SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

MASTER OF SCIENCE IN ENVIRONMENTAL AND LAND PLANNING ENGINEERING

ANALYSIS OF THE MUNICIPAL SOLID WASTE MANAGEMENT AND TREATMENT IN KHARTOUM STATE AND DESIGN OF A MIXED WASTE PROCESSING FACILITY

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental and Land Planning Engineering

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DEDICATION

To the 2019 Sudanese Revolution Martyrs

"O Allah forgive them, have mercy on them, give them strength, and pardon them. O Allah be generous to them and cause their entrance to be wide and wash them with water and snow and hail. O Allah cleanse them of their transgressions as white cloth is cleansed of stains. O Allah give them an abode better than their home, and a family better than their family and a partner better than their partner. O Allah take them into Paradise and protect them from the punishment of the grave and the punishment of Hell-fire."

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ABSTRACT

The poor management of municipal solid waste (MSW) is associated to adverse environmental impacts. In contrast, the treatment of the organic waste fraction, in particular, can substantially reduce the Greenhouse Gas (GHG) emissions should it been landfilled. Waste treatment or recycling also helps with resource recovery by partly substituting the use of some raw materials. This thesis intends to provide a comprehensive investigation of the current situation of the management and treatment of the MSW in Khartoum State with a particular emphasis on recycling activities of the major waste streams namely organic (49.5%) and plastic waste (12.7%) fractions, as they are the two streams with proven treatment trials. The investigation was carried out through site visits, interviews with concerned parties, a survey of plastic recycling facilities, review of available documents as well as personal observation.

Provided the current municipal solid waste (MSW) composition, disposal practices, and collection method, this study suggested the design of a semi-manual mixed-waste treatment facility coupled with an organic treatment facility (windrow biostabilization) as a treatment scenario with a collective capacity of 219,000 tons of waste per year, of which around 111,690 is compostable and is sent to the biostabilization facility. Moreover, the recyclables recovered (including paper, cardboard, plastic, ferrous and nonferrous metals) are expected to amount to 58,896 tons annually. Lastly, the emissions of both current and proposed scenarios were obtained using version 2.0 of the Solid Waste Emission Estimation Tool (SWEET) developed in 2018.

It was concluded from the data that the design of a proper waste management system in the state requires a special focus on waste collection activities. Scaling up the collection rate will not only improve the sanitary situation but will eliminate open waste burning activities since it was found to be a major contributor (1,590,027 CO_2eq) to the current emission scenario at 1,590,027 tons CO_2eq. Notwithstanding, the efforts made by the Japanese International Cooperation Agency (JICA) to scale up the waste collection rates to 80% in 2020, it was reported that the collection rate is believed to be even lower now than the 65% reported by JICA in 2014, which highlights more complex issues with waste collection systems. Waste collection and transportation services need further planning and better management including MSW data, which needs to be managed timely and accurately at each point of the process. Providing accurate and updated quantity measurements will aid in making more informed decisions in the future and support better planning, operating, and monitoring, and consequently providing improved services.

Currently, the Khartoum state government does not own nor operate any MSW treatment facility. Waste treatment activities are dominated by the private sector. This thesis investigated the plastic recycling sector through a structured survey for eight (21%) of the private recycling plants. Survey findings indicated that High-density Polyethylene (HDPE) and Polypropylene (PP) are recycled into products locally, while Polyethylene Terephthalate (PET) is only primarily-treated and exported. The average amount of plastic recycled was found to be 6,205 tons annually.

This thesis presents a preliminary design of a combined waste sorting and organic treatment facility that is intended to be constructed and operated by the government of Khartoum state. This design is expected to cut down significantly on the secondary waste transportation costs. Moreover, the revenues from the recyclables sales are to guarantee the sustainability of the operation of the entire process and the organic waste treatment particularly. However, in order to implement a more successful organic waste treatment plan, source separation and separate collection of at least the organic fraction must be introduced.

Keywords: Municipal solid waste management, Developing countries, Khartoum, Sudan, Mixed waste processing, Organic waste composting, Biostabilization, Plastic waste recycling.

SINTESI

La cattiva gestione dei rifiuti solidi urbani (RSU) è associata a impatti ambientali negativi. Al contrario, il trattamento della frazione di rifiuti organici, in particolare, può ridurre in modo sostanziale le emissioni di gas serra (GHG) in caso di discarica. Il trattamento o il riciclaggio dei rifiuti aiuta anche con il recupero delle risorse sostituendo parzialmente l'uso di alcune materie prime. Questa tesi intendeva fornire un'indagine completa della situazione attuale della gestione e del trattamento dei rifiuti solidi urbani nello Stato di Khartoum con un'enfasi particolare sulle attività di riciclaggio dei principali flussi di rifiuti, vale a dire le frazioni di rifiuti organici (49,5%) e di plastica (12,7%), in quanto sono i due flussi con provata possibilità di trattamento. L'indagine è stata condotta attraverso visite in loco, interviste alle parti interessate, sondaggio per gli impianti di riciclaggio della plastica, revisione dei documenti disponibili e osservazioni personali.

Considerando l'attuale composizione, pratiche di smaltimento e metodo di raccolta dei rifiuti solidi urbani (RSU), questo studio ha suggerito la progettazione di un impianto di trattamento dei rifiuti misti semi-manuale accoppiato con un impianto di stabilizzazione della frazione organico (compostaggio di andane) come scenario di trattamento, con una capacità complessiva di 219.000 tonnellate di rifiuti all'anno, di cui circa 111.690 compostabili e avviate alla sezione di biostabilizzazione. Si prevede inoltre che i materiali riciclabili recuperati (inclusi carta, cartone, plastica, metalli ferrosi e non ferrosi) ammonteranno a 58.896 tonnellate annue. Infine, le emissioni degli scenari attuali e proposti sono state ottenute utilizzando la versione 2.0 del Solid Waste Emission Estimation Tool (SWEET) sviluppato nel 2018.

Dai dati si è concluso che la progettazione di un adeguato sistema di gestione dei rifiuti nello Stato richiede un'attenzione particolare alle attività di raccolta dei rifiuti. L'aumento del tasso di raccolta non solo migliorerà la situazione sanitaria, ma eliminerà le attività di combustione dei rifiuti aperti, poiché si è scoperto che è un importante contributo (1.590.027 CO2eq) all'attuale scenario di emissioni a 1.590.027 tonnellate CO2eq. Nonostante gli sforzi compiuti dalla Cooperazione internazionale giapponese (JICA) per aumentare i tassi di raccolta dei rifiuti all'80% nel 2020, è stato riferito che il tasso di raccolta è ritenuto addirittura inferiore al 65% riportato da JICA nel 2014, cosa che evidenzia una problematica più complessa con il sistema di raccolta dei rifiuti. I servizi di raccolta e trasporto dei rifiuti richiedono un'ulteriore pianificazione e una migliore gestione, inclusi i dati sui RSU, che devono essere gestiti in modo tempestivo e accurato in ogni punto del processo. Fornire misurazioni di quantità accurate e aggiornate aiuterà a prendere decisioni più informate in futuro e supporterà una migliore pianificazione, funzionamento e monitoraggio e, di conseguenza, fornendo servizi migliori.

Attualmente, il governo dello stato di Khartoum non possiede né gestisce strutture per il trattamento dei rifiuti solidi urbani. Le attività di trattamento dei rifiuti sono dominate dal settore privato. Questa tesi ha analizzato il settore del riciclaggio della plastica attraverso un'indagine strutturata per otto (21%) impianti di riciclaggio privati. I risultati del sondaggio hanno confermato che il polietilene ad alta densità (HDPE) e il polipropilene (PP) vengono riciclati in prodotti localmente mentre il polietilene tereftalato (PET) viene principalmente trattato ed esportato. La quantità media di plastica riciclata è risultata essere 6.205 tonnellate riciclate ogni anno.

Questa tesi presenta un progetto preliminare per un impianto combinato di selezione dei rifiuti e biostabilizzazione dell'organico che dovrebbe essere costruito e gestito dal governo dello stato di Khartoum. Si prevede che questo progetto ridurrà notevolmente i costi di trasporto dei rifiuti secondari. Inoltre, i ricavi delle vendite dei riciclabili servono a garantire la sostenibilità del funzionamento dell'intero processo e in particolare il trattamento dei rifiuti organici. Tuttavia, al fine di attuare un piano di trattamento dei rifiuti organici più efficace, è necessario introdurre la separazione alla fonte e la raccolta separata almeno della frazione organica.

Parole Chiave: Gestione dei rifiuti solidi urbani, Paesi in via di sviluppo, Khartoum Sudan, Trattamento dei rifiuti misti, Compostaggio dei rifiuti organici, biostabilizzazione, Riciclo dei rifiuti di plastica.

ACRONYMS

Acronym	Meaning
ACT	Active Composting Time
CDM	Clean Development Mechanism
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
GOS	Government of Sudan
FPFT	Fixed Place Fixed Time
HCE	Higher Council of Environment and Rural and Urban Development
HDPE	High-Density Polyethylene
HH	Household
JICA	Japanese International Cooperation Agency
KSCA	Khartoum State Cleaning Authority
LDPE	Low-Density Polyethylene
LF	Landfill
LOC	Locality
MBT	Mechanical Biological Treatment
MOE	Ministry of Environment, Natural Resources, and Physical Development
MP	Master Plan
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSWMT	Municipal Solid Waste Management and Treatment
MWPF	Mixed Waste Processing Facility
PET	Polyethylene Terephthalate
PP	Polypropylene
RFTF	Recovery Factor Transformation Function
SRF	Solid Recovered Fuel
SWEET	Solid Waste Emission Estimation Tool
TS	Transfer Station
UNFCCC	United Nations Framework Convention on Climate Change
WTE	Waste to Energy

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CHAPTER (1): INTRODUCTION

Recently, solid waste has become such a challenging issue and a growing concern around the world. The rapid urbanization rate, the growing Gross Domestic Product (GDP) and the rise of consumer culture collectively result in a consequent increase in the generation patterns of solid waste. Additionally, waste composition and complexity of the disposed products can be more problematic than waste volume [1].

Solid waste poses a particular challenge in the developing countries where there are limited investments in this area as well as poor management and disposal practices by both governments and individuals. Domestic solid waste, which constitutes a large percentage of the municipal solid waste (MSW), is mostly openly dumped in the streets and often burned due to the unreliable waste collection services [2][3]. Furger et al. in 2013 [4] stated that when solid waste is left untreated, there would be unquestionable adverse impacts on both the environment and human health. On top of the visual pollution, inappropriate waste disposal pollutes soil and water bodies due to the release of leachate produced by the organic waste in open dumps and poorly-managed. It also harms air through the release of greenhouse gases due to the decomposition of organic matter and the uncontrolled waste burning in residential areas. Concerning human health and safety, solid waste piles often lead to drains clogging and potentially floods during rainy season, which create a favorable breeding environment for rodents and insects that can spread diseases such as cholera, malaria and dengue fever. Moreover, using waste-polluted water for drinking or irrigation exposes consumers to many diseases [4][5].

Both management and treatment of solid waste, in Sudan generally, and in Khartoum state particularly, pose a significant challenge to the government. Due to lack of guarding policies and regulations, together with the absence of law enforcement, waste can be found openly-dumped within the residential areas, markets, and streets; and often ends up being burnt if it is not collected. Mixed/unsorted wastes, mostly disposed of in plastic bags, sit in front of the houses or in a nearby dumpster, which exposes it to scavenging by both people and stray animals [4]. The solid waste collection efforts to present are evidently inadequate as piles of waste are observed in almost every street around the state. Collection activities hence need to be promoted and optimized as the adopted approach of the house-to-house collection is considered a costly and tedious approach [6]. Moreover, Khartoum state also has a continually increasing population as it is considered the center of development of the country, where there are better employment chances and better services provision compared to other states in Sudan [5]. Therefore, waste management and treatment facilities must be designed in such a way to accommodate future population growth.

This study aims to provide a detailed overview of the current situation of solid waste management and treatment in Khartoum state in order to suggest a feasible scenario to improve the management and treatment services and better the overall sanitary conditions in the state. This dissertation is intended to answer the following questions:

i. What is the current situation of the municipal solid waste management in Sudan in general and Khartoum state in particular?
ii. What are the past and the current municipal solid waste management and treatment efforts?
iii. What are the suggested future scenario(s) for waste management and treatment in Khartoum?
iv. What are the tailored recommendation(s) and practices that are capable of putting it on the right track towards achieving an ISWM system?

Khartoum state represents the case study for this thesis bearing in mind that all the management efforts are currently exerted in this state. However, the Government of Sudan (GOS), in collaboration with JICA, is currently looking into the possibility of replicating the waste system strengthening project implemented in Khartoum in 2014 – 2017 into other states in Sudan; namely, North Kordofan state in the south-western region and the Red Sea state in the northeastern part of the country, according to an interview with a JICA official in September 2019. The focus of this study has also been entirely directed towards domestic solid waste, meaning that other types of waste, i.e., medical waste, industrial waste, C&D waste, special waste, etc. are beyond the scope of this research.

This research was put together based on (1) field visits to waste management sites in Khartoum state, (2) personal observations, (3) review of the KSCA documents, (4) a survey of the plastic recycling plants in Khartoum state, (5) interviews with concerned governmental officials as well as concerned non-governmental international organizations, and lastly (6) literature review. The findings were then used to determine the possible approaches and practices towards achieving an IWM system in Khartoum. In addition, the second version of the Solid Waste Emission Estimation Tool (SWEET) was utilized to determine the baseline emission scenario and the emissions estimation after the suggested treatment plan. The Abt Associates and the SCS Engineers on behalf of the Environmental Protection Agency (EPA) and the Climate and Clean Air Coalition Municipal Solid Waste Initiative developed the tool in 2018. This tool helps in estimating the annual emission of pollutants with a focus on methane and black carbon [7].

CHAPTER (2): LITERATURE REVIEW

2.1. MSWMT in the developed countries (Europe)

The generation of solid waste is linked to human activity, the economic growth of a country or a region leads to the production of more waste and consequently there arises the need for developing waste prevention and management strategies. The IWM was defined by [8] as:

"The selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals."

The IWM strategies evolve with time in order to respond to the changing environmental laws and regulations. On the other hand, and in an attempt to decrease the amount of waste linked to economic development, the EU revised the sixth environmental action program (2002-12) in 2005, resulting in a changed idea about solid waste from a burden to an opportunity or a resource. Hence, the directive set up new targets for the member states to be identified as *recycling states*, and it included leveling up the MSW recycling rate to 50% and the C&D waste to 70% by the year 2020 [9].

The Directive 2008/98/EC on waste compiled by the EU member states to provide a working framework for the different states on waste to limit waste generation and optimize the treatment and disposal of waste. The directive defined waste as:

"Any substance or object which the holder discards or intends or is required to discard." and defined a waste holder as *"the waste producer or the natural or legal person who is in possession of the waste."*

The key provisions of this directive obliged all holders of waste to deal with and dispose of the waste in compliance with the described working frame and the state measures. The waste hierarchy (see figure 1 below) concept was first introduced to EU's waste management policies in the year 1975 and into the EU's waste framework directive (1975/442/EEC), emphasizing certain waste management practices compared to others. The (2008/98/EC) directive reintroduced the waste hierarchy, which states the priorities when it comes to waste management options and suggests moving up the suggested waste pyramid. The directive gave more significance to waste prevention in the first place, followed by reuse (before the material turns into waste) and lastly by the different processes once the material has become waste; which are preparing them for reuse, followed by recycling, then recovery, and finally disposal, i.e., landfilling [10][9]. On the other hand, the American EPA identified four necessary management actions which are: (1) Source reduction (2) Recycling and composting (3) Combustion and (4) Landfilling; these processes are meant to be interactive but can be implemented in a hierarchal order [8].

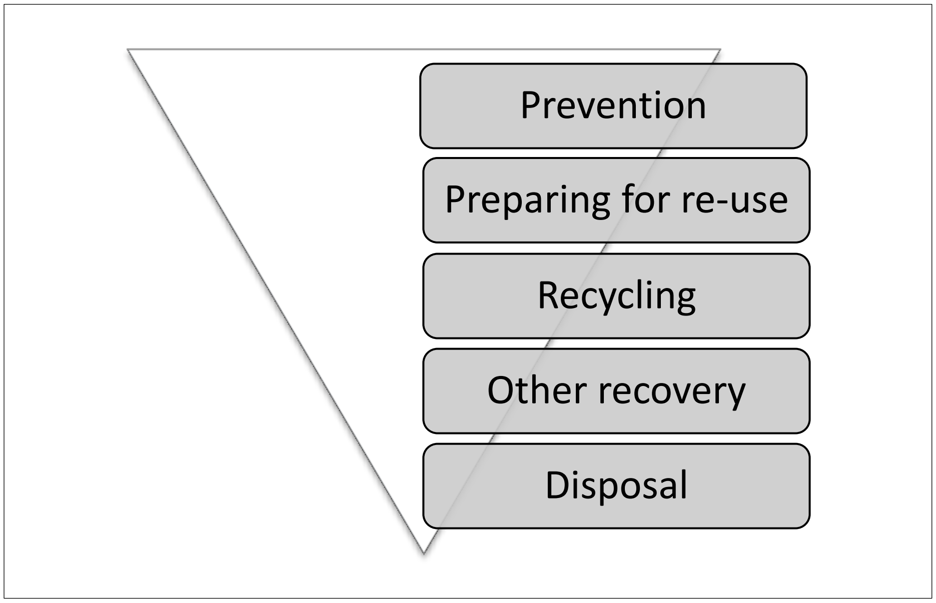

Figure 1: The EU approach on waste management or waste hierarchy. Source: EU Commission, 2010, P. 6.

Working up the waste hierarchy, meaning moving away from waste disposal and heading up towards recycling, is considered the right track towards achieving a circular economy and away from landfills. The backbone of an advanced waste management system is the special consideration of the environmental impacts and resources lifecycle. The European Union's legislative building for waste management was formed to enable the member states to realize the stated goals. The interactive framework is constituted from regulations for an integrated environmental policy that takes into account and has an influence on all the aspects of human activities and human health, and a framework law intended to reduce waste production and toxicity while guaranteeing controlled handling of waste. The EU's legislative building is complemented by a set of comprehensive directives regarding waste treatment and disposal processes. This set of directives one can tell apart three main sets of directives, which are [10]:

- Directives regarding the practices and technologies of waste management;
- Directives prioritizing specific waste streams and materials; and
- Directives related to the supervision and monitoring of waste management processes.

