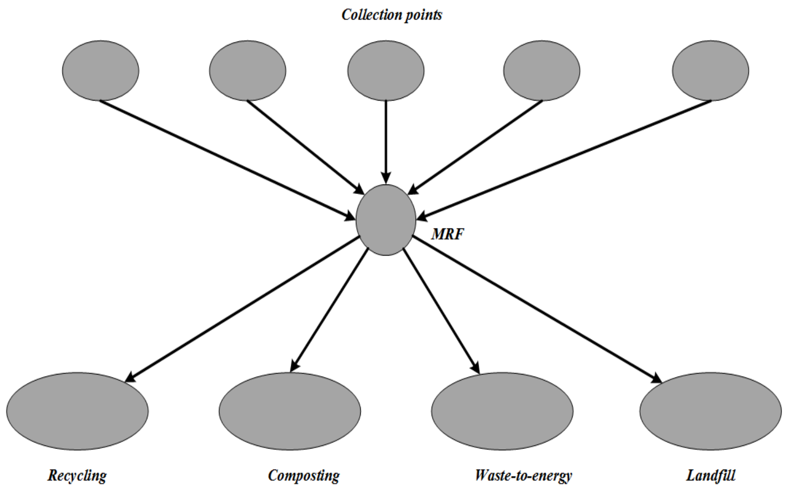

FIGURE 9. MS NETWORK STRUCTURE.

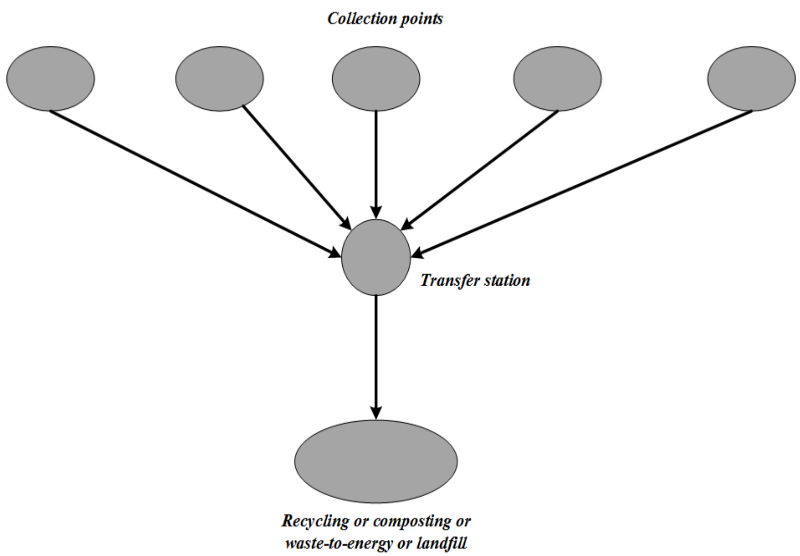

FIGURE 10. TSM NETWORK STRUCTURE.

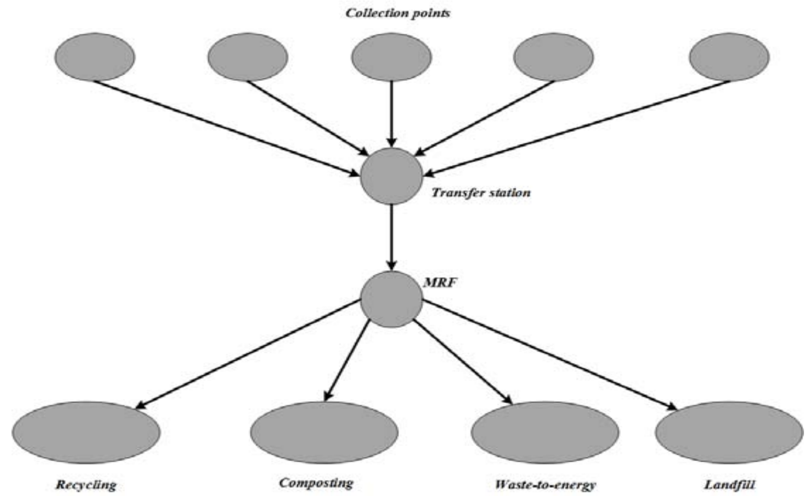

FIGURE 11. TSM-MS NETWORK STRUCTURE

.