2.1.1. Waste Prevention (Source Reduction)

Waste prevention also known as source reduction, is the minimization of the volume of waste or its toxicity/hazardousness, implying a sustainable use of a product or material. In other words, prevention can be referred to as the quantitative (reducing the amount of waste) or qualitative (reducing the toxicity and the negative impact on the environment and human health) actions taken before a product turns into waste. A sound SWM system starts with source reduction, and it is attracting more attention due to the increasing world population, which implies the increased amount of waste and the fast depletion of natural resources.

Waste prevention can be achieved by improving the industrial sector and promoting public awareness. It can be encouraged through producing environment-friendly designs/products using more secondary raw materials and less or no hazardous substances; eco-friendly products should be designed in such a way that they consume less energy during their lifespan and can, themselves, be turned into secondary raw material [9]. Prevention measures can be promoted by the organization of awareness-raising campaigns, whether interactive or through different media outlets and availing information to the public on waste prevention measures or products' reuse and waste minimization so as to encourage the individuals and communities to adopt such environment-friendly actions. Waste prevention can be achieved by everybody in a given community and at different levels, including residential areas, public and private sectors, through decreasing products' consumption or using them more efficiently; this also includes minimizing the waste resulting from the manufacturing process, for instance [8]. Moreover, the EU approach to waste management suggested two steps in order to prevent products from becoming waste, which is, think before buying and think before throwing [9].

2.1.2. Reuse and Preparing for Reuse

It is essential to distinguish between the terms "reuse" and the term "preparation for reuse." On one hand, article three (3) of the Directive 2008/98/EC defined the term "reuse" as the repeated usage of a product for the same initially intended purpose; therefore, this term implies that the product/material is not yet considered waste. The reuse of products such as pieces of furniture and clothes has many benefits on the environmental, economic, and social levels. According to [9], many EU states are introducing policies for the promotion of reuse and the encouragement of previously-owned goods markets. On the other hand, "preparing for reuse" was defined as the processing or modification of wasted materials or products in such a way that the products can be reused without further pre-processing; this will result in avoiding the consumption of primary material (raw material) and energy, which otherwise would have been used up to manufacture a new product [11].

The idea of reusing waste is using a product again for the same purpose before it becomes waste or giving it another life after it had become waste [10]. The EU member states shall take proper measures to advocate for the "reuse" and "preparing for reuse" culture through supporting repair setups, the use of economic tools, procurement criteria, etc. [11].

2.1.3. Recycling (Material Recovery)

The EU's directives on waste management defined the recycling process as any recovery process through which disposed products can be reprocessed into new products, materials, or substances for serving the original purpose that they were conceived for or another purpose. Waste recycling includes material recovery, i.e., through composting of the organic waste fraction or through Mechanical Biological Treatment (MBT) to produce Solid Recovered Fuel (SRF) but does not include energy recovery [12].

Recycling is the most positively viewed management practice. It supplies the market with secondary raw materials by separating the reusable products (recyclables) from the waste. Waste recycling has many advantages, including the reservation of finite natural resources, and as a result, it decreases the need for mining and the related material treatment and the energy consumed in the process. Furthermore, product recycling decreases the amounts of waste disposed of and hence elongates the lifespan of a landfill. Additionally, it increases the efficiency of incinerators through the elimination of the "non-combustibles," for instance, metal and glass waste streams.

On the other hand, recycling can be problematic if it is not carried out correctly. For instance, certain recycling operations include the management of toxic substances but might end up being managed improperly or even discharged into the environment without any kind of treatment; composting, for example, is a recycling process that can have negative impacts on the environment such as contaminating groundwater and air. Moreover, the realization of successful recycling programs requires a constant market demand for recycled products or materials. In turn, stable markets depend on the production of stable supply. A scarcity of supply had been evident in specific recycling sectors including metal and plastic; therefore, governments and the different industries must collaborate to achieve a supply and demand balance so that the secondary-material supply does not exceed the demand. All of previously mentioned cannot be facilitated without public education, as it is a critical component in increasing the amount of recyclables and the number of recycled products. An increased willingness for recycling will result in a cultural change that will require buyers to consume more recyclable products and consequently require industries to use more secondary materials in manufacturing and to adopt more innovative designs [8].

It is worth mentioning that recycling operations still demand the consumption of energy and primary/raw materials, meaning that it will still have a negative impact on the environment jointly with the advantages of utilizing the secondary materials [12].

2.1.3.1. Organic waste treatment

Organic waste prevention represents the most desirable option for waste management according to the waste hierarchy. Nonetheless, since it cannot be prevented entirely, other treatment options should be considered. The next option for the management of organic waste treatment is material recovery through composting, followed by valorization and disposal as the least-preferred alternative. However, it should be noted that some treatment options that can only be practical for source-separated bio-waste [13].

1. Composting (aerobic digestion)

Organic waste composting is a form of material recovery, compost, employing aerobic microorganisms. The finished products can be used as a soil conditioner or can be used for other uses depending on the quality of the product; in order to achieve the highest quality possible, it is best to be applied to the source-separated feedstock to guarantee the absence of contaminants. Notwithstanding, according to [14], some technologies are currently under-development to produce higher quality compost starting from mixed-waste. There are several methods for the application of waste composting, such as open or enclosed systems. Open systems occupy more space, slower, less demanding in terms of technicality, and less strict in terms of emissions control. The process duration depends heavily on the technology in use and ranges between several weeks to months [13].

2. Anaerobic digestion

This treatment option is carried out using microorganisms again but under anaerobic conditions. It can either be operated alone or combined with aerobic composting. It can recover both energy (electricity, heat, fuel partial substituent) and material (digestate). The digestate can be stabilized and sanitized through composting, and the material recovered in this case is both qualitatively and quantitatively comparable to that of the aerobic digestion. It should be noted that green waste or lignin-rich materials cannot be decomposed through this process [13].

3. Pyrolysis and gasification

These two thermal treatments can be applied to MSW in general and bio-waste in particular. The pyrolysis implies subjecting the organic waste to pressure under anaerobic conditions, and the process can be rendered more efficient through the use of contaminant-free feedstock. The resulting products of this technology are gaseous products, which can be used to generate electric energy, liquid (tar), and solid (char), which can be landfilled or further processed and turned into a gas. On the other hand, the gasification process is instead operated aerobically at a higher temperature, and the resulting product is gaseous and thus can also be used for the generation of electricity, and a solid residue (char) which should be landfilled.

Both pyrolysis and gasification are, however, still under development; nonetheless, they are considered promising technologies, especially in the field of electricity generation [13].

4. **Fermentation**

The products of the fermentation process, like anaerobic digestion, are biogas. Fermentation can be used as a basis for other evolving technologies for the production of biofuels. However, these biofuels require turning lignin-rich waste materials into fermentable waste [13].

2.1.4. Other Recovery (Energy Recovery)

The fourth option of the ISWM hierarchy is the “other recovery operations” which is, according to the EU’s Directive 2008/98/EC, is defined as any process which its primary outcome is using waste to replace other materials in serving a particular purpose or processing waste in order to serve the specific purpose in a plant or the economy. One should note that the term recovery includes material recovery (recycling) and energy recovery operations [12]. Energy recovery (combustion) represents the last resort before sending the waste to the landfill. The idea behind it is to recover any value left of the waste before final disposal; this had led to the development of appropriate technologies for this purpose [15].

Waste to energy (WTE) or combustion facilities offer three key advantages, the first one being the energy recovery (in the form of steam or electricity), the second being that they significantly reduce the waste volume and the third being the possibility of exploiting the incinerators bottom ash in the building and construction industry. Energy recovery profitability can vary from one country to another; nonetheless, waste volume reduction is considered very attractive in elongating the lifespan of landfills. Also, it is necessary when landfills are located far away from the generation point in order to decrease transportation costs because with the increasing population emerges the need for locating the landfill further away from the residential centers [8]. The main disadvantages of incineration are the need for a high capital cost of construction, the relatively high level of technicality required for safe and economical operation, and the social acceptance due to the incineration emissions and the hazardous nature of the resulting bottom ash. The American EPA responded to these challenges through creating new guidelines for solid waste combustion plants as well as landfill requirements. There are also regulations concerning the design, construction, and operation of the WTE facilities that are meant to protect human and environmental health [8].

2.1.5. Disposal (Landfill)

Disposal, or landfilling, is the oldest form of waste treatment. It is the least-desired option in the ISWM scheme, and it is the reason why the last spot at the pyramid is booked for it. Waste disposal in a sound ISWM implies that the maximum value of waste had been achieved. However, disposal is a necessity since all of the waste management and treatment technologies will inevitably result in residuals that require landfilling in addition to the fact that some waste materials are non-recyclable [8][9].

Landfills have adverse impacts that caused them to be placed at the end of the hierarchy. The most hazardous impact is the release of the greenhouse gas (GHG), methane, which is also an explosive gas. Methane gas is generated through the digestion of organic matters by the microorganisms. The biodegradation also causes the release of toxic chemicals, i.e., heavy metals causing leachate production, which in turn can seep into the ground contaminating soil, ground and surface water. In order to protect human health and the environment, landfills must be designed, operated, and managed after closure properly. It is worth mentioning that modern landfills are well-engineered, and they stopped the receipt of hazardous waste and bulk liquids. Landfills can also be turned into an energy source through the recovery of methane gas and possibly carbon dioxide (sanitary landfills). Moreover, after the closure, landfill areas can be turned into recreational zones [8].

Awareness of these risks resulted in calls for legislation forces member states to reduce the quantity of organic waste disposed in the landfill by 35% by 2016 in order to reduce the methane gas generation. Moreover, the directive also encourages the collection of methane gas and exploiting it in energy generation. The EU legislation has caused a decrease in the amount of waste landfilled in the EU member states by 25% compared to the amounts reported in 1995. However, landfills remain the most commonly-used method across the EU [9].

2.1.6. Implementation of ISWM

Applying an Integrated solid waste management (ISWM) scheme to domestic solid waste implies the use of multiple technologies in addition to all of the management practices as per the ISWM hierarchy. Currently, there are solely a few examples where a sound and customized ISWM plan is established. In order to implement an ISWM program for municipal solid waste, Salvato et al. [8] suggested performing an optimization analysis using all the existing alternatives; nevertheless, up to this date, there is no available proven methodology to carrying out such an analysis.

2.2. MSWMT practices in the developing countries (Africa)

2.2.1. Management Practices

The developing countries, including African countries, are characterized by a rapid urbanization rate, which is only expected to increase in the future joint by a consequent increase in the generated waste by the different sectors. The primary issue in these countries is that they do not currently possess the adequate infrastructure and waste management technologies to meet the predicted future increase in waste quantities. Moreover, the problem of e-waste has also emerged in recent years and expected to continue to increase, especially in Senegal, Uganda, and South Africa [16]. Many studies published about the developing countries such as [16] suggested that the dominant waste fraction in the developing countries is the biodegradable organic fraction, mainly composed of kitchen waste and has been confirmed by the waste characterization studies implemented in those countries. In a study about waste management in Africa, [17], stated that:

"Current reasons for the poor management of waste in Africa, include, amongst others, weak organizational structures; lack of appropriate skills; inadequate budgets; weak legislation; lack of enforcement; low public awareness; corruption, conflict; political instability; and lack of political will. At the heart of the problem is a failure in governance."

Bello et al. [16] stated that one of the biggest challenges in the continent of Africa regarding the management of solid waste is the inadequate capacity not just in terms of investments but in terms of technology and infrastructure. Moreover, the lack of policies and regulations regarding waste production and disposal and, in some cases, lack of law enforcement is a key reason influencing higher generation rates and improper waste disposal practices. On the other hand, private sector involvement in the field of solid waste management and treatment is almost lacking, either as a contributor or as a business opportunity. The poor management of solid waste poses a significant impact on human health, the environment, and the economy as well; this is because improper waste management leads to more costs than that of good management practices [3].

The low waste collection rate, coupled with the current management behaviors by the individuals such as indiscriminate open dumping, which ends up leading to open dumping, often leads to diverse health, environmental and economic impacts [17]. Pervez Alam reported that when solid waste is left untreated, it has unquestionable adverse impacts on both the environment and human health. On top of visual pollution, inappropriate waste disposal negatively impacts water bodies and soil due to the release of leachate produced by the organic waste in poorly-managed landfills and open dumps; it also has an impact on air through the release of greenhouse gases due to the decomposition of organic matter and the uncontrolled waste burning in residential areas. With regards to human health and safety, solid waste piles often lead to drains clogging and potentially floods during rainy season; it also creates a breeding environment for rodents and insects, which can spread diseases like cholera, malaria, and dengue fever. Moreover, using waste-polluted water for drinking or irrigation exposes users to many diseases, according to the US public health services [4].

2.2.2. Waste Generation

According to the World Bank [3], solid waste generation is heavily influenced by the economic development of a given country or region, as well as the level of industrialization, climate, and social norms. Economic development is inextricable of waste generation since the increasing affluence means the increased consumption of products and services. It was also noted that the generation rate in the urban areas is two-folds of that in the rural areas [3]; this is because the rural population is relatively more impoverished and thus seldom purchases packaged goods and generally has higher reuse and recycle rates. Therefore, waste production rates for a specific country or region are heavily influenced by the urban population rates rather than the rural.

In sub-Saharan Africa is the waste generation rate is roughly 62 million tons per annum. Waste generation rate in Africa per capita, it falls in the range of 0.09 to 3.0, with an average value of 0.65 kg per capita per day. In comparison, the OECD region has an average of 2.2 per day, and the values ranging between 1.1 to 3.7 kg per person per day [17][3]. Globally, Africa is the region that produces the least quantity in waste per year at 5% compared to 44% for the OECD countries with almost half of the global generation rate.

For Africa, the projected solid waste generation rate in 2025 is expected to fall somewhere between 161 and 244 million tons per year, with the most part generated in the sub-Saharan region [17][3]. The average waste collection rate for the African content is at 55% while it is 44% for sub-Saharan Africa, compared to a 98% collection rate for the OECD countries as the collection rate is inextricable to the income level [17]. The collection rate is in Africa is, however, expected to rise to 69% in the year 2025[3].

2.2.3. Waste Composition

The global waste composition is mainly comprised of organic waste at 46% of the total composition, followed by paper waste at 17%, other[1] wastes 18%, plastic 10%, and glass at 5% [3][2]. Waste composition, according to [3], is affected by many elements, including economic development, location, climate, culture, and energy source. The economic development is linked to an increasingly wealthy population; middle and high-income countries tend to discard more packaging materials such as plastic (11%) and paper (31%) more than organic waste (28%), whereas in the lower-income countries the dominant waste fraction is the organic one (up to 64%). Geographical location and climate impact the composition of the waste through the choice of the building materials, ash resulting from domestic heating, dust in dry environments, and moisture content of the waste in humid environments. As for the energy source for cooking or heating, it mainly affects the ash content as countries that rely on wood/coal produce more ash content than those using energy from the district heating/electricity grid [3].

The average data on the waste compositions on the African continent, states that it is mostly made up of biodegradable organic waste (57%); this is compared to about 13% of plastic waste and about 9% of paper waste, which makes up to 70% of the entire waste composition. Organic waste is a major contributor to global GHG emissions, making the management and treatment of the organic fraction or turn it into a valuable product (compost or biogas) necessary for the elimination of any related potential emissions. Waste represents an unlimited resource for the continent, especially if source separation of the organic fraction is achieved as it will result in a high-quality product [17].

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[1] The "Other" waste fraction comprises textiles, leather, rubber, multi-laminates, e-waste, appliances, ash, other inert materials

[2] These are only approximate values, given that the data sets are from various years.

In comparison with the developed countries (OECD), one can spot the difference in the composition in the organic fraction, 57% in the developing countries compared to 27% in the developed ones, and the paper fraction with 9% in the developing and 32% in the developed countries respectively.

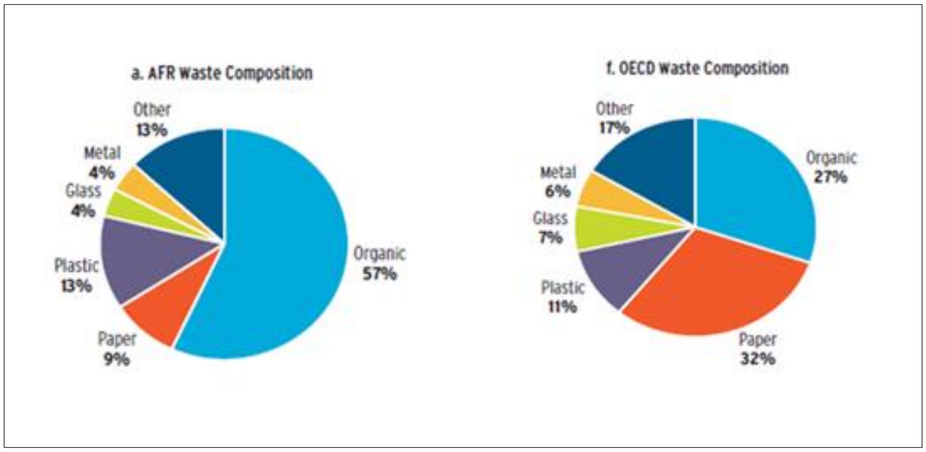

Figure 2: A comparison of the waste composition between the developing countries (AFR) and the developed countries (OECD). Source: World Bank, 2012.

Plastic waste represents a growing concern for Africa, especially with the absence of proper technology for recycling and a lack of awareness concerning the use of plastic bags and plastic products. The percentage of plastic in sub-Saharan Africa is greater than that of the global average and that of the high-income countries where there are proper recycling facilities. The improper waste disposal and the low collection rate, coupled with the lack of proper treatment technologies rate, cause the spread of plastic into the environment [17].