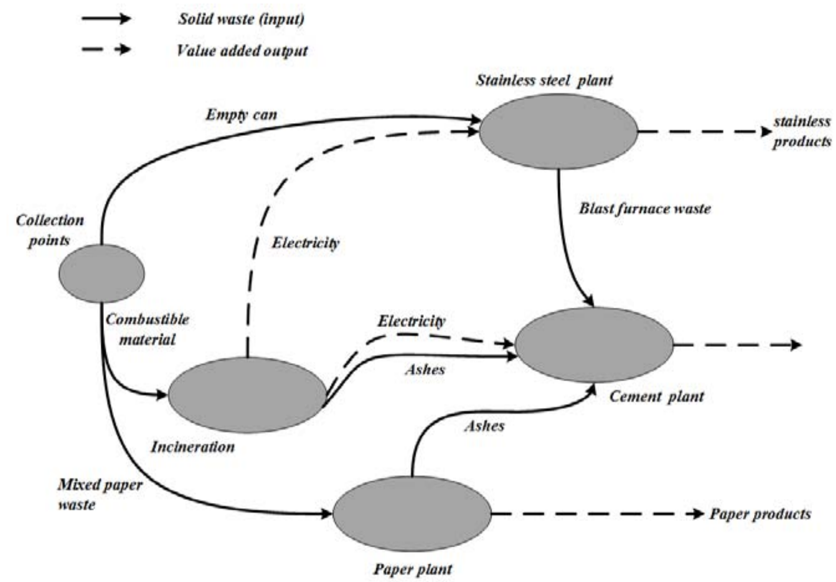

FIGURE 12. URBAN SYMBIOSIS.

TABLE 7. PROPOSED APPLICATION AREAS AND STRATEGIES FOR SUCCESS FOR DIFFERENT SW NETWORK STRUCTURES.

Network	Proposed application areas	Strategies for SWM success
DS	• Municipalities that has locally available and easily accessible treatment and/or disposal facilities resulting in reduced transportation costs and GHG emissions.	• PAYT and EPR are best service policies to promote recovery, reuse, and recycling if treatment facilities are available in the region. Bag limits is the best policy to reduce SW disposal if disposal facilities are available in the region. • Source separation at the pre-collection stage is best if treatment facilities available; else, mixed stream is best for disposing. • Drop-off sites can be used if treatment facilities are available. • Optimization models can be used to design a DS network that involve determining districts and streamlined flow of SW from collection points to treatment and disposal facilities.
MS	• Municipalities that has locally available MRF facility or planning to build MRF facilities resulting in increased facility costs. • The goal is to reduce GHG emissions by increasing SW recovery/recycling and at the same time generate revenue by SW recovery.	• PAYT and EPR are best when input MRF technology is used. Flat rate and bag limits are best when output MRF technology is used. • If input MRF technology is available, source separation at the pre-collection can increase recycling. If output MRF technology is available, mixed stream can help to reduce costs and at the same time MRF technology can help to convert residuals to value adding output. • Optimization models can be used to design MS network that involve determining optimal location, technology, and flow of SW streams.
TSM	• Small scale municipalities or municipalities which has treatment and disposal facilities at farther distance. The SW s consolidated to transportation costs and GHG emissions.	• Flat rates and bag limits are best if SWs are consolidated to be sent to WTE systems or landfill. PAYT and EPR is best if SW is consolidated to be sent to treatment facilities. • Mixed stream is best if SWs are consolidated to be sent to WTE systems or landfill. Source separation is best if SWs is consolidated to be sent to treatment facilities. • Optimization model can be used to design TSM network that involve determining the location of transfer station and flow of SWs.