On the other hand, Africa is considered a huge market for cheap and poor-quality electronics that have a short service life making the continent the largest dumping area for such hazardous waste as the electrical and electronic equipment waste (WEEE) or E-waste [16]. This waste stream poses serious health hazards on both humans since it is heavily managed by the informal sector, and the environment [3].

2.2.4. Collection and Transportation

MSW waste collection efficiency varies from one country or region to another and ranges from as low as 41% in and as high as 98% in low-income and high-income countries, respectively. Conversely, the cost of the collection services compared to the entire waste management budget in high-income countries is less, at around 10%, than that of the lower-income countries where around 80 to 90% of the budget is spent in waste collection.

The municipal solid waste collection system in the African countries is mostly described as inefficient and unreliable at a percentage of 46% compared to 98% in the OCED countries. The local government mostly provides the collection services with little involvement from the private sector, which is specially licensed to work in city centers and affluent areas [16][3].

The waste collection services offered by the local governments usually follow the process illustrated in figure (3) below:

Figure 3: The Solid Waste transportation process by the local governments in African developing countries.

The informal sector in developing countries like the case of Africa plays a huge and active role in the waste collection, sorting and recycling and thus diverting waste from the landfill; this is especially valid for plastic, paper, and metal. Therefore, the integration of the informal waste pickers presents an opportunity for waste management while providing them with better working conditions and income [17].

Collection by the public sector is usually carried out using the door-to-door approach, and waste is disposed of manually onto the waste trucks. Afterward, waste is transferred to the transfer stations (TS) for compression and loading into bigger trucks to be in turn transferred to the final disposal sites or landfills in an effort to cut down on the transportation costs [16].

2.2.5. Treatment and Disposal

The key difference between the developing and the developed countries is that in the latter invest in high-cost systems for waste management and treatment, whereas the developing countries are still engaging the same inefficient management and treatment practices [16]. Waste for Africa represents an unexploited resource with only 2.7% recycling rate and less than 1% organic waste composting, losing a high percentage of recyclables and organic waste to dumpsites and landfills every year[16][3].

The table below (table 1) details the municipal solid waste treatment and disposal practices in the African region. Most of the waste generated ends up in landfills or dumpsites at 49.5% and 43.8 consecutively, which represents about 93%. A small percentage of 2.7% goes to recycling while composting of organic waste and waste incineration are as low as 0.95%.

Table 1: Municipal solid waste disposal practices in African countries. Source: World Bank, 2012.

Waste Disposal Practices	Percentage (%)
Landfills	49.5
Dumps	43.8
Recycling	2.7
Composting	0.95
Incineration	0.95
Other	2.1

2.3. SWMT in the Republic of Sudan

2.3.1. Background

The Republic of Sudan is located in North-Eastern Africa; it is considered one of the sub-Saharan African developing countries, and it is categorized as a low-income country, according to the World Bank [3]. The capital city of Sudan is called Khartoum, and it is located in the area of the study, Khartoum state. The Republic has an estimated population of 42.8 million in 2019, according to the World Bank[3]. Around 20% of the total number live in the state of Khartoum [18]. The northern region of the country is mostly deserted and barely receives any rainfall, whereas the other regions of the country have a semi-desert climate. The average rainfall reaches 100 – 200 mm in the northeastern areas and 200 – 300 mm in the northwestern areas. The temperature in the dry season, April to June, ranges between 25 - 40°C and 20 - 35°C during July to October. The temperature declines gradually from 25 to 15°C between March and November.

The Khartoum state understudy has a land area of 22,142 km^2 [19], which is comparable to the size of the Lombardy region in northern Italy. Khartoum state is characterized by a rapid economic development and urbanization rate in Sudan that had led to a significant increase in the city's population due to the influx from other states seeking better public services and improved livelihoods and, as a result, emerges the problem of solid waste. The results of the last nationwide enumeration census in 2008, Khartoum state, was inhabited by 5.3 million. The Sudan Central Bureau of Statistics (CBS) previously projected that the state would be inhabited by 6.2 and 7.4 million capita the 2012 and 2016, respectively[4]. It was projected that by 2020, the Khartoum state would have a staggering 8,643,559 capita applying a 4% annual increase in the population [18]. Khartoum state constitutes three provinces of Khartoum to the South, Bahri (or Khartoum North) to the East and Omdurman to the West. Each of the Blue Nile, White Nile, and the River Nile divide the three cities but they are well connected by bridges. The previously stated provinces are further divided into seven localities, namely; Khartoum locality (LOC), the capital city, and Jabal Aulia locality in Khartoum province, Bahri and Sharg Elnil localities in Bahri province and lastly Omdurman, Karari and Umbadda localities in Omdurman province.

[3] https://data.worldbank.org/country/sudan
[4] http://www.cbs.gov.sd

Khartoum state lies in the northern part of the country. The temperature in the state is generally hot, with an average value above 30°C and reaches over 40°C during the dry season from March/April to July/August. Precipitation takes place during the three months of July, August, and September, with an annual average of 150 mm and the highest in August at 60 mm. The relative humidity ranges between 22% in the evening and 37% in the morning; hence the state has a dry climate. On the other hand, the recorded average of wind speed is 14 km/hour, with the highest of 17 and the lowest of 12 km per hour[5]. Due to its unique location at the confluence of the two Niles, Khartoum state is prone to flooding in case of heavy rainfall. Floods were experienced recently in the years 2007, 2009, and 2013 [20] and 2020.

2.3.2. MSW Management Practices

2.3.2.1. Local Government and Foreign Aid

Most of the improvement efforts to solid waste management and treatment in Sudan are directed towards the state of Khartoum, where the capital city, Khartoum, is located. Unquestionably, some efforts are made in other states such as Gezira, Red sea, Kordofan, etc. but they are small in scale in comparison with the efforts in the study area, Khartoum. In response to the annually increasing population, the Khartoum State Cleaning Authority (KSCA) was established in 2002 by the state government [21]; however, the capacity of the authority could not meet the demand resulting from the continuous influx to the state and thus failed to maintain a sanitary condition in the region. The KSCA works in collaboration with the localities (LOC) and administrative units (AU) level governments. Municipal solid waste collection and transportation to the respective transfer stations (TS) is carried out by the localities and supervised by the KSCA. On the other hand, the KSCA operates the transfer stations (TS) and the landfills (LF) and is in charge of the transporting the compressed waste from the TS to the respective LF. There are many stakeholders in MSWM in Khartoum state. Their responsibilities are stated in table (2) below:

Table 2: The organizational framework of the governmental bodies that are responsible for waste management. Source: JICA, 2017, P.61.

Organization	Municipal Solid Waste Management Responsibility
MOE (national level)	▪ Develop national policies and plans on the environment ▪ Implement public education programs and promote R&D ▪ To coordinate foreign SWMT support to the GOS and the state governments
HCE (state level)	▪ Develop SWM policy for Khartoum state ▪ Supervise SWM activities carried out by the KSCA, LOC, and AU. ▪ Implement SWM activities beyond the scope of the KSCA, LOC, and AU, i.e., general environmental issues

[5] Weather Base

Organization	Municipal Solid Waste Management Responsibility
KSCA (state level)	▪ Make detailed plans and operate TS and LF ▪ To set standards for waste collection, evaluate and support LOC with collection ▪ Build the capacity of the KSCA and the LOC staffs ▪ Coordinate with LOC and strengthen the coordination with SWM stakeholders ▪ Coordinate the media and produce IEC materials, reports and information related to SWM
LOC (locality level)	▪ Collect MSW and carry out cleaning activities at the locality level ▪ Implement public relations and awareness-raising activities at the localities ▪ Build the capacity of the LOC and the AU staff ▪ Coordinate with the different AU at the given locality ▪ Establish a good relationship with partners and stakeholders at the locality level ▪ Develop SWM IEC materials in coordination with KSCA
AU (administrative unit level)	▪ Participate in the development of the SWM plans ▪ Collect and analyze data from different AU and share the results with the LOC ▪ Coordinate with the Popular Committees (PC) at the quarter/neighborhood level ▪ Implement the public education programs developed by the localities
PC (quarter level)[6]	▪ Cooperate with the localities in carrying out SWM activities when/if required ▪ Aid the LOC and AU in reaching community members

The Japanese agency for international cooperation (JICA), in 2013, in response to a request from the Government of Sudan (GOS) represented by the ministry of environment (MOE), conducted a thorough assessment of the waste management system by a team of Japanese experts in collaboration with the Khartoum state government, the KSCA, and the MOE. At the time of the assessment, the waste generated was estimated to be around 5,000 tons per day, of which only 65% (3,200 tons) was collected, transported to the Transfer Stations (TS). At the TS, waste compaction takes place before transporting the waste to final disposal in one of the three landfills located in each of the three major cities within the state [20]. The state then benefitted from a grant aid project for the enhancement of the overall cleaning services, the JICA project that was aimed at the strengthening of MSWM in Khartoum state. The project contributed to [20]:

- The revision of the master plan (MP) of solid waste management in Khartoum State;
- Improved capacity of waste collection and transportation through the provision of collection vehicles and the construction of an equipped central workshop for vehicle maintenance along with the and the organization of training sessions for the maintenance technicians;
- Improved operation and management of the landfills through the donation of heavy equipment for waste management at the disposal sites and the proposal of landfill improvement plans; and
- Improved the institutional and financial framework of solid waste management in the state.

[6] The Popular Committee (PC) is the lowest governmental/authoritarian level, which is a group of 15 neighborhood residents representing a community at the given neighborhood/quarter.

The government of Japan (GOJ) handed over the grant aid equipment to the Sudanese counterpart (GOS) in January 2016 [6]. Further details about the grant equipment received are reported in table (3), while more details on the increase of collection capacity will be discussed in the following sections.

Table 3: The breakdown of the equipment granted by the Japanese Government through the JICA to the GOS in 2016. Source: JICA, 2017, P. 2 and 3.

Component	Equipment type	Use(s)	Quantity
Waste collection equipment	Compactors	Used for collection of residential and commercial waste	42
	Container carrier (arm type)	Mainly used for collecting waste from markets	56
	Containers		56
Landfill management equipment	Bulldozers	Used to place and compact waste and soil cover	3
	Excavators	Used to excavate and obtain soil for soil cover	2
	Water tanker	Used to transport drinking water to the site	1
Total	-	-	104

It worth mentioning that the "preventive maintenance" introduced by the grant aid project through the construction of a workshop and the provision of maintenance equipment that is intended to enable the KSCA to conduct the periodic inspection as well as typical maintenance works on the different waste management equipment. Moreover, the agency also provided technical training sessions for the technicians and developed organizational systems such as rules and manuals for the facility operation, i.e., work discipline, safety regulations, compensation of work accidents, and training guide. Nonetheless, maintenance works have not been conducted adequately, and as a result, many vehicles remain out of service. The JICA recommended that the KSCA should carry out preventive maintenance periodically and more strictly [6].

The solid waste flow in the year 2016 is depicted in figure (4) below. It shows that the collection rate was equivalent to 65%; and that around 35% of the waste generated ends up being openly burned, recycled, illegally dumped or misreported; while 92% of which ends up in one of the three existing landfills in addition to the Bahri temporary disposal site.

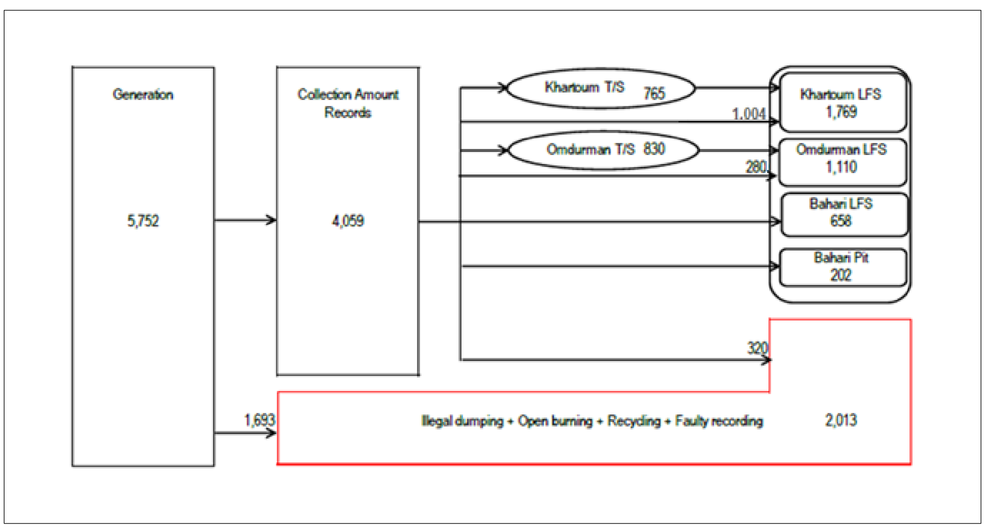

Figure 4: Municipal solid waste flow in the state of Khartoum in the year 2016. Source: The MP, 2016, P.7.

2.3.2.2. Social Aspect of Waste Management

In order to assess the current domestic (food waste, glass, ash, earth and dust, wood, paper and cardboard, and plastic) waste management practices in Khartoum, Elbaroudi et al. [22] in 2015 conducted a study based on household-based questionnaires. The study highlighted the social aspect of the management system; primary data were collected to investigate the transportation and storage of domestic solid waste produced by 87 randomly selected households in the three different major cities of Khartoum state. The study showed that the preferable waste storage methods in the state are plastic bags (74%); metallic/plastic drums comes second with about 20% of the users. As for the temporary waste storage location, since most people reside in houses with yards, 86% of the respondents stated that they temporarily store their waste within their premises waiting for the collection vehicles; while, 1% of them kept the waste outside the household and 7% in nearby streets/open dumpsters.

The survey also included questions about the collection services frequency (weekly), around 55% of the surveyed household informants reported that waste is collected twice, 31% reported once, 7% thrice a week, and 1% more than three times. Merghani, who stated that the KSCA collects the household waste two to three times per week based on the house-to-house collection method, confirmed the previously reported data. The waste collection vehicles pass in front of each house in the neighborhood, and it is the responsibility of the household head to take out their waste before the vehicle passed [21].

Alnagrabe carried out a questionnaire intended to assess the efficiency of the collection system put in place by the administrative unit (AU) government. The results of the study detailed that out of the 360 sampled HHs, 34.7% responded with once, 10.3% twice, and 2.8% thrice times a week while 50.2% cited that it is generally irregular and unreliable [23]. Elbaroudi investigated the behavior of the residents in case of a delay or absence of the collection services. The results showed that only 3% reported transferring their daily waste to collection points, whereas 17.2% reported disposing of it in the vicinity of the house. While, the majority (71.3%) reported it disposing of it in “other places,” i.e., retaining it inside the household awaiting the collection vehicles [22]. Elbaroudi interpreted this behavior as evidence of the awareness of citizens in the region.

The JICA team noted that public relations and public awareness were not regarded as an essential part of the waste management processes, and thus, residents think that they have no role in the process and tend to refuse to pay the waste collection fees. Public relations and public awareness are new departments in the waste management hierarchy at the locality level, and therefore, it is often neglected, and the budgeted allocated to it is used for other activities such as vehicle procurement. Nonetheless, the role of the two departments is getting acknowledgments, and equivalent departments were formed in the MOE and the KSCA in 2016. Such activities are expected to have more support in the future [6][18].

2.3.3. MSW Production

Waste production per day for the Khartoum state was as well reported in a couple of studies; however, the difference of the values reported is insignificant. Elbaroudi et al. [22] in 2015 reported that the quantity of waste that is produced by the three cities in Khartoum state was approximately (4,800 tons/day) and it is expected to increase by a rate of 4.04% annually so by 2020 it would be around 5,769 tons per day. In another study by [19], the reported amount of waste generated per day was 4445 tons in the year 2013. In a study made by JICA in 2012, the waste production rate was 4,890 tons per day. They have predicted that by the year 2019, 2022, and 2028 waste quantity would increase up to (6,480), (7,741), and (9,344) tons per day, respectively [20]. The most recent survey made was in October 2016 by the Energy and Waste Treatment Services Company (EWASCO) in collaboration with JICA and the KSCA, through which reported that only the domestic (residential) solid waste contributes to the daily production rate by 2,688 tons per day from the total amount [24].

Table 4: The amount of MSW generated by each of the seven localities in Khartoum state in 2016. Source: The Khartoum state MP, 2016, P.16.

Component	Khartoum	Omdurman	Bahri	Jabal Aulia	Umbadda	Sharg Elnil	Karari	State Total
Population (capita)	891,389	714,145	846,524	1,342,343	1,392,841	1,221,689	994,227	7,385,158
UGR (kg/cap/day)	1.53	1.12	0.82	0.71	0.51	0.52	0.61	0.78
MSW gener. (tons/day)	1,364	801	691	946	712	629	609	5,752

2.3.3.1. Plastic waste production

This dissertation sheds light on plastic waste because of the high dependence on plastic bags and products especially in the different states' capitals. This dependence has caused high plastic pollution that is evident around the streets and highways connecting the different states. Moreover, it was noted from literature that most of the recycling businesses are active in plastic waste recycling.

Fadlalla [25] in 2010 investigated the plastic waste management in Khartoum state and reported the quantity of plastic imported into Sudan from the year 2005 to 2009 in the form of virgin plastic resins, plastic products, and PET preforms. The virgin plastic amount imported increased from 54,580 tons in 2005 to 108,856 in 2009. Whereas the imports of ready-made plastic products showed a sharp decline to 55,571 tons, which represents almost half of the quantity imported during 2006 (107,420 tons); however, the amount increased in 2010 up to 80,945 tons per year.

Moreover, the amount of PET performs imported had increased two-folds in the year 2010 compared to 2005 amounting to 22,444 tons; it was also noted that the PET reforms to virgin plastic resin were 0.206; whereas the biannual data for the year 2010 showed a 0.09 increase in the PET reform/virgin plastic resin ratio to 0.296. Fadlalla justified this sharp increase the PET preform importing to the rise in the water and soft drinks industry in the country and as well to the transition from glass to plastic bottles. Further details are provided below.

Table 5: The quantities of different plastic products and raw materials imported in Sudan from the year 2005 to 2010. Source: Fadlalla, 2010.

Item	2005	2006	2007	2008	2009	2010 (Jan-Jul)
Virgin plastic resin	54,580	64,403	65,146	75,233	108,856	58,565
Plastic products	107,420	55,571	53,790	62,860	80,945	38,271
PET reforms	9,611	10,400	9,915	15,811	22,444	17,336[7]
Reforms/resin	0.176	0.16	0.152	0.21	0.206	0.296

The study also forecasted the future increase in the PET preforms imported quantities for the next five years, reaching 59,652 tons in 2015, which is double that of 2010. On the other hand, it is worth mentioning that the plastic material imports in the year 2009 amounted to USD 353,180,000 compared to USD 152,770,000 in the year 2005, while the 2010 biannual report alone showed that the plastic materials imports totaled USD 192,021,000 [25].

2.3.4. MSW Composition

The waste composition available for the state of Khartoum reported in the project design document (PDD) presented by PECS Oil Company to the UNFCCC as a first of its kind composting project in Sudan. The waste composition study was implemented by the Khartoum state's Ministry of Environment, the Khartoum state cleaning Authority, in the year 2008. The composition percentages were calculated with 90% confidence intervals, and it included domestic waste, industrial, commercial, and institutional waste. However, the method used by the KSCA for waste characterization was not detailed in the report [26]. The percentages reported were as follows:

Table 6: Municipal solid waste composition in Khartoum state as reported by the MOE, KSCA in 2008.

Waste Fraction	Percentage (%)
Organic material	49.5
Plastic	12.7
Paper and cardboard	11.8
Dust and ash	13.4
Metals	1.7
Glass and ceramics	3.5
Cotton and jute	4.6
Wood	0.2
Leather	0.4
Couch	0.3
Other	1.9
Total	100

[7] The PET preform imported quantities were expected to reach up to 30,000 tons by the end of the year 2010.

Another study implemented by the Research and Consultancy Centre (IRCC) in 2013 for all Khartoum state's localities' waste streams based on sectorial classification surveys was reported in Mofadel et al. [19]. The fraction of the waste stream in the state is as follows:

Table 7: The solid waste (residential, industrial and sewage sludge) composition conducted by the Industrial Research Consultancy Centre (IRCC) for Khartoum in 2013.

Waste Fraction	Percentage (%)
Paper and cardboard	20.74
Plastic	17.45
Organic compounds	31.44
Dust	2.69
Steel	1.69
Wood	0.39
Skin	1.1
Glass	6.7
Cotton	0.5
Tires	0.4
Hair	0.02
Melamine	0.03
Marble	0.03
Jute	0.09
Ceramics	1.29
Plant leaves	1.59
Animal Manure	12.96
Other	0.89
Total	100

The Energy and Waste Treatment Services Company (EWASCO) implemented a different study in October 2016 in collaboration with the KSCA and JICA to determine the quantity and composition of waste produced in Khartoum state. The limitation of the study is that it was only conducted in two localities out of the seven total localities and only in a total of four residential areas with a total of 28 HHs each. Thus the total sample size was 112; moreover, this study only included the residential solid waste, meaning that other types of municipal solid waste such as commercial and institutional waste were not considered [24]. The results of this study are reported in the table below:

Table 8: The residential/household solid waste composition provided by the EWASCO in collaboration with JICA and KSCA in 2016.

Waste Fraction	Percentages (%)
Food waste	45.51
Bones and shells	0.78
Garden waste	6.53
Paper	2.46
Cardboard	2.15
Textiles	2.30
Diapers	3.74
Plastics packaging	2.97

Waste Fraction	Percentages (%)
Plastic bags	7.89
PET bottles	1.46
Rubber	0.26
Glass and ceramics	2.81
Aluminum cans	0.39
Metal (Tin and steel)	1.13
Hazardous waste	0.51
Soil	17.26
Other	1.87
Total	100.00

The reader should keep in mind the different years the three studies/surveys were implemented which are the years 2008, 2013 and 2016. In order to compare the data presented by the different studies, first, we have to adopt a standardized waste composition; for this purpose, the waste types defined and adopted by the World Bank were used. The advantage of this classification is that it groups the recyclable, while the rest of the waste streams (non-recyclables) fall under one category, which is labeled as "Other." The following table (9) lists the waste types/streams and the possible sources for them:

Table 9: The different types of waste and the possible sources as defined by the World Bank in 2012. Source: World Bank, 2012.

Type	Sources
Organic	Organic Food scraps, yard (leaves, grass, brush) waste, wood, process residues
Paper[8]	Paper scraps, cardboard, newspapers, magazines, bags, boxes, wrapping paper, telephone books, shredded paper, and paper beverage cups.
Plastic	Bottles, packaging, containers, bags, lids, cups
Glass	Bottles, broken glassware, light bulbs, colored glass
Metal	Cans, foil, tins, non-hazardous aerosol cans, appliances (white goods), railings, bicycles
Other	Textiles, leather, rubber, multi-laminates, e-waste, appliances, ash, other inert materials

By comparing the two studies involving the KSCA (tables 6 and 8) to the one implemented by the IRCC (table 7), one can note a relatively high degree of inconsistency especially concerning the organic fraction; where the percentages reported are 49.5%, 31.44% and 45.51% sequentially (Table 10). The organic waste fraction reported by the IRCC is low compared to the other studies because the waste composition analysis included industrial waste and sewer sludge. Also, the waste composition reported is suspected to contain medical waste partially; as the cotton stream (0.5%) collected from hospitals is suspected to be contaminated.

[8] Paper is organic; but unless it is contaminated by food residue, paper is not classified as organic

Table 10: Comparison of the waste fractions of the different MSW composition studies in 2008, 2013 and 2016.

Waste Fraction (%)	KSCA (2008)	IRCC (2013)	EWASCO (2016)
Organic	49.5	31.44	45.51
Paper and cardboard	12.7	17.45	12.32
Plastic	11.8	20.74	4.61
Glass	3.5	7.99	2.81
Metal	1.7	1.69	1.52
Dust and ash	13.4	2.69	17.26
Other	1.9	0.89	1.87
Remaining Fraction	5.5	17.11	14.1
Total	100	100	100

Further comparison can be made for the major recyclable streams such as plastic, paper, glass, and metal in the three studies. Regarding plastic waste, the percentages reported were 12.7, 17.45, and 12.32%[9] for the KSCA, IRCC and EWASCO respectively. It can be noted that the difference between the first two percentages stated is insignificant in contrast with the latter. However, the average value for the plastic waste stream in sub-Saharan Africa is around 13%. Another significant waste stream is paper and cardboard. The paper percentage reported for the first, second and third studies are 11.8, 20.74 and 4.61 percent, the data provided by the three studies vary considerably, and the highest in the figure provided by the IRCC, which is two-fold of that of the KSCA and five-folds of that of the EWASCO. Nonetheless, the African average is 9%. Thus, the 11.8% makes more sense for the "paper and cardboard" waste stream.

According to the 2012 World Bank report, the typical value for the glass and metal streams is 4% for both. Regarding the "glass and ceramics" fraction, the figures listed are 3.5, 7.99[10] and 2.81 percent in tables 6, 7, and 8, respectively. Therefore, the percentage of 3.5% reported by KSCA in 2008 is reasonable. On the other hand, metal comprised up to 1.7, 1.69 and 1.52[11] % in the three (3) studies successively. It can be noted that the first study (KSCA) and the second (IRCC) have similar values, whereas the value reported by the EWASCO is slightly less.

A significant component of waste in Sudan is "dust" due to the dry/dusty environment. In the first study, it composed up to 13.4% of the total waste stream, while it comprised 2.69% and 17.26% of the daily stream in the second and third studies respectively. Lastly, the sources of the "other" waste fraction, which makes up to 1.9%, 0.89% and 1.87% correspondingly, were undefined in none of the studies.

In conclusion, the study by the KSCA in 2008 is the most coherent with the expected/average waste composition in the developing countries even though the method, limitations, and survey samples were not detailed. Nonetheless, the results of the 2008 study by the KSCA will be adopted hereafter. Lastly, the KSCA waste composition data was adapted according to the waste streams defined by the World Bank (represented in table 9 above) in order to compare it to the standard waste composition in the

[9] Summed up for EWASCO bags, bottles and containers
[10] Numbers summed up for IRCC glass and ceramics
[11] Numbers summed up for EWASCO metal and aluminum

developed countries of the OCED and the developed countries of Africa. Please refer to the figure (5) below:

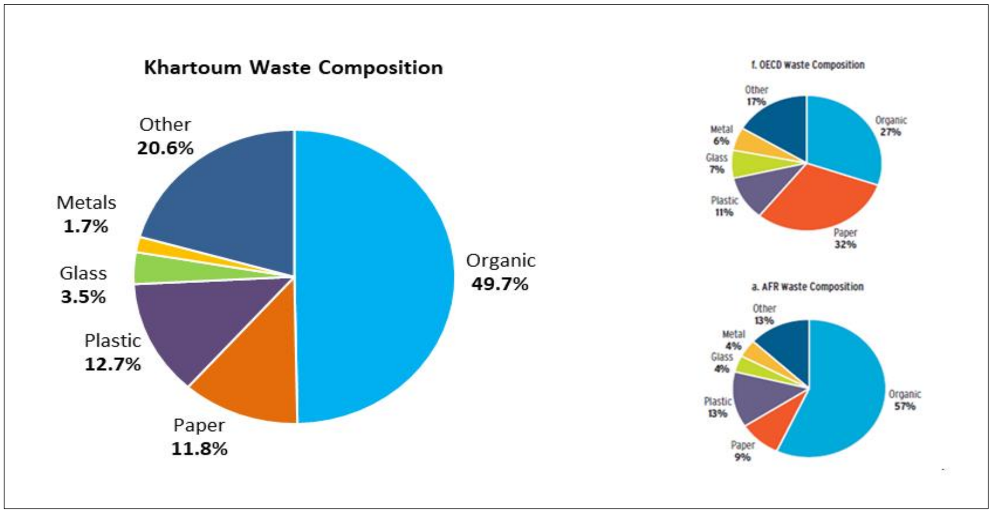

Figure 5: The figure depicts the waste composition of Khartoum state in comparison with the waste composition of the OECD and African countries. Sources: KSCA, 2008, and World Bank, 2012.

2.3.5. MSW Collection and Transportation

2.3.5.1. Collection

According to the survey made by JICA, the waste collection rate as of 2016 was estimated at 65% (3,739 tons) of the daily amount generated of 5,752 tons [20] whereas Mofadel et al. in 2016 stated that only 60% of the waste ends up being collected [19]. It was estimated that the waste generation in 2020 would be around 7,094 tons per day, while the collection goal is 70%. The ultimate collection goal in 2028 is 80%.

Under the existing system, the seven localities' governments are responsible for collecting the municipal solid waste in their respective territories and transporting the waste to the transfer stations or, in some cases, directly to the landfills. As mentioned previously, the questionnaire made by Alnagrabe in 2015 involved assessing the efficiency of the collection system put in place by the admin unit government, out of the 360 sampled HHs, 34.7% responded with once, 10.3% twice, and 2.8% thrice times a week while 50.2% cited that it is generally irregular and unreliable [23].

The JICA Project Coordinator at the Higher Council for Environment (HCE) attributed the inadequate performance by the KSCA to the poor coordination between the different levels mentioned above, inadequate capacity, and scarce financial and skilled human resources. The Master Plan (MP) of the

Khartoum state identified several solutions/issues regarding the waste collection process and the transfer stations' operation; which are:

- Recruit full-time employees at the locality level and increase their pay;
- Adopt a more practical collection service level of two days per week and expand the Fixed Place Fixed Time (FPFT) collection system. Moreover, different areas (i.e., quarter) require different vehicle type;
- Low trip production rates (trip production refers to the number of collection trips a truck can make in one shift);
- The low number of trailers that transport waste from transfer stations and landfills;
- Tens of collection vehicles are out-of-order including compaction equipment at the transfer stations;
- Waste management vehicles are procured from different manufacturers which render complicated the maintenance process; and
- Waste collection activities need to be managed more efficiently; moreover, data collection, and documentation need to be improved, and a robust feedback system put in place.

KSCA and LOC collect and transport waste with old vehicles and equipment because of the poor funding from the state government and any kind of subsidy from the Government of Sudan [20]. Table (11) below details the collection rates of the different localities; and while generally, all the rates are low, it can be noted that even lower collection rates in outer localities of Jabal Aulia, Karari and Sharg Elnil; this indicates that waste management in these localities requires further strengthening.

Table 11: Amount of MSW collected and the collection rate in each of the seven localities in Khartoum state in 2016. Source: The Khartoum state MP, 2016, P.12.

Component	Khartoum	Jabal Aulia	Omdurman	Umbadda	Karari	Bahri	Sharg Elnil	State Total
MSW generated (ton/day)	1,364	946	801	712	609	691	629	5,752
MSW collected (ton/day)	886	484	544	501	366	470	378	3,739
Collection rate (%)	65%	**53%**	68%	68%	**60%**	68%	**60%**	65%

The amount of waste collected was estimated based on the number of trips made by the collection vehicles from the localities to the respective TS multiplied by the average weight of the collection trucks. Similarly, the quantity of waste disposed of was estimated based on the number of trips the trailers make to the landfill plus the amounts transferred to the central stations. Whenever weighbridges are unavailable, the estimates were made using the following equations:

Amount collected = No. of trips of collection vehicle from LOC to TS x unit weight (UW)

Amount disposed = No. of trips of trailers from TS to LF x 25 tons + no. of trips of collection vehicle from LOC to TS x unit weight (UW)

A discrepancy of 1,700 tons was reported in 2016 between the quantity of waste collected and disposed of at the LF. The reasons for which were attributed to (i) errors due to the different estimation methods, (ii) poor or lack of documentation at the landfill sites, (iii) illegal dumping of the truck drivers before reaching the landfill, and (iv) the informal sorting activities taking place at different levels.

The collected waste ends up in one of the transfer stations (TS), for compaction and thus lesser transportation costs, or directly in one of the landfills (LF) in Khartoum when it is closer to the waste generation point due to the small number of functional TS. It was found out that less amount of waste ends up in the LF compared to the amount transported to the TS; this was attributed to the informal sorting by waste pickers and waste collection workers, and illegal dumping by collection truck drivers [19]. After the completion of the JICA project in July 2016, the existing waste collection equipment comprised 705 in total. More details are provided in the table (12) below:

Table 12: The status of waste collection trucks in the state and the localities as of July 2016 after the grant aid. Source: The Khartoum State MP, 2016, P. 11.

Area	Khartoum	Omdurman	Bahri	Jabal Aulia	Umbadda	Sharg Elnil	Karari	Khartoum State	
Number of vehicles									
Total number	119	104	95	95	111	100	81	705	-
Compactors	57	36	28	34	39	33	34	261	37%
Dump trucks	45	41	49	36	48	41	23	283	40%
Arm roll	10	12	13	8	6	7	5	61	9%
Tractor	7	15	5	17	18	19	19	100	14%
Age of vehicles									
1988 – 2000	4	0	3	0	4	0	0	11	1.6%
2001 – 2005	27	21	15	8	13	11	6	101	14.3%
2006 – 2010	40	40	28	32	41	36	54	271	38.4%
2011 – 2015	48	43	49	55	53	53	21	322	45.7%
Condition of vehicles									
Operating	73	69	90	**48**	**62**	**60**	**42**	444	**63%**
Out-of-order	45	29	5	**47**	**42**	**40**	**39**	247	35%
Ceased	1	6	0	0	7	0	0	14	2%
Volume of vehicles									
Total volume	1,194	854	828	815	999	856	816	6,362	-
Compactors	754	444	339	405	479	384	402	3,207	50%
Dump trucks	280	216	347	225	343	277	241	1,929	30%
Arm roll	110	104	112	83	69	81	59	618	10%
Tractor	51	90	30	102	108	114	114	609	10%

The percentage of new equipment (2011 -2015) is around 46% of the total number. As detailed in the table (3) previously, a number of 42 compactors and 56 Arm type carriers with containers were procured by the Japanese grant aid project so as to increase the waste collection capacity [6]. The receiving localities are responsible for recruiting drives and collection workers. The JICA team highlighted that the mere abundance of equipment and workforce does not guarantee the provision of adequate and satisfactory collection services. In fact, the collection and transportation activities need further planning, implementation, and management, including data, which needs to be managed timely and accurately at each point of the process. For instance, weighing scales should be installed at all the existing and the planned TS and LF as well as a proper data recording system in order to provide accurate estimations as possible of the amount of waste collected and transported. Providing accurate and updated quantity measurements will aid in making more informed decisions in the future and support better planning, operating and monitoring, and consequently improved services [6] [20].

It can be noted from the table (12) above that about 2% of the vehicles are out of service, and 35% of the vehicles have not been operational for over one year and require urgent maintenance, meaning that the actual number of vehicles conducting collection activities 63%. It can also be noted that the condition of the trucks in the outer localities is severe, especially in each of Jabal Aulia and Karari localities, with 1 – 3 trucks under service, followed by Umbadda and Sharg Elnil with only around 20 functional vehicles.

On the other hand, the JICA estimated that in 2017, a number of 660 must be in service in order to meet the demand due to the projected increase in the amount of waste generated. Whereas by 2028, some equipment will have to cease operation, and it is predicted that only 513 trucks will be fit for waste collection, and there will be a need to procure a total of 555 trucks, 2,751 arm-roll containers, and 11,120 compactor containers. The state government will also have to consider introducing more compactors and arm-roll trucks to the collection system and phase out the use of small-capacity vehicles, i.e., dump truckers and tractors [6].