TSM-MS	• Municipalities that emphasizes on recovery and recycling. However, treatment facilities at farther distances. • The goal is to increase recycling and at the same time reduce treatment and disposal costs	• Flat rates and bag limits are best. • Mixed stream is best. • Optimization models can be used to design TSM-MS network that require determine the location of transfer station, MRF facility, MRF technology and stream lined flow of materials
US	• Municipalities with several businesses and industries • The goal is to form collaboration and symbiotic relationships resulting in reduced costs and zero waste.	• Requires stakeholders' involvement to develop and implement symbiotic relationships. • Pre-sorted stream is the best waste fractioning strategy • Optimization models can developed to determine the effective symbiotic relationships

Table 7 presents the proposed application areas and strategies for success for different SW network structures. Although, SW network structure consists of these five basic structures, any combination of these can be used by municipalities to form a "Hybrid" SW network structure depending on the SW streams and the accessibility of pre-treatment and treatment facilities. For, example, a municipality having treatment facilities locally and a disposal facility (landfill) at a far distance can use a combination of DS and TSM networks.

VI. CONCLUSIONS

In this paper, we conduct a comprehensive study on the literature study in the area of Solid Waste Management (SWM) from a supply chain perspective. Firstly, different stages of the SW supply chain are comprehensively studied. Secondly, SW categories, composition, and generation are studied to understand their impact on SW planning, operation, and optimization. Third, a conceptual framework combining performance measures, decisions, and effective modelling strategies is developed. Finally, various SW network structures are identified and evaluated. The following are some of the important insights that are gleaned from this research:

1. A number of varying trade-offs exist between different stages of the SW supply chain. This makes supply chain decision making in SW complex.
2. In most cases, localized supply chain planning and optimization results in conflicts with regional SW supply chain infrastructure planning. Therefore, it is important to develop a globalized plan for SWM.
3. Predictive analytics are important at different stages for strategic, tactical and operational planning of SWM.
4. Supply chain decisions based on value-chain, dematerialization, sustainable production, and extended producer responsibility need to be the driving force in SWM such that SW can be reduced.
5. SW systems developed based on urban symbiosis, circular economy, and closed-loop supply chains are rarely studied in SWM.

VII. FUTURE RESEARCH DIRECTIONS

Ample research has been conducted in SWM in various contexts, such as SW categorizing approaches and different modeling approaches to better understand the SWM systems and to determine the optimal solutions for various decisions. However, many gaps still exist. For example, many correlated decisions are made separately to arrive at local optimal solutions resulting in higher total operational cost, reduced material recovery, and recycling. In addition, better strategies to reduce, reuse, and recycle SW are still needed to relieve environmental impact. In addition to the insights gleaned from the literature review, we propose two future research directions to bridge some of the gaps in the SWM literature.

7.1. Concurrently planning all stages in SWM

Currently, the planning of activities in different SWM stages are disconnected and are performed separately by different entities (Zhang et al, 2011). The pre-collection and collection stage activities are planned by local authorities, whereas the pretreatment, treatment, and disposal stage activities are planned by regional authorities. This results in increased costs, reduced recycling, and increased disposal of SW due to improper alignment of activities across different stages. The non-alignment of decisions across various stages serve as barriers to both local and regional decision making as the regional level decisions rely on conflicting local level decisions culminating from different municipalities. For example, the level of waste fractioning at the pre-collection stage impacts the technological requirements in pre-treatment stage. Different waste fractioning strategies at different municipalities hinders the pre-treatment technology selections resulting in less efficient technology that reduces the SW recovery rate. Therefore, it is important to concurrently plan all the stages in SWM. The alignment of decisions of all stages towards a common goal can be achieved by synchronizing the strategic decisions at all stages. Figure 11 shows sequential steps to apply the optimization model in order to concurrently plan all the stages in SWM for a particular region.