The strengthening of the waste management by the Japanese Agency [6] involved proposing the Fixed Place Fixed Time (FPFT) solid waste collection method; a pilot project (PP) was implemented in a total of four pilot quarters in each of Khartoum and Karari localities and as a result, the time needed for the waste collection was decreased by up to 24%. The program succeeded in increasing the satisfaction of the pared residents plus cut on the fuel consumption and the time spent on collection as compared to the previous house-to-house collection method according to a brief questionnaire carried out by the JICA team in collaboration with KSCA before and after the implementation of the FPFT pilot project. The results revealed that the collection services were satisfactory in two LOC with 79% and 86%, compared to 50% and 41% before the implementation. Additionally, up to 88% and 89% of the residents quoted placing the waste at the designated collection point. Over 85% in both quarters reported that the collection vehicles were on schedule. On the other hand, both the total amount of collected “waste collection fees” and the “fee collection rate” had increased in both pilot areas compared to the data before the pilot project. According to [6], only 10% of the households paid the waste collection fee before the PP, but about 40% paid one year after. It is demonstrated that the better the collection services, the more residents are willing to pay. It is worth noting that in 2015, the fees collected from the beneficiaries comprised 82% of the total income, while the national and state subsidies comprised the remaining amount. The amount doubled compared to 2011, meaning that the budget can be drawn entirely from residents without depending on subsidies. Nonetheless, the increasing inflation rate should always be accounted for [6].

However, the LOC failed in maintaining the project performance and returned to the previous collection method except in one quarter as of 2017. The program management noted several challenges encountered during the implementation, including:

- Inadequate number/volume of vehicles dispatched to the specific quarter;
- The size of the vehicle with respect to the width of the streets; and
- Time delays due to the waste sorting by collection workers, long offloading waiting time at the TS, or instead sent directly to the LF.

Consequently, the JICA suggested that a rigorous analysis of the targeted areas should be conducted before the introduction of the FPFT system.

On the other hand, to further increase the collection capacity in Khartoum city, the national capital, the state government hired a private company for waste collection; the collected amount is estimated at 200 tons/day [20]. The company is most likely to continue providing its services to the government.

2.3.5.2. Transportation

According to the Khartoum State MP, there are only two (2) functional TS in the whole state in each of Khartoum and Omdurman localities. The Omdurman TS has no weighbridge and processes around 830 tons per day, while the TS in Khartoum is equipped with a weighing bridge and processes about 765 tons per day [18].

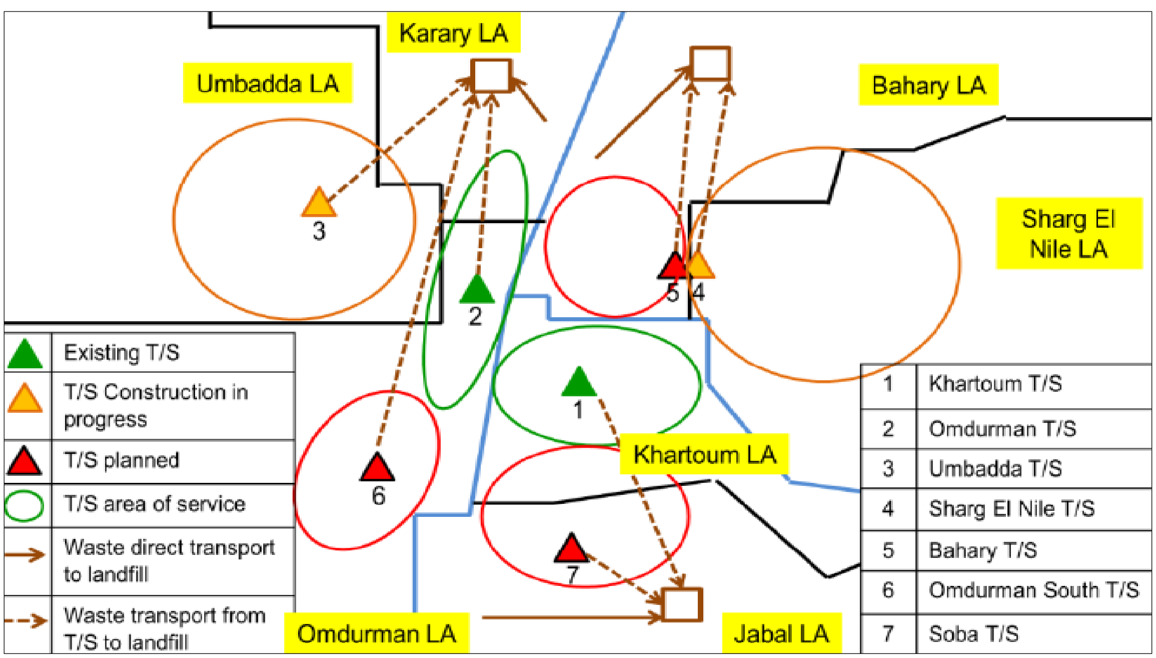

Figure 6: The existing and planned LF and TS in all seven provinces and the area served by each. Source: MP, 2016, P. 42.

Figure (6), provides the schematic locations of the existing and the planned transfer stations (except for Karari and Jabal Aulia TS), services zones, and the MSW flow in 2020. According to the JICA, there is an urgent need to construct more transfer stations and procure secondary transfer equipment (e.g., trailers) as the currently functional two TS process only around 1,300 tons of waste per day.

Operations at Bahri TS were suspended in 2015 due to complaints from neighboring farm owners and residents; as an alternative, a new site was identified to be used as a temporary station to serve Bahri and Sharg Elnil localities. However, because it is only temporary, it does not have any minimum design requirement, i.e., fences and gates. Heavy equipment was used to load the waste (which is unloaded directly on the ground) into large dump trucks in order to transport them to the locality landfill. Ultimately, that proved inefficient, and the site continued to be used as a temporary open dumping site serving Sharg Elnil and the southern part of Bahri locality. The construction of at least one TS in the Bahri area was deemed both necessary and urgent so as to at least one TS serving the three cities of the Khartoum state. The construction of the additional TS was included in the KSCA 2016 annual plan. However, according to the KSCA, basic preparations such as budget allocation, site acquisition, and preparation were not achieved; thus, construction and rehabilitation of the existing stations were deferred to 2020 [6].

Table 13: The table below details the design requirements for the new TS and the rehabilitation of the two existing TS. Source: JICA, 2017, P. 71. The Khartoum State MP, 2016, P. 43.

Activity	Service Area	Design capacity	Design requirements
Construction of Umbadda TS	Umbadda	900 ton/day Minimum of 3 discharge points	Sorting area and drop-off area Entry and exit weighbridges
Construction of Sharg Elnil TS (Combined)[12]	Sharg Elnil and Bahri	1,050 ton/day Minimum of 3 discharge points	Sorting area and drop-off area Entry and exit weighbridges
Construction of Bahri TS (Combined)[13]	Sharg Elnil and Bahri	600 ton/day Minimum of 2 discharge points	Sorting area and drop-off area Entry and exit weighbridges
Construction of South Omdurman TS	The southern part of Omdurman	400 ton/day Minimum of 2 discharge points	Drop-off area Entry weighbridge
Construction of Soba TS	The southern part of Khartoum and Jabal Aulia	1,350 ton/day Minimum of 3 discharge points	Sorting area and drop-off area Entry and exit weighbridges
Rehabilitation of Khartoum TS	Khartoum	1,190 ton/day Minimum of 3 discharge points	Sorting area and drop-off area Entry and exit weighbridges
Rehabilitation of Omdurman TS	Omdurman	1,050 ton/day Minimum of 3 discharge points	Sorting area and drop-off area Entry and exit weighbridges
Construction of Karari and Jabal Aulia TS	Karari and Jabal Aulia	Feasibility study to construct the TS should be done after the operation of new TS	

One of the major issues that the new TS will be designed to resolve are the delays experienced while offloading the waste by the collection trucks that directly affects trip production rate, and delays experienced when loading the waste into the trailers in order to be transported to the landfill, which will cause consequent delays of the landfill operations. Thus, accurate estimates/projections of the expected incoming amount of waste to the TS must be provided and considered in their design/sizing.

[12] The word "combined" indicates the TS will serve both of the localities of Sharg Elnil and Bahri

[13] As above

Furthermore, the new plan prioritized the construction of specific central stations as opposed to others, namely the Jabal Aulia and the Karari localities. The plan also detailed that the TS will be equipped with weighing bridges, and two years after operational (the year 2022) waste sorting equipment will be introduced to the transfer stations. The construction plan of the Jabal Aulia TS was tentative because the suggested location of this station depends on the lifespan of the Khartoum LF. In addition, the need for a station at the Karari locality was not considered as urgent, as the locality is already served by the landfill to which the waste is directly transported. Therefore, the feasibility of the construction of these two TS will be studied after the other four (4) planned stations are entirely constructed and functional.

2.3.6. MSW Treatment

The public sector is Sudan does not perform any kind of SW treatment, nor does it organize/supervise these activities, and as a result, there are no data available on the treatment efforts in Sudan in general and Khartoum in particular. Two main issues were identified by the MP, which are: the lack of information on the market and the informal nature of the sporting activities in the country as no source separation is taking place [18].

2.3.6.1. Organic waste treatment

In Khartoum state, the organic waste fraction makes up to 49.5% of the total daily generation rate. It renders the decision of treating only the organic waste, either for energy or material production, a huge opportunity, and helps to avoid the adverse health and environmental impacts of untreated organic waste. For the stated reason, a project design study made by a Sudanese company called Petroleum Engineering Consultancy Services (PECS) Company Limited proposed "Omdurman Landfill Municipal Solid Waste Composting Project" as a Clean Development Mechanism (CDM) project and presented for the United Nations Framework Convention in Climate Change (UNFCCC). The suggested CDM project was the first of its kind in the Republic of Sudan, and it was estimated that the amount of annual average GHG emission reductions is equivalent to 46,789 tCO_2e [26]. The project was eventually approved for registration as a CDM project and was set up within the Omdurman landfill premises. A sorting plant was as well constructed so as to separate the organic waste fraction and send it straight to the composting plant. The layout of the plant layout is as follows as reported in [26]:

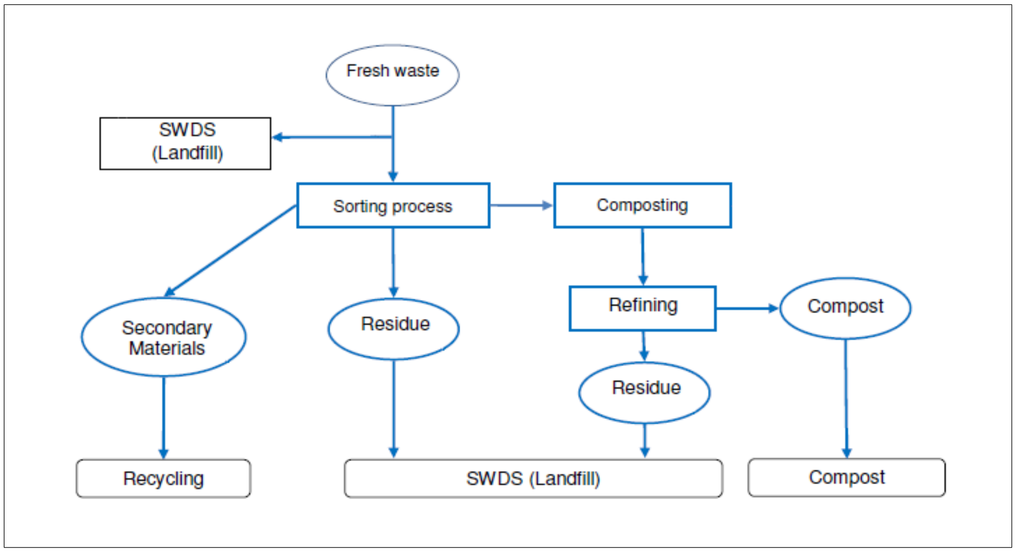

Figure 7: The layout of the composting plant in the Omdurman Landfill Site. Source: adapted from PECS, 2014, P.12.

The waste sorting plant, composting plant, and a PET pellet plant was constructed in 2014 in the Omdurman landfill, which was constructed by the same PECS itself in 2008. The plant was operational until December 2016 [6]. The recycling facility at the Omdurman LF ceased operation nearly two years after construction [18].

2.3.6.2. Plastic Recycling

The major challenge with plastic waste and, in particular, the PE plastic bags is the improper waste disposal practices coupled by the bags design and light weight, causing them to travel for long distances in windy days which is noticeable around Khartoum state as well as other states and alongside the highways connecting the different states of Sudan.

In a study carried out by Alnagrabe et al. [23] in the state of Khartoum, in an attempt to assess the environmental impact of Polyethylene (PE) plastic bags. A survey involving 360 HHs around the state was carried out; the study showed that 92.8% of the respondents reported using more than four (4) plastic bags per day, whereas only 1.4% of the sample HHs reported not using PE bags at all. The study also linked the increased use of disposable bags to the increased number of HH residents as well as the income level of the HH. On the other hand, it was revealed that plastic bags are preferred for their convenience (availability, weight, price, applications); however, lack and inconvenience of the alternatives makes it specifically challenging to reduce their use [23]. In a different survey carried out by Fadlalla [25] that targeted soft drinks and water industries in Khartoum, revealed that the PET plastic waste from these factories falls in the range 0.5 – 3%; the percentage varies according to the efficiency of machinery deployed and the quality of the plastic preforms.

The JICA project completion report, 2017, stated that there are around 37 small-scale plastic recycling plants, including the Omdurman LF PET pellet plant, all of which are privately owned and depend on the informal sector for sorting and labor [6][18]. However, the challenge with PET recycling in the state in the absence of recycling technologies thus, all the PET recycling plants only perform primary treatments (shredding, washing, and balling) in readiness for exporting [25].

2.3.7. Waste Disposal

Waste disposal in the state takes place in either one of the three existing landfills in each of the three major cities in Khartoum state, which are Khartoum, Bahri, and Omdurman. The total area of the three sites is about 1,000 ha, and they operate 24 hours a day; however, the compliance with a periodic soil cover is not optimal and is attributed to the unavailability of heavy equipment for landfill operation at these sites [20].

The Omdurman landfill (Abu Weleidat) is the most recently constructed. PECS Company constructed it in 2008. It is the second-largest landfill in Khartoum State (550 ha), and therefore, expected to have a lifespan of several decades. It was estimated, in 2016, that this LF receives an amount of waste equivalent to 2,907 tons each day.

As of June 2015, and based on a topographic study, it was estimated that the remaining lifespan of the Khartoum landfill (Tayba Elhasanab) is 6.7 years, which means that it will only remain operational up to the year 2021. However, there are plans for expansion instead of constructing a new landfill for Khartoum (Khartoum and Jabal Aulia localities). The Khartoum LF, receives 501 tons per day as of 2016, is not served with paved access roads making it inaccessible during the rainy season which increases the rate of illegal dumping; according to an interview with the KSCA, the official stated that the waste from the Khartoum area is transported to the disposal site in Omdurman. Other issues highlighted by [27] to which poor waste management at this disposal site are attributed are the inadequate funding, the constant natural increase in the amount of waste, lack of public awareness on the effect of prevention, reduction and disposal actions; this, on top of the risky working conditions, e.g., lack of personal protective equipment (PPE) for the workers.

The Bahri landfill (Hattab) site, with a land area of 750ha, was initially an open dumping area. In 2008, the KSCA had planned to improve it further to the level of controlled dumping [6]. As of 2016, this site receives 1,239 tons of waste per day. Moreover, the Bahri transfer station came out of service in 2015, resulting in using a nearby pit temporarily as a disposal site to avoid the direct waste transfer to the Bahri landfill so as to cut on the waste transportation costs. However, the temporary transfer station is located in an agricultural area and where crops are planted, and irrigation water is most likely extracted.

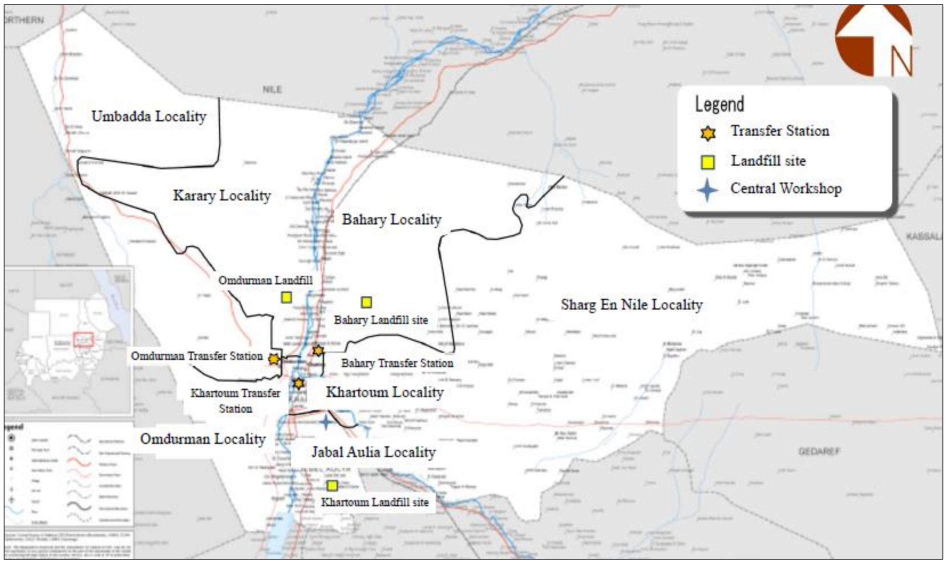

Figure 8: The map shows the locations of the existing transfer station and landfills in Khartoum state. Source: JICA, 2017.

It is worth mentioning that both hazardous and medical wastes are disposed of and will continue to be disposed of at the Haskanita LF in Umbadda locality in Omdurman city. Table (14) detailed the types of wastes that are acceptable at the different landfills in the states.

Table 14: The following table shows the types of waste that can be received at each landfill in the state of Khartoum. Source: Khartoum state MP, 2016, P. 48.

Waste categories	Khartoum LF	Omdurman LF	Bahri LF
MSW (domestic, commercial, etc.)	Acceptable	Acceptable	Acceptable
Industrial waste (non-hazardous)	Not acceptable	Acceptable	Not acceptable
Hazardous waste	Not acceptable	Not acceptable	Not acceptable

The JICA project design report in 2014 stated that all the existing landfill sites fall under the category of open dumping areas [20]. However, the project completion report in 2017 suggested that the landfills were operating as controlled dumpsters since 2017 and planned to operate as sanitary landfills with drainage, gas vents, and daily soil cover (without leachate recirculation) as of the year 2020 [6].

The management of the three landfills in Khartoum is carried out by under-qualified and understaffed conditions; moreover, the landfills are not provided with electrical power supply, steady water supply, paved access roads, and access controls and security. The exception is the Omdurman landfill, where it has fencing, administrative offices, gates, paved roads, electric supply; this can be attributed to the fact that it was constructed recently in 2008; nonetheless, the water supply is unstable. Another challenge that is present at the transfer station and the landfill sites is the informal sector (waste pickers or scavengers) due to the lack of access controls [6]. In 2014, it was forecasted by the JICA experts that the three landfills of Khartoum, Bahri, and Omdurman are expected to receive a total of (501), (1,239), and (2,907) ton/day of waste respectively in the year 2016 [20].

In order to operate the landfill at level (2), the waste disposal cells should be equipped with a gas vent, a drainage system, ridges, and a soil cover while the landfill site should be served with fences, gates, and administration offices. According to JICA, landfill sites have a deep groundwater level, and generally, the amount of rainfall in the state is low on top of the hot and dry climate almost all year round, and thus there is no risk of contamination, and there is no need for leachate circulation and treatment systems. Therefore, level two landfill set up is deemed sufficient for waste disposal in Khartoum state.

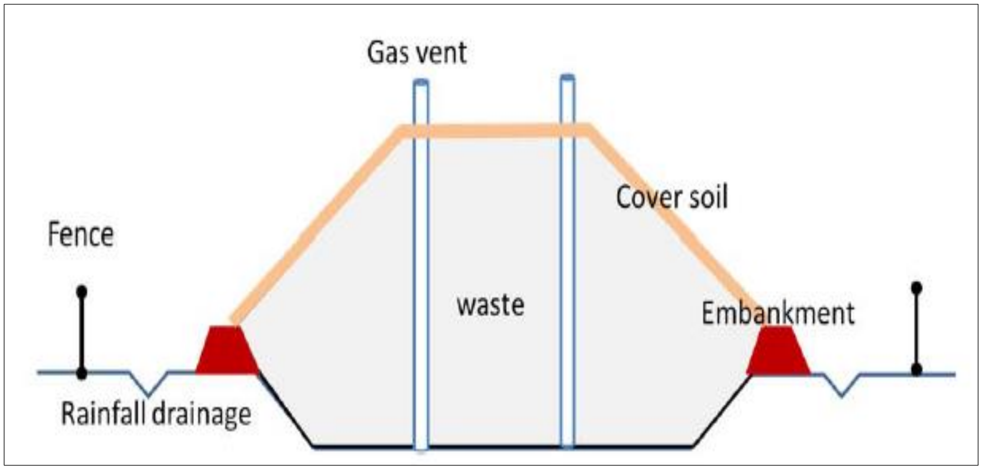

Figure 9: Sketch of a sanitary landfill with bunds and daily cover that illustrates the planned landfill design in year 2020/2021. Source: Khartoum state MP, 2016, P. 48.

CHAPTER (3): CURRENT SIUATION OF MSWMT IN KHARTOUM

The information and data reported in this section of this document is based on: interviews with the Khartoum state government officials at different levels, a desk review of the documents provided at these levels, interviews with different businesses of the recycling sector, field visits to the Omdurman landfill, the Omdurman organic waste treatment facility, Khartoum transfer station, Bahri disposal site, and observation.

3.1. Materials and Methods

Below, table (15) and (16), are the details of the sites visited and the officials interviewed for obtaining the data reported in this chapter of the thesis. Additionally, the interview questions and documents reviewed are briefly described below.

Table 15: List of the institutions and sites visited:

No.	Visits	Date Visited
1	Japanese International Cooperation Agency (JICA)	May, 12, 2019
2	Higher Council for Environment (HCE)	May, 30, 2019
3	Khartoum State Cleaning Authority (KSCA)	June, 10, 2019
4	Omdurman Landfill (Abu Weleidat)	June, 17, 2019
5	Omdurman Composting Facility	June, 17, 2019
7	Omdurman Plastic Recycling Facility	June, 17, 2019
8	Bahri Temporary Disposal Site	Dec, 28, 2018
9	Khartoum Transfer Station	June, 19, 2019

Table 16: List of the persons interviewed:

No.	Person interviewed	Position	Institution	Date Interviewed
1	Musab Birair	General Manager	KSCA	Aug, 28, 2018
2	Halima Mohammed	Program Coordinator	JICA	May, 12, 2019
3	Gussai Ahmed Hamdan	JICA project coordinator at HCE	HCE	May, 30, 2019 Aug, 31, 2020
4	Abubaker Ahmed	Operations Manager	KSCA	Jun, 10, 2019
5	Ayman Eltahir	Monitoring and Evaluation Manager	KSCA	Jun, 10, 2019
6	Ashraf Abdelrahman	Omdurman LF Site Manager	KSCA	Jun, 10, 2019 Jun, 17, 2019 Aug, 31, 2020 Sep, 03, 2020
7	Shayma Mohammed Elhaj	Omdurman LF Site Supervisor	KSCA	Jun, 17, 2019
8	Hassan Ali	Khartoum TS Site Manager	KSCA	Jun, 19, 2019
9	Mohammed Tawfig	Program Manager	PECS	Jul, 22, 2020
10	Halima Abdallah	HSE Officer	LAST Trade Co.	May, 02, 2020
11	Eight (8) plastic recycling owners	Business owners/managers	Plastic recycling facilities	Between Jun, 01, 2019 and Jul, 29, 2020

The interviews questions varied from one institution to another and from one interviewee to another. Questions asked to the Project Coordinator included updated information about activities funded by the Japanese cooperation, the status of the implementation, program impact evaluation and the future plans for waste management in Sudan. On the other hand, the interview with the JICA Project Coordinator investigated the progress of the implementation of government of Sudan contribution to the project, the implementation of the JICA project activities and the impact of the Japanese aid on the waste management situation in the state. The interview of the KSCA Officials focused mainly on the operation of the different disposal sites and the different transfer stations. The questions also focused on the implementation status of improvements proposed by the JICA and those proposed by the Khartoum state master plan (MP) obtained at the HCE. The General Manager of the Omdurman Composting Facility was interviewed in order to obtain further information of the reasons why the composting facility ceased operation shortly after operation and whether similar projects were implemented in the state.

Moreover, a random sample of eight (8) private plastic plants representing (21%) of the total stated in the literature were selected by this study to investigate the plastic recycling activities in Khartoum state. The interviews were conducted mainly remotely through telephone calls between June 1st 2019 and July 29th 2020, and data was collected through a structured survey of ten (10) questions as listed below:

1. Is it a privately-owned business?
2. What is the average amount of plastic being recycled (daily/annually)?
3. What are the types of plastic recycled (High Density Polyethylene (HDPE)/Polyethylene Terephthalate (PET)/Polypropylene (PP)/Low Density Polyethylene (LDPE)/Other)?
4. What are the end product/s?
5. What is the market for your finished products (local/international)?
6. How is the plastic supplied for recycling (formal/informal, private/public)? Are there supply issues?
7. Do you perform wastewater treatment or any other treatments for undesired streams?
8. Do you know of any environmental policies or regulations imposed on the industry?
9. What are the challenges facing this industry?
10. Additional information.

Additionally, different documents were obtained at different institutions including JICA, HCE and KSCA including the Khartoum state master plan, EWASCO composition study report, model AU solid waste management services manual, solid waste transportation and final disposal, solid waste disposal report, and future of ISWM in Khartoum state.

On the other hand, the Recovery Factor Transformation Function (RFTF) Matrix was used in order to obtain and compare different semi-manual sorting lines layouts; whereas the Solid Waste Emission Estimation Tool (SWEET) was utilized in order to evaluate the emission scenarios of the current management and treatment practices as well as the proposed treatment scenario.

3.2. MSW Management Practices

Waste management in this document includes all the activities directed towards waste control, starting from positive attitudes, policies, and regulations regarding waste generation, collection, treatment, transfer, and disposal. In the study area, it is evident that correct solid waste management practices need to be heavily promoted. Moreover, waste collection from the generation points such as households, markets, and institutes, etc., needs to be optimized in order to reduce transportation costs and increase the adjacent treatment share of the overall budget dedicated to waste management and treatment.

Solid waste management has many stakeholders, including the different governmental levels, the communities, the private sector and the informal sector. In Khartoum state, for instance, the individuals' behavior is contributing to the poor management of the solid waste; however, it could as well be attributed to the unreliable waste collection system in place as well as the lack of communal bins and containers in public places. Waste and open dumping sites are scattered around the streets in the residential and market areas. On the other hand, the community contributes to the management and treatment activities through the cleaning campaigns usually organized at the neighborhood levels and through waste sorting and recycling through the informal sector (waste pickers or scavengers). Waste pickers are active in different stages of the waste flow, starting from scavenging at the residential areas' level (the household waste disposed to be collected) by emptying waste containers looking for recyclable and other valuable items. The second and the third stages are at the transfer stations and the landfill sites, in which they can enter freely due to the lack of access controls. Waste pickers were noted waiting for the waste transfer trucks, and as soon as it offloads the waste, they start picking recyclable (mainly plastics) and other items. The waste piles are also subjected to stray animals looking for food.

The private sector's contribution to the solid waste management in Khartoum is also limited to collection services in different areas around the state and especially within the capital city of Khartoum in addition to small-scale recycling activities such as the reported 37 plastic recycling plants in Khartoum [6]. Currently, there is no enforced SWM law or bill. Activities such as waste recycling and the legal status of private companies engaged in SWM activities are not regulated; additionally, there are no such bylaws at the locality level according to [18].

In Khartoum, the state government efforts are mainly exerted towards waste collection and disposal. Street sweeping activities mainly happens in Khartoum city. The collection, and partly the transportation from LOC to the TS, the process is organized by the KCSA, whereas the implementation is carried out by the localities (LOC) and administrative units' (AU); whereas, the KSCA manages the operation of all the transfer station (TS) and landfills (LF), besides waste transportation between the two sites.

Under each administrative unit (AU), there are three central units, which are the administrative, fee-collection, and technical units. The latter is responsible for waste collection. The officials stated that the waste collection and transportation workers, supervisors and inspectors are under temporary employment; as a result, the work collection workers resort to waste sorting in order to increase their income; permanent employment means the workers can enjoy the benefits and would no longer need to slow down the process for waste sorting.

The bureaucracy and the autonomy of this hierarchy are causing a considerable miscommunication and misplanning of the process. Further to that, a major problem that waste management in general and collection, in particular, is the staff turnover; for instance, the frequent change of the locality (LOC) general managers hindered the implementation of the suggested improvements to the waste collection system according to the JICA teams while conducting the project. Such continuous changes in the structures responsible for solid waste management had led to issues such as lack of an organizational framework with clear criteria, and lack of clear and specific job descriptions for some of the staff. On top of that, supervisors and inspectors should be well-trained to manage crews and engage the community. Moreover, there appears to be an imbalance in the distribution of inspectors and supervisors between the two units of Revenue Collection and Cleaning Works. Inspectors assigned to the Revenue Collection Unit are more than double those assigned to the Cleaning Unit in some of the AU Cleaning Offices. However, with the pending introduction of waste fees attached to electricity and water bills, the fee collection inspectors may be re-distributed to the Cleaning Unit. As a response, a proposal for forming a committee headed by the state Secretary-General to reform the hierarchy and recruit qualified workers as fulltime employees. On the other hand, KSCA is responsible for the development of a standardized operational framework for the LOC and the AU. The state also plans to decentralize the collection process, meaning that it would be carried out at the AU level and having them work more closely with the communities.

3.3. MSW Collection and Transportation

3.3.1. Collection

As mentioned previously, KSCA is the body responsible for the planning and supervision of the municipal solid waste collection, and it is implemented at the locality level by the administrative units (AU). The common waste collection method is house-to-house which takes place once or twice a week according to an assessment made by all the seven localities (including all the 106 AU) in late 2016 (table 17). Whereas commercial waste is collected on a daily basis and so as for large waste generators, i.e., markets, in addition to street sweeping activities and the cleaning campaigns that rarely take place.

Figure 10: Solid waste scattered in the street of Khartoum state. Omdurman city, Khartoum, Sudan

Table 17: An assessment of waste collection services offered by the different localities in the state of Khartoum in 2016. Source: The Khartoum state MP, 2016, P.70.

Locality (AU)	Collection Services Status
Khartoum (15)	Service coverage is over 75% in six AU and above 50% in the other nine. The collection services frequency reported is twice a week for all of the AU. The common waste disposal method at the AU level is door-to-door (9/16 AU).
Omdurman (16)	Service coverage is reported as 100% in four AU, over 75% in other four and below 50% in seven AU. On the other hand, the collection frequency is daily in four AU, twice a week in seven and once a week in six AU. The prevailing collection system is based on common collection-points.
Bahri (16)	Collection service coverage is over 75% in three AU, while most of the AU (12 AU) fall in the range 50-74%. The common waste disposal method is by the door, with all the 16 AU above 50%. The frequency of the collection is mainly once and twice a week.
Umbadda (16)	The collection service coverage was reported at 100% in eight AU and the other eight above 50%. The waste collection mainly takes place a week while the common discharge method in the locality is door-to-door (100% in 12 AU).
Jabal Aulia (16)	The locality reported that the service coverage is between 50-75% in five AU while it is less than 50% in the remaining seven AU. The frequency reported was twice a month, and 12/16 AU discharge their waste in front of the residences. The locality reported that private companies serve four out of the 12 AU, and no further details were provided.
Sharg Elnil (17)	Eight (8) of the total number of AU are provided with a coverage of over 50%, five AU is below 50% while the remaining four AU is not reached at all. The frequency adopted by this locality is once per week. In addition, most of the AU have their waste disposed of either in front of their residence and at common discharge points.
Karari (10)	The collection service coverage was reported above 75% at four AU, whereas, in general, seven of them are reached with a rate of 50%, one AU is above 50%, and two of them are not reached with the services at all. The prevalent collection frequency is twice a week reported in five of the AU and also an "at-the-door" disposal preference reported in five AU.

Collection service levels are defined by the frequency of the collection service offered by the service provider and the location of the discharge points where the waste generators bring out their waste. The highest service level would be to have the collection truck come daily and to collect the waste in front of the residence; however, this service level is costly and time-consuming and would result in inefficient utilization of the trucks and low service coverage overall. In response, the promotion of the waste management project by the Japanese Agency [6] involved adopting the Fixed Place Fixed Time (FPFT) waste collection method; a pilot project was implemented in a few neighborhoods around the state, and it was found that the time needed for the waste collection was decreased by up to 24% [6]. The project succeeded in some of the areas while failed in others according to the JICA Project Coordinator at the HCE; nonetheless, it represents a huge opportunity for leveling up waste collection services and creating customer satisfaction, which builds confidence and collaboration of the targeted communities. Further details were presented in the previous sections (refer to section 2.3.5.). The lessons learned from the implementation of the FPFT revealed that the efficient application of such a system, first, requires a comprehensive analysis and significant improvement of the functionality of the waste management process from collection to landfill management with a particular focus on the waste management equipment, i.e., waste collection vehicles. The successful implementation of the program depends heavily on the efficient use of the waste collection equipment and program planning. The effective operation of TS and the LF also plays a vital role in the program as the longer the time the collection vehicle spends offloading at the TS or the LF affects the adherence to the time fixed at a specific PP area. Additionally, the collection route in a given area needs to be identified carefully in order to eliminate the unsuitability of the vehicle number, size (dimensions), and capacity for a given area. For instance, the failure to provide a reasonable estimate of the amount of waste that is produced at a collection point will lead to reaching the full capacity of a vehicle before collecting the whole amount and thus a delay to the program schedule. Another example would be using larger vehicles for areas with narrow road networks resulting in a vehicle inability to reach the selected discharge/collection points. After the success of the FPFT collection system in increasing the satisfaction of the residents with the collection services and leading to more efficient use of the resources, the KSCA decided to expand the project to other areas of the state.

Figure 11: The FPFT applied by the Japanese grant in Omdurman and Khartoum city.

Initially, Khartoum state government decided to expand the project to 21 administrative units according to the JICA; however, the KSCA reported that it did not go as planned. Nonetheless, it will be gradually introduced to the localities in the future, and it will be left to the locality office to determine the number of AU (3 – 4) each year in which the FPFT shall be applied [18]. The KSCA did not report any new pilot activities during the past couple of years and yet to prepare a solid expansion plan to follow.

Before the grant aid project, the KSCA reported that 15% of the total number of vehicles in the state was over 12 years old, and 35% of them required were nonoperational and awaiting maintenance works. Jabal Aulia and Karari localities reported that 50% of the allocated trucks were nonfunctional. On the other hand, the fact that the existing collection vehicles were procured from 14 different manufacturing companies/countries, which further complicates the maintenance process. It is important to note here that the Khartoum state government does not allocate sufficient funds in its annual budget to cover the costs of maintenance of the LF equipment and the waste collection vehicles, which is the reason behind the failure to carry out periodic maintenance. The comparatively higher reliance of outer localities (Jabal Aulia, Umbadda, Sharg En Nile, and Karari localities) on tractors, compared to inner localities (Khartoum, Omdurman, and Bahri localities) was observed which was believed to be the reason of the lower collection rates reported in these localities. Nevertheless, after the procurement of new trucks, new trucks were distributed to outer localities to achieve some kind of balance in the waste management services compared to the central localities because the population of the outer area will increase more compared to inner localities. According to the JICA Project Coordinator, in 2019, stated that the localities did not reach the intended collection rate of 80% in 2016 [20]. In fact, despite foreign aid, waste collection services are less frequent, regular, and reliable compared to 2016. As a consequence, people tend to dispose of the accumulated waste bags in open dumps and streets that are scattered around the three regions. This situation was further aggravated by the deteriorating economic crisis and the recent political unrest.