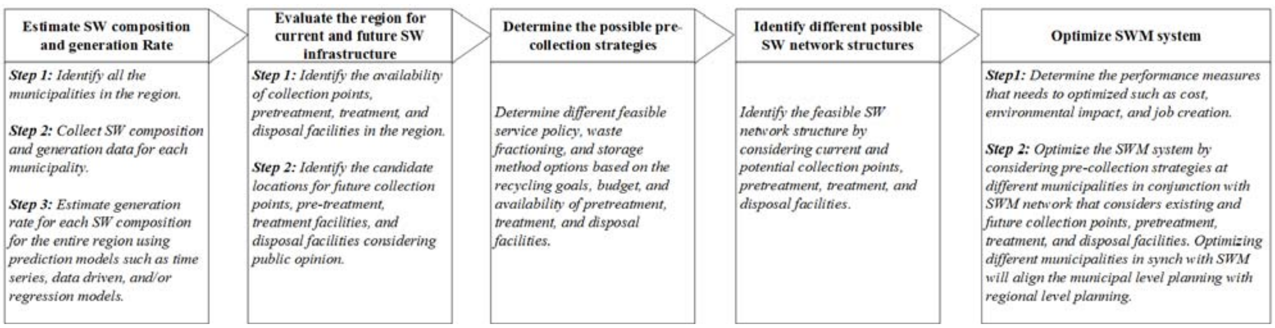

FIGURE 11. OPTIMIZATION MODEL STEPS TO CONCURRENTLY PLAN DIFFERENT STAGES IN SWM.

7.2. Formalizing urban symbiosis network (USN) in SWM

The literature shows that the rate of waste generation is continuously increasing (Hoornweg & Bhada-Tata, 2012). Without a better strategy to reduce, reuse, and recycle SW, the society will face lacking resources for handling SW. Urban Symbiosis, therefore, is becoming an attractive strategy to reduce, reuse and recycle SW. The literature indicates that only Geng et al. (2010) has studied the role of Urban Symbiosis in the field of SWM. In the USN, different business entities collaborate for sharing services, utilities, and resources in order to reduce wastes, costs and environmental impacts. The USN requires collaborations between municipalities, commercial establishments, institutions, businesses, and industries such that the output of one entity becomes the input raw material for other entities and hence strive for a net zero waste community. This can reduce the SWM burden of municipalities as entities can transfer resources directly among themselves. The USN can be formalized or implemented in a particular region by the steps shown in Table 8.

Acknowledgment

The authors would like to acknowledge the Ms. Kara Escajeda, City Manager of Nolanville, Texas for providing important insights related to solid waste management. In addition, the authors would like to thank Dr. Mohana Asha Latha Dubasi for providing feedback on this manuscript. The authors would also like to thank the editor and anonymous reviewers for their valuable feedback.

TABLE 8. STEPS TO FORMALLY DEVELOP US NETWORK

Steps	Description
Step 1: Stake holder engagement	Identify the stakeholders or businesses that can engage in the US network for a specific region. This requires the understanding of the input resources used and the outputs produced for each business entity. The first priority for all the stakeholders or businesses is to look for reuse and recycling opportunities.
Step 2: Symbiotic Relationships	Identify the symbiotic relationships between different business entities for different product, by-products, and SW streams. A symbiotic relationship involves matching the outputs of one business entity (including SW streams) to the input of another business entity.
Step 3: Model development	Develop models such as Life Cycle Analysis (LCA), optimization, and simulation in order to gauge the symbiotic payoff for a given symbiotic relationship. A symbiotic payoff is the value created by a particular symbiotic relationship. A symbiotic pay-off is a performance measure that can be used to measure economic, environmental, and social benefits for a particular symbiotic relationship.
Step 4: Decide on developing symbiotic relationship	Compare the symbiotic pay-off with the decision maker's desired pay-off. If the pay-off is higher than the desired pay-off, develop the symbiotic relationship for the product, by-product, and/or SW stream. Otherwise, do not develop the symbiotic relationship.

REFERENCES

Agamuthu, P., & Victor, D. (2011). Policy trends of extended producer responsibility in Malaysia. Waste Management & Research, 29(9), 945-953.

Atmos News. (2014). Retrieved from TRASH BURNING WORLDWIDE SIGNIFICANTLY WORSENS AIR POLLUTION: https://www2.ucar.edu/atmosnews/news/12239/trash-burning-worldwide-significantly-worsens-air-pollution

Beigl, P., Lebersorger, S., & Salhofer, S. (2008). Modelling municipal solid waste generation: A review. Waste management, 28(1), 200-214.

Bovea, M. D., Ibáñez-Forés, V., Gallardo, A., & Colomer-Mendoza, F. J. (2010). Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. Waste Management, 30(11), 2383-2395.

Coutinho-Rodrigues, J., Tralhão, L., & Alçada-Almeida, L. (2012). A bi-objective modeling approach applied to an urban semi-desirable facility location problem. European Journal of Operational Research, 223(1), 203-213.

Das, S., & Bhattacharyya, B. K. (2015). Optimization of municipal solid waste collection and transportation routes. Waste Management, 43, 9-18.

De Bruecker, P., Beliën, J., De Boeck, L., De Jaeger, S., & Demeulemeester, E. (2017). A model enhancement approach for optimizing the integrated shift scheduling and vehicle routing problem in waste collection. European Journal of Operational Research.

Di Maria, F., Micale, C., & Morettini, E. (2016). Impact of the pre-collection phase at different intensities of source segregation of bio-waste: An Italian case study. Waste Management, 53, 12-21.

Edjabou, M. E., Jensen, M. B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C., & Astrup, T. F. (2015). Municipal solid waste composition: Sampling methodology, statistical analyses, and case study evaluation. Waste Management, 36, 12-23.

Eiselt, H. A., & Marianov, V. (2015). Location modeling for municipal solid waste facilities. Computers & Operations Research, 62, 305-315.

Eiselt, H. A., & Marianov, V. (2014). A bi-objective model for the location of landfills for municipal solid waste. European Journal of Operational Research, 235(1), 187-194.

Elia, V., Gnoni, M. G., & Tornese, F. (2015). Designing Pay-As-You-Throw schemes in municipal waste management services: A holistic approach. Waste Management, 44, 188-195.

EU EPA. (2008). Municipal solid waste - Pretreatment & Residual management.

Farrell, M., & Jones, D. L. (2009). Critical evaluation of municipal solid waste composting and potential compost markets. Bioresource technology, 100(19), 4301-4310.

Ferri, G. L., Chaves, G. D. L. D., & Ribeiro, G. M. (2015). Reverse logistics network for municipal solid waste management: The inclusion of waste pickers as a Brazilian legal requirement. Waste Management, 40, 173-191.

Gallardo, A., Carlos, M., Peris, M., & Colomer, F. J. (2015). Methodology to design a municipal solid waste pre-collection system. A case study. Waste management, 36, 1-11.

Gellynck, X., Jacobsen, R., & Verhelst, P. (2011). Identifying the key factors in increasing recycling and reducing residual household waste: A case study of the Flemish region of Belgium. Journal of Environmental Management, 92(10), 2683-2690.

Geng, Y., Tsuyoshi, F., & Chen, X. (2010). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. Journal of Cleaner Production, 18(10), 993-1000.

Gundupalli, S. P., Hait, S., & Thakur, A. (2017). A review on automated sorting of source-separated municipal solid waste for recycling. Waste Management, 60, 56-74.

Hoornweg, D., & Bhada-Tata, P. (2012). WHAT A WASTE A Global Review of Solid Waste Management. World Bank.

Iriarte, A., Gabarrell, X., & Rieradevall, J. (2009). LCA of selective waste collection systems in dense urban areas. Waste Management, 29(2), 903-914.

Jeswani, H. K., & Azapagic, A. (2016). Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. *Waste Management*, *50*, 346-363.

Kinobe, J. R., Bosona, T., Gebresenbet, G., Niwagaba, C. B., & Vinnerås, B. (2015). Optimization of waste collection and disposal in Kampala city. Habitat International, 49, 126-137.