The employment of private companies for the promotion of the collection services was noted in Khartoum state after the failure of the Khartoum State Company in the year 2012 due to poor management and allegedly corruption. The gap was reportedly filled with twelve (12) private companies. While there is little information available about all these companies, it was reported that most of these companies failed to collect and transport waste in the state due to their limited capabilities and lack of experience in the waste management sector. Details about some of the operating companies are provided below:

- **Ozone Company:** It is a Moroccan company that is contracted by the Khartoum government to collect waste from the central area of Khartoum locality and some of the neighborhoods in the eastern and southern side of the city based on a monthly payment. The company was as well later on responsible for serving the presidential and administrative sectors such as the presidential palace and different ministries. It was reported that the company benefitted from customs exemptions for importing the waste collection vehicles. It also managed to recruit the already-trained workers by the state government by offering them higher salaries.

- **NCS (Nadar Collection Services)**: The company is owned by a Sudanese company called GIAD so as to increase the collection rate at the center further and is paid based on the amount collected. The KSCA official added that other small enterprises are operational, but the KSCA has no record of them. It was estimated that the daily collection rate is about 200 tons per day [20]. Also, private collection contractors are working in some areas in both of Sharg Elnil and Jabal Aulia localities. It was reported that this company had stopped operating in 2019.

- **Costilla Company:** Costilla is a national company that was operating in the Bahri area. The state government terminated the contract with this company due to financial issues. Its tasks were then taken up by the Ozone company.

- **El Riyadh Company:** It is a national private company owned by investors operating in residential areas in Khartoum. The company is reportedly leasing waste collection vehicles from the Khartoum locality itself.

- **Sarmaj Company:** There are no details available about this company other than the service area, which is Omdurman city and the fact that it is operational up to this date.

Another methodology of waste collection companies exist in the state such as "LAST for waste management and scrap trading" which is a private company that serves as a broker between some industries, mainly tobacco industries, and the recycling businesses. The company receives the waste and scraps from suppliers e.g. plastic wraps, paper and cardboards, woods, metallic drums, water tanks, and plastic container and performs manual separation. Reusable materials received are sold as scraps while the remaining quantity are sold as raw materials for recyclers. The company has an average capacity of around three (3) tons per week according to an interview was conducted with the Safety and Environmental Health Officer.

Different localities fund their activities through fees collection from residential, services, and private sectors. They are claimed based on actual visits to the neighborhoods and other entities by the fee-collection worker. The residential areas are categorized into different classes (first, second, and third), and the waste collection fees vary accordingly. The fees collected are used to fund the waste collection activities and the administrative fees at the locality level; however, in recent years, people grew more reluctant to pay the fees, as the system is considered inefficient, unreliable, and even nonexistent in some areas of the state. Thus, the funding of the collection services cannot be sustained, especially in addition to the inadequate governmental funding. On the other hand, the Ministry of Finance (MOF) avails the KSCA's budget for the operation of the various TS and LF. Additionally, investments on new facilities and equipment for both localities and the KSCA have a separate budget from the MOF as well as foreign aid.

According to the KSCA officials, there is inadequate financial reporting and documentation regarding waste management activities. The weaknesses of the financial system captured in the MP included:

- There is no information on the overall costs of SWM
- Collection services fees do not cover the costs of SWM facilities and only the collection costs
- Difficulty in developing funding plans for SWM improvement projects
- Difficulties in allocating suitable funds for sustainable operations of equipment procured under foreign assistance
- Difficulty in allocating responsibility for proper management of SWM financing

Also, several improvements were suggested, such as:

- Ensure proper budget and expenditure management
- Availing separate budgets of KSCA, LOC, and AU
- Detailed and standardized reporting system for all localities
- Provision of detailed information and reports on fees collection rates

3.3.2. Transportation

To utilize efficiently the collection trucks, the trucks must make 2 – 3 trips per day in the waste collection areas. It is, therefore, essential to reduce both the time the truck spends in the collection zone to collect the waste and to reduce the time the truck spends to unload the waste and return to the collection zone. Transfer stations come into use if the landfill is far from the collection zones, then it is necessary to introduce a transfer station between the collection areas and the landfills where the collection trucks empty the waste into trailers that run between the transfer stations and the landfills. When the landfills are more than 15 kilometers distant from the waste collection zones than transfer stations are required, and the combined costs of collection and transfer become less than the case of operating waste collection especially with the installation of waste compaction equipment to decrease the transfer cost further and elongate the life of the landfills. The transfer station can also support recycling efforts by installing facilities for drop-off of recyclables, separation, and preliminary processing.

As detailed previously, in 2016, only two transfer stations were operational in the state of Khartoum; while five other transfer stations were planned to be constructed by the year 2020. The sorted plastic is planned to be entirely recycled by the KSCA, while the iron and paper will be recycled in collaboration with other companies. According to KSCA officials, there is currently a total of three (3) operational TS, including Khartoum and Omdurman in addition to the new Umbadda TS that was operational by mid-2019. The status of the other planned stations are currently under construction including the Karari and the Jabal Aulia stations that were to be constructed after the operation of other ones. Further details are provided in table (18).

Table 18: Updates about the planned transfer station in Khartoum. Source: KSCA Interview, Sep, 2020.

Activity	Service Area	Land Area (m^2)	Location	Status
Construction of Umbadda TS	Umbadda and part of Omdurman locality	41,000	ElFaiha 10	100% (Operational since 2019).
Construction of Bahri and Sharg Elnil TS (Combined)	Sharg Elnil and Bahri	29,638	Matari Elhalfaia 11 (East to the old site)	100% (Operation expected in late September 2020)
Construction of South Omdurman TS	The southern part of Omdurman	26,354	Abu Se'id 45	90%
Construction of Soba TS	The southern part of Khartoum and Jabal Aulia	7,895	Soba Elsenaat 12	95%
Rehabilitation of Khartoum TS	Khartoum	30,000	Elremeila	No rehabilitation works
Rehabilitation of Omdurman TS	Omdurman	18,000	The Omdurman industrial area	No rehabilitation works
Construction of Karari TS	Karari and part of Omdurman	11,200	Elthawra 45	100% (not accepted by the nearby residents)
Construction of Jabal Aulia TS	Jabal Aulia	16,854	Alandalos 26	90%

According to a site visit, it was noted that informal waste sorting takes place at the transfer stations; piles of sorted waste (plastic and paper) were noted at the transfer station, waste pickers, and as well waste traders' shops were noted around the site. The Khartoum TS (15.560793, 32.512048) receives an amount of waste between 400 – 900 tons a day and operates 24 per day, divided into two shifts. The TS is equipped with a weighing bridge that is currently nonoperational, two ramps and a single compactor that can reduce the waste volume to a quarter of its original volume in readiness for transferring it to the corresponding landfill. The area inside the Khartoum TS can sometimes be used as temporary waste storage. The transfer stations operate using big trailers (large trucks 75 m^3) for waste transfer to the respective landfills. The TS of Khartoum operates an average of eight (8) trailers and around 30 trips to the LF. The transfer station in Omdurman locality (15.6622915, 32.4728092) is located in the Omdurman industrial area and equipped with a single ramp with no compaction machine and a weighing scale. The station has an average of five to seven (5 – 7) per day with (20 – 27) trips to the LF with an average capacity of around 500 tons per day. Moreover, the operations at the temporary Bahri disposal site were ceased during the past year (2019) in anticipation of the currently-under-construction transfer station for the Bahri (Khartoum North) city.

Lastly, the issues related to the solid waste collection and the operation of the transfer stations could be summarized in the following points:

- Locality staff needs to be given permanent staffing status and have their wages re-considered;
- Many trucks are outdated and require challenging repair works;
- Low trip production rates;
- Waste collection activities need to be carried out efficiently;
- Low number of trailers for secondary waste transportation at the transfer stations;

- Compaction facilities at the transfer station are either non-operational or non-existent;
- Omdurman transfer station has only a single ramp; and
- The TS and the LF sites are accessible to waste pickers, which slows down the operations.

3.4. Municipal Solid Waste Treatment

As previously detailed in section 2.2.4, the waste composition of the state is dominated by organic waste at 49.5%, plastics at 12.7%, and paper at 11.8%. While there was no data available for paper treatment in literature, activities of organic and plastic waste treatment were reported. Nonetheless, at the Khartoum state transfer station, it was noted that piles of cardboard were separated and kept aside, which indicates the presence of paper waste treatment activities. It can be noted that the processing of the organic fraction alone can lead to a remarkable decrease in the amount of waste sent to the landfills, whereas treating the three major contributors will lead to a significant 74% decrease in the amount of waste disposed at the landfill.

The private sector dominates solid waste treatment efforts in the state. As mentioned before in this report, there are around 37 small-scale private plastic recycling plants, and there is an organic waste recycling plant inside the Omdurman landfill owned by the PECS Company. As for the composting plant, it became non-operational shortly after its completion, as reported by the JICA in 2017 [6].

In principle, the recycling system is composed of the separation of recyclable materials from the generated waste, processing of these materials to make them easy to transport and ready for recycling and finally the utilization of these materials by end-users, either in the production of new products or through re-use after slight processing. While there are no available records on plastic recycling plants at the KSCA and hence it is difficult to estimate how much plastic is recycled each year. The same applies to the other recyclable streams. There are three stakeholders doing these tasks in Khartoum. There is some waste separation at the source by the generators themselves, although this is very rare. The waste pickers in the streets and the collection crews separate the recyclable materials from the waste already discharged waste. They then sell the separated materials at informal “recycling shops,” which are mainly located surrounding the transfer stations and landfills. These recycling shops do some processing of the recyclable materials, such as cutting, separation of hard and soft plastics, and packaging. The end-users or their agents then purchase the processed materials.

Many uncertainties surround the solid waste sector in the country as a whole because that much and key information regarding waste management is unavailable. For instance, they are no available data on the number of the existing recycling facilities, the breakdown of the facilities based on the waste stream recycled, the amount of waste being recycled, the technologies available, the secondary raw material/product demand, and marketability.

As a result, the MP suggested forming a steering committee for conducting field surveys in order to provide more data in order to make more informed decisions when it comes to waste management and treatment. The principal activities of this committee are as follows [18]:

- Identify the stakeholders in the recycling sector;
- Estimate the type of materials and the amounts recycled;
- Collect and analyze the data on the cash flow in the recycling sector;
- Determine the issues and challenges facing the industry in order to facilitate them to contribute to waste reduction;
- Develop a suitable role for the public sector in promoting recycling activities and create a recycling friendly environment;
- Develop an institutional framework aimed at the strengthening and the active involvement of the roles of different stakeholders in the field;
- Develop recycling facilities design requirements and recommendations to support recycling activities; and
- Prepare a detailed annual action plan dedicated to supporting the recycling sector.

3.4.1. Organic Waste Treatment

The dominant waste fraction in the study area is the organic fraction, making up to 49.5% of the daily waste production. It slightly increases in summer as a result of the increase in the consumption of vegetables and fruits [26]. Bearing in mind that the country's economy relies significantly on agriculture, both composting and anaerobic digestion represent a promising option for waste treatment. Mainly because they do not only treat waste and thus limit the adverse related negative impacts but because the material recovered can be used to substitute the chemical fertilizers in agricultural and horticultural sectors partially. The PECS Company took this opportunity to design a turned-windrow composting plant that was registered as a Clean Development Mechanism (CDM) project, within the premises of the Omdurman landfill (Abu Weleidat). The design also incorporated a manual sorting facility for the recovery of the recyclables. The plant was operational for only three months. The finished product samples were sent to the National Laboratory for quality assurance and had the first few batches of compost sold to the nearby farms. The landfill site was visited in late 2019; by then, the plant was nonoperational, as was reported by the JICA in 2017 [6].

The whole composting plant is situated on the Eastern side of the landfill (15.835000 N, 32.439167 E), whereas the entrance of the landfill is at the South-western corner, near which the landfills cells are located. Therefore, the flow of the process is not optimum. Nonetheless, the sorting plant can be easily accessed, and there is enough space in front of the plant for offloading the incoming waste. The waste is then loaded into the sorting plant through conveyor belts. The sorting plant was designed to accommodate around 1,000 tons per day. Other waste and recyclables are picked and thrown down the specified dumps while the organic waste is allowed to travel through the belt to a trommel screen placed downstream.

Figure 12: The figure shows the premises of the Omdurman landfill including the cells, offices, sorting facility, composting pad and plastic recycling plant. Source: Google.

The composting pad lays on an open area across the sorting facility on which the organic materials are left to degrade and mature. Water tankers were used for controlling the moisture content of the compost heaps. The product of the process is then passed through a sieve and a destoner. The site is powered through the general electricity network and a generator as a backup. The finished compost samples were sent to the University of Khartoum (UofK) Department of Agriculture’s laboratories for testing and ensuring the absence of the pathogens and toxic and nontoxic contaminants, which negatively affect the quality of the compost and limit its usage.

The KSCA officials reported that the odors released during the operation were not very offensive, and no complaints were ever received. Moreover, leachate production was not experienced, and the officials attributed this to the hot and dry climate almost all year round; also, the landfill area is characterized by the low groundwater table levels; therefore, there is little to no risk of soil and water contamination.

Figure 13: Photos taken at the organic waste composting facility in the Omdurman landfill site showing some of the machines used at the treatment plant.

According to an interview with the General Manager of the organic waste composting project (22, July, 2020), the reasons for project failure are difficulties encountered with the state government. He identified the lack of governmental subsidies as the major issue. The KSCA in 2019, through an interview with a KSCA official, reported that the state government is planning to handover the already-set-up plant to a Sudanese vehicle company called GIAD for operating it; however, the facility remains non-operational up to this date.

3.4.2. Plastic Waste Recycling

There are no reported efforts made by the public sector to tackle the problem of increasing plastic waste and plastic pollution in Khartoum and other states. According to the KSCA officials, there had been trials to manage the plastic recycling by the state; the trials ended up failing due to the informal sorting and recycling activities. The issue of the informal recyclables sorting at the transfer stations and the landfills can be resolved by the installation of proper access controls (fences and gates) and the appointment of watch guards. In addition, the set-up of treatment facilities means recruiting adult informal sorters for manual sorting activities.

In 2017, [6][18] reported that around 37 small-scale private recycling plants are operating in the state of Khartoum. However, the Khartoum State Cleaning Authority (KSCA) had no records of these recycling plants, and thus there is no available information on what type and how much plastic is recycled annually. In an effort to form a better understanding of the plastic waste recycling activities in Khartoum, a random sample of eight (8) private plastic plants representing (21%) of the total stated in the literature were selected by this study to investigate the plastic recycling activities in Khartoum state. This was carried out through a structured survey of ten questions:

1. Is it a privately-owned business?
2. What is the average amount of plastic being recycled (daily/annually)?
3. What are the types of plastic recycled (High Density Polyethylene (HDPE)/Polyethylene Terephthalate (PET)/Polypropylene (PP)/Low Density Polyethylene (LDPE)/Other)?
4. What are the end product/s?
5. What is the market for your finished products (local/international)?
6. Raw material supply (formal/informal, private/public)? Are there supply issues?
7. Do you perform wastewater treatment or any other treatments for undesired streams?
8. Do you know of any environmental policies or regulations imposed on the industry?
9. What are the challenges facing this industry?
10. Additional information.

The survey was filled through face-to-face (12.5%) and telephone interviews (87.5%) with the owners of the plastic plants. Survey results showed that all the currently operating plants are private businesses with an average capacity of (2) tons per day. There are a few larger recycling facilities serving the industrial sector with a capacity up to five (5) tons per day. The annual average of plastic waste processes according to the sample was 6,205 per annum of which 53% was HDPE and PP, and 47% PET. Detailed results are tabulated below:

Table 19: Amounts and types of plastic recycled by the eight plastic plants surveyed in tons:

Recycling plant	Plastic recycled	Daily min.	Daily max.	Annual min.	Annual max.	Annual avg.
Plant 1	HDPE	1	1.5	365	547.5	456.25
Plant 2	PET	3	5	1095	1825	1460
Plant 3	HDPE and PP	2	5	730	1825	1277.5
Plant 4	PET	1	2	365	730	547.5
Plant 5	HDPE	1	1	365	365	365
Plant 6	PET	2	3	730	1095	912.5
Plant 7	HDPE	1	1.5	365	547.5	456.25
Plant 8	HDPE and PP	1	3	365	1095	730
Total	-	12	22	4380	8030	6205

While the amount and the type of plastic varied from one plant to another, the majority of the facilities surveyed (62.5%) reported that the type of plastic recycled is HDPE, two of them (40%) process both HDPE and PP polymers. The HDPE and the PP raw materials, both virgin and secondary, are transformed into useful products through “injection” and “blow molding”.

The plastic products produced vary from household (HH) furniture to kitchen utensils and food containers; the demand for such products is constant in local markets either inside or outside the state. On other hand, only pretreatment (mechanical) processes such as sorting, washing, shredding are applied to the PET and eventually balling in readiness for exportation. The interviewees from the PET recycling plants (37.5%) stated that China was the primary importer but stopped importing plastic since January 2018, shifting the markets to Turkey, Saudi Arabia, and Egypt.

The raw materials (waste) are supplied from the Khartoum as well as other states (30% and 70% respectively). The fluctuation of the supply that is mainly caused by the harvest season given that the main suppliers are in the other states where agricultural activities are dominant and during the scholastic year as many of the waste pickers are school-aged. One interviewee (12.5%) reported being supplied by a waste and scrap collection company.

The survey results showed that the recycling industry is not currently guarded by any kind of environmental law and regulations, where 75% of the interviewed facility owners reported that no water treatment takes place at the facilities; it is instead released to the environment. The percentage of waste in the water stream reached up to 20% according to some, with an average of 10%. Whereas, 25%, cited that they operate a closed-loop system and the only undesired waste stream is the packaging material (solid waste) of the primary and secondary raw material received at the site.

While the recycling sector is not subjected to any environmental regulations, it is heavily taxed and barred from the use of advanced technologies due to some restrictions that are attributed to the energy demand of such technologies that cannot be met. The unsteady electric energy supply posed a challenge for most facility owners.

Figure 14: The PET plastic recycling facility showing the receipt area, the manual sorting line, grinder and the finished product.

3.5. Solid Waste Disposal

The solid waste collected from the different areas of the state ends up in one of the three landfills in each of the three cities of Khartoum, Bahri, and Omdurman, which serve as disposal sites. The operation of the three main landfills is carried out without technical guidelines and insufficient staffing, both qualitatively and quantitatively. The Khartoum landfill, for instance, lacks minimum working conditions standards, such as electric power, paved access roads, site access control, and security. One primary concern is the uncontrolled activities of the waste pickers at and surrounding the landfills; the KSCA is reportedly considering some countermeasures in discussions with the police and social organizations.

Existing landfills in Khartoum state are operating continuously, i.e., they are receiving waste 24 hours a day and 365 days a year. Based on an analysis made in early 2016, it was found that the peak operating time of the landfill is between 11 am to 03 pm, whereas it receives the lowest number of trips from 09 pm to 09 am due to the difficulty of operating at night at the LF site. Hence, the operation time of the landfills will be gradually limited to 16 hours a day from 08 am to midnight. However, the site will continue to operate for 24 hours until proper access controls and security are put in place.

As mentioned previously, all the landfills receive only municipal solid waste except for the Omdurman LF, which accepts both municipal solid waste as well as non-hazardous industrial solid waste. In contrast, hazardous and medical waste (33 tons per day) will be disposed of at the Haskanita landfill located in Umbadda locality. It is worth mentioning that the management of hazardous and medical waste is the responsibility of the KSCA, while the operating costs are borne from hospitals themselves, which amounted to 16 million SDG in the year 2017. Nonetheless, the medical sector encounters the same challenges as the residential sector, where the collection rates are inadequate. It was reported as well that vehicles deployed for the collection of such waste do not meet the safety requirements. Further to that, it was estimated that the landfill would soon reach its maximum capacity, and there is a need for modern incineration plants for the treatment of medical waste. Another major issue in this regard is the plastic medical waste is being illegally collected for recycling regardless of the existing medical waste sorting regulations.

Currently, the landfills at the Khartoum state are considered open dumping sites due to the lack of basic requirements. The Khartoum state master plan identified four different levels of landfills based on the site engineering; where the first level, level (1), is classified as "controlled dumping," the second level (2) is Sanitary landfill with daily bund and cover, level (3) Sanitary landfill with a leachate recirculation system. Lastly, level (4) is a Sanitary landfill with leachate treatment. Further details on the requirements of each level are detailed in the table (20) below:

Table 20: The four different levels of landfills identified by the Khartoum state MP. Source: Khartoum State MP 2016, P. 47.

Landfill requirements	Level (1)	Level (2)	Level (3)	Level (4)
Daily soil cover	✓ (periodic)	✓ (daily)	✓ (daily)	✓ (daily)
Administrative offices	✓	✓	✓	✓
Fences and gates	✓	✓	✓	✓
Embankments		✓	✓	✓
Drainage facility		✓	✓	✓
Gas removal facility		✓	✓	✓
Leachate collection			✓	✓
Leachate re-circulation			✓	✓
Leachate treatment				✓
Liner				✓

Based on the table above (20), it can be noted that the disposal sites in the state do not qualify for level (1) except for the Abu Weleidat landfill in Karari locality. The plan was to operate the sites as level (1) since 2008 and to transition into the level (2) in 2020 for Omdurman and Bahri landfills and year 2021 for the Tayba Elhasanab disposal site. The second level of the sanitary level with daily bund and cover is depicted in sections 2.3.7., figure (9). On the other hand, both level (3) and (4) are deemed unnecessary due to the low rates of rainfall and the mainly hot and dry environment; thus, setting up a system/facility for leachate collection or treatment is an unnecessary cost that can be avoided without compromising the environmental health.

The hot weather in the climate almost all year round causes the organic matter in the landfill cells to degrade fast, leading to excessive methane gas production, which leads to fires. Hence, when conducting improvements to the current landfill or designing future landfills, should include methane gas; also, all landfills should be equipped with fire protection systems and equipment.

The rehabilitation works suggested by the JICA team were not implemented as of August 2020 according to an interview with JICA project coordinator at the MOE and KSCA officials.

3.5.1. Khartoum Landfill (Tayba Elhasanab)

Table 21: The description and the status of the Khartoum landfill (Tayba Elhasanab). Source: MP 2016 and KSCA Interview Sep 2020.

Component	Description
Location	15.3856143 N, 32.5700909 E
Distance from center	25 km to the South of Khartoum city
Land area	21 ha (to be expanded by an additional 20 ha)
Opening year	February 2007
Lifespan	2021 (will be expanded)
Amount of waste disposed per day	2016: 1,200 - 1,700 tons (measured) 2020: 1,903 ton/day (projected) 2028: 3,440 ton/day (projected)
Operated as level (1)	No
Operated as level (2)	No

Tayba Elhasanab landfill, 25 km to the South from the city center, receives waste from Khartoum province that is the Khartoum locality, the capital city, and Jabal Aulia locality. The LF has an area of 21 ha (0.21 km^2), and it is as well surrounded by farms from the northern and eastern sides and residential area of Tayba Elhasanab to the west which is located at around 5 km distance; though the adjacent areas from the south and the west are currently unexploited. The Khartoum LF is the smallest in size compared to the other landfills in the state, even though it receives the most substantial amount of waste of about 1200 – 1700 tons per day. The landfill contains two cells that are closed, one that is currently receiving the waste and a fourth cell currently under construction.

The landfill site is served with an office and was recently equipped with a generator so that the admin staff can work at night; it was to be fenced as part of the JICA project; however, it was found out that the landfill area has expanded beyond the legal limits. The soil cover is not applied on a daily basis. The previous reasons disqualify the Khartoum disposal site from operating at level (1), which is a controlled dumping site. Furthermore, it is not served with paved access, making it difficult to reach during the rainy season.

Figure 15: Khartoum LF and the surrounding land use (1000m). Source: Google Earth.

The remaining capacity as of 2015 was 4,490,130 cubic meters and is estimated to reach its maximum capacity by August 2021. However, in response to a request made by the KSCA, the Khartoum state government leased a neighboring private land of 20ha for a period of 20 years. The expanded area should be operated as level (2) whereas the old site will be improved, in order for it to be operated at least as the first level which is controlled dumping, through equipping it with access controls (i.e., fences and gates) and a weighbridge, and ensure a periodic soil cover for the disposed waste [18].

3.5.2. Omdurman Landfill (Abu Weleidat)

Table 22: The description and the status of the Omdurman landfill (Abu Weleidat). Source: MP 2016, Field visit Sep 2019 and interview Sep 2020:

Component	Description
Location	15.8352808 N, 32.4360237 E
Distance from center	30 km to the North of Omdurman city
Land area	550ha (every 20 ha area should be developed every five years)
Opening year	September 2008
Lifespan	Several decades (±50 years)
Amount of waste disposed per day	2016: 800 - 1,100 tons (measured) 2020: 1,857 ton/day (projected) 2028: 3,179 ton/day (projected)
Operated as level (1)	Yes
Operated as level (2)	No

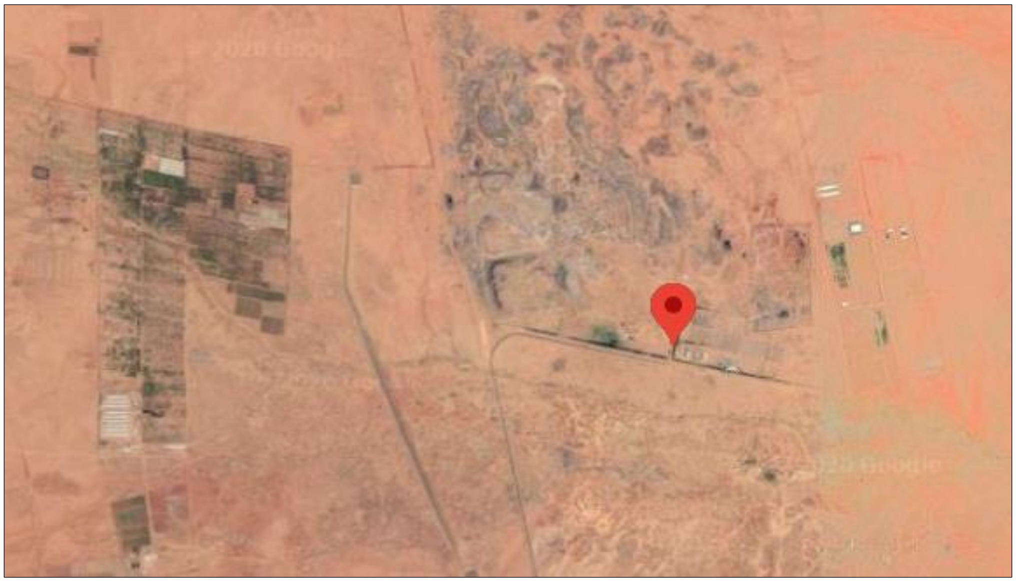

Figure 16: Omdurman Landfill facility and the surrounding land use. Source: Google Earth (1000m)

According to a site visit, the landfill is located 30 km to the North of Omdurman city center over an area of roughly 5.5 km^2, and it contains 39 waste disposal cells (3m depth x 25m width x 310m length). The Omdurman landfill operates 24 per day, and it receives waste from each of Omdurman, Karari, and Umbadda localities; it also receives waste from Khartoum and partly Jabal Aulia localities during the rainy season due to the inaccessibility of the Khartoum landfill (Tayba Elhasanab). The LF site is equipped with a weighing scale and administrative offices, and it is served with the public electricity network under the “services sector” for which the fees are subsidized. Besides, data recording and documentation are relatively better in this site compared to the other landfills.

Figure 17: The figure shows the access to the Omdurman city landfill, the scavengers sorting the waste as it is being offloaded of the collection truck, a bulldozer leveling the freshly deposited waste and some waste vendors inside the premises of the landfill. Omdurman city, Khartoum, Sudan.

The surrounding land uses are from the northern side is a village called Elfadneya, about two km away. The Sudanese Armed Forces (SAF) farms occupy the eastern side of the landfill and another privately owned farm from the west. Elfateh village is situated 5 km to the south of the facility. There are two observation wells, 425 feet deep. They are used to perform biannual tests on the groundwater by the HCE. The test results, so far, showed that the disposal activities had no adverse effect on groundwater. However, the last test was conducted in 2018.

This disposal site is already operated as level (1). Thus, the currently in-use dumping section of the landfill should be covered with soil as final cover once full while the next dumping area, with a planned capacity of nine (9) million cubic meter and a lifetime of around ten (10) years starting from 2020, shall be developed as the second level (sanitary landfill with bund and daily cover).

3.5.3. Bahri Landfill (Hattab)

Table 23: The description and the status of the Bahri landfill (Hattab). Source: MP 2016 KSCA Interview Sep 2020.

Component	Description
Location	15.767951 N, 32.707027 E
Distance from center	25 km to the Northeastern of Bahri center
Land area	770 ha
Opening year	March 2009
Lifespan	Several decades (±50)
Amount of waste disposed per day	2016: 600 - 700 tons (measured) 2020: 1,129 ton/day (projected) 2028: 1,970 ton/day (projected)
Operated as level (1)	No
Operated as level (2)	No

The Bahri landfill (Hattab LF) receives waste from each of Bahri and Sharg Elnil localities that amounts to about 650 tons per day. Despite the fact that this disposal site has the largest size of all, yet, it receives the least amount of waste. This could be attributed to the fact that the waste generation rates at both Bahri and Sharg Elnil localities are low with respect to the other localities; also, the latter has one of the lowest collection rates compared to the other localities (refer to table 11 for detailed figures). Farms and residential areas occupy the surrounding area.

Figure 18: The location Bahri landfill showing the neighboring land use. Source: Google Earth (2000k)

The landfill was initially operated as an open dumping site since 1997. According to the Khartoum state officials, there had been trials to operate it as a controlled dumpsite since 2008 but the trials haven't been successful. On the other hand, according to the JICA plan, it is expected to be transitioned to the next level (sanitary landfill with bunds and daily cover) starting from the year 2021.

3.5.4. Bahri Temporary Dumpsite

Table 24: The description and the status of the Bahri temporary dumpsite. Source: MP 2016, Field visit 2019 and KSCA interview Sep 2020:

Component	Description
Location	15.6755228 N, 32.6035826 E
Distance from center	8 km to the east of Bahri center
Land area	Around 15 ha
Opening year	2015 (to 2019)
Lifespan	Temporary
Amount of waste disposed per day	2016: 200 tons (measured)
Operated as level (1)	No
Operated as level (2)	No

The need for this disposal site emerged due to the operation suspension at Bahri transfer station in 2015 after the receipt of concerns from residents in the surrounding areas. The Bahri pit was initially intended to serve as a transfer station; however, the fact that it did not comply with the minimum design requirements rendered it difficult, and as a result, its function was changed into a temporary disposal site for Bahri and Sharg Elnil localities. Even though it is a temporary site, yet it has been operating longer than planned. Adjacent farms surround the location of this facility, and it is only five (5) km from the city center. Waste dumping in the Bahri pit was finally ceased in late 2019 according to KSCA.

Figure 19: Bahri Temporary Dumpsite. Source: Google Earth (500m). The photo on the right is the taken of the temporary disposal site in November 2018.

CHAPTER (4): MSW TREATMENT SCENARIO

In Khartoum state, residents dispose of waste in a mixed manner; therefore, any short-term treatment plan should take into consideration that the incoming waste (feedstock) of the treatment facility is mixed-waste. The available technologies for the treatment of a mixed waste stream resulting from mixed disposal and collection processes are as follow:

- Mechanical-biological treatment (MBT) is applying a sequence of mechanical treatments for waste sorting, followed by a biological treatment step for the biostabilization of organic waste.
- Incineration is employed for the reduction of waste volume and hazardousness. The heat generated by the process can be recovered and transformed into another form of energy; however, particular types of wastes, i.e., food waste have high moisture content thus are not suitable for incineration in general and energy recovery in particular.
- Landfilling, notwithstanding the engineering improvements and environmental protection measures that can be applied to this method, i.e., liner, soil cover, leachate and gas collection and treatment systems [13].

The solid waste situation in Sudan and especially in Khartoum state, being the most populated city, is critical and requires immediate intervention. In other words, there is a need to make strict policy reforms, pass on new laws and regulations and enforce them, promote waste collection services, design and construct treatment facilities, promote and facilitate recycling startups and design and implement public educational programs.

Given the waste composition available of Khartoum state, it can be noted that the organic fraction makes up to 49.5% of the total quantity produced; therefore, the treatment of the organic waste fraction will divert almost over a million tons of organic waste per year over the next ten (10) years. However, this option entails the recovery of the organic fraction from a mixed-waste stream.

Another feasible scenario for waste treatment in Khartoum is upgrading the three landfills in use into sanitary landfills with the installation of LFG capturing system. This proposal was already included in the JICA project aimed at strengthening the solid waste management in Khartoum state detailed in section 2.2.6. However, the JICA experts opted out from including a leachate collection and treatment system as it was deemed unnecessary due to the low rainfall, low water table at the landfill sites, and low amount of leachate produced. Besides, the LFG will be vented in order to avoid the high investment costs [6].

4.1. Suggested MSW Treatment Scenario

The MSW treatment scenario suggested by this study is the design of a mixed-waste processing facility (MWPF) using a semi-manual recyclables recovery process coupled with an organic waste treatment facility. The selection of this MSW is both disposed of and collected as mixed waste and hence this was taken into consideration when designing the treatment site.

On the other hand, the facility was located adjacent to the Khartoum transfer stations (TS) so as to cut down on the secondary transportation costs partly. Whereas, the transfer station is to continue operating part of the waste generated in the locality of Khartoum due to the large amounts expected in the near future. This proposed facility is expected to recover the three major streams of organic, plastic, and cardboard in addition to metals. There is currently no evidence of glass recycling activities in the country; however, glass has to be negatively sorted along with other possible contaminants to the organic stream. The scenario selected is motivated by the following points:

- Turning waste from an unwanted burden into a valuable resource;
- Provide secondary raw materials to the market (plastic, cardboard, metals, etc.) while the organic fraction can be bio-stabilized and used for landfill cover or other non-agricultural purposes.
- Create more employment opportunities compared to the second option (incineration);
- Establish a basis for recycling and support waste recycling activities by both investors and the private sectors;
- Decreasing the amount of waste sent to the landfills;
- Cut down on waste transfer costs and harmful carbon emissions;
- Exploit the presence of plastic, paper and metal recycling businesses;
- Availability of affordable treatment technologies for the organic waste fraction; and
- Contribute to the overall environmental health and human wellbeing.

The facility is intended to receive a mixed waste stream based on the current collection system in Khartoum state. The processing of the mixed waste stream into valuable secondary raw materials can be achieved automatically through the exploitation of the different properties of materials or semi-manually through the deployment of both process equipment and human sorters. Semi-manual separation was adopted in this design in order to:

- Lower capital investment costs;
- Create job opportunities for the informal sector; and
- Ensure flexibility; ability to change the sorting techniques if needed.

On the other hand, the organic waste treatment facility was designed as an aerobic biostabilization facility for the same motives in addition to the fact that the process is less technically and financially demanding compared to the other available technologies for the treatment of the organic fraction.

Details about the treatment options for organic waste were previously provided in section 2.3.6. For this thesis, the technology selected for the treatment of the organic waste fraction is aerobic biostabilization. It was selected because it represents the second preferred option for organic waste fraction and particularly bio-waste.

Moreover, biostabilization is considered one of the most affordable and least-complex technologies of organic waste treatment. It offers the following advantages:

- It represents a solution for waste management and reduces waste quantities;
- It is perfect for the high organic content in the MSW stream;
- Biostabilization is a simple and cheap technology;
- Provides employment opportunities and income generation activity; and
- It reduces landfill emissions of greenhouse gases (GHGs) and other related adverse impacts.

4.2. Downstream Market for Recyclables

The recyclables sorting facility (MWPF) can either benefit from the direct sales of the recovered recyclables or provide primary treatment of specific waste streams such as PET since it is treated mechanically and baled for exportation. However, this option requires further sorting for plastic and more land area. In this case, no further treatment will be carried out. The main goal of this proposal is to treat the organic waste; however, since organic waste composting is not considered a profitable practice and faced with sustainability issues; the facility is expected to benefit from the recovered recyclables sale to cover partially the operational costs