Kumar, A., & Samadder, S. R. (2017). An empirical model for prediction of household solid waste generation rate–A case study of Dhanbad, India. Waste Management, 68, 3-15.

LeBlanc, R. (2017). What Is a Waste Transfer Station? Retrieved from the balance: https://www.thebalance.com/what-is-a-waste-transfer-station-2877735

Louati, A. (2016). Modeling municipal solid waste collection: A generalized vehicle routing model with multiple transfer stations, gather sites and inhomogeneous vehicles in time windows. Waste Management, 52, 34-49.

Malinauskaite, J., Jouhara, H., Czajczyńska, D., Stanchev, P., Katsou, E., Rostkowski, P., ... & Anguilano, L. (2017). Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy, 141, 2013-2044.

Minoglou, M., & Komilis, D. (2013). Optimizing the treatment and disposal of municipal solid wastes using mathematical programming—a case study in a Greek region. Resources, Conservation and Recycling, 80, 46-57.

Mueller, W. (2013). The effectiveness of recycling policy options: waste diversion or just diversions?. Waste management, 33(3), 508-518.

Münster, M., Ravn, H., Hedegaard, K., Juul, N., & Söderman, M. L. (2015). Economic and environmental optimization of waste treatment. Waste Management, 38, 486-495.

Nguyen-Trong, K., Nguyen-Thi-Ngoc, A., Nguyen-Ngoc, D., & Dinh-Thi-Hai, V. (2017). Optimization of municipal solid waste transportation by integrating GIS analysis, equation-based, and agent-based model. Waste Management, 59, 14-22.

Nixon, J. D., Dey, P. K., Ghosh, S. K., & Davies, P. A. (2013). Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process. Energy, 59, 215-223.

Pagell, M., Wu, Z., & Murthy, N. N. (2007). The supply chain implications of recycling. Business Horizons, 50(2), 133-143.

Pressley, P. N., Levis, J. W., Damgaard, A., Barlaz, M. A., & DeCarolis, J. F. (2015). Analysis of material recovery facilities for use in life-cycle assessment. Waste Management, 35, 307-317.

Ramachandra, T. V., Bharath, H. A., Kulkarni, G., & Han, S. S. (2018). Municipal solid waste: Generation, composition and GHG emissions in Bangalore, India. Renewable and Sustainable Energy Reviews, 82, 1122-1136.

Rada, E. C., & Cioca, L. (2017). Optimizing the Methodology of Characterization of Municipal Solid Waste in EU Under a Circular Economy Perspective. Energy Procedia, 119, 72-85.

Shahabi, H., Khezri, S., Ahmad, B. B., & Zabihi, H. (2012). Application of artificial neural network in prediction of municipal solid waste generation (Case study: Saqqez City in Kurdistan Province). World Applied Sciences Journal, 20(2), 336-343.

Shi, X., Thanos, A. E., & Celik, N. (2014). Multi-objective agent-based modeling of single-stream recycling programs. Resources, Conservation and Recycling, 92, 190-205.

Simmons, A. M. (2016). The world's trash crisis, and why many Americans are oblivious. Retrieved from LA Times: http://www.latimes.com/world/global-development/la-fg-global-trash-20160422-20160421-snap-htmlstory.html

Wagner, T. P. (2013). Examining the concept of convenient collection: An application to extended producer responsibility and product stewardship frameworks. Waste management, 33(3), 499-507.

Xue, W., Cao, K., & Li, W. (2015). Municipal solid waste collection optimization in Singapore. Applied Geography, 62, 182-190.

Zhang, Y. M., Huang, G. H., & He, L. (2011). An inexact reverse logistics model for municipal solid waste management systems. Journal of Environmental Management, 92(3), 522-530.

Zhou, C., Gong, Z., Hu, J., Cao, A., & Liang, H. (2015). A cost-benefit analysis of landfill mining and material recycling in China. Waste Management, 35, 191-198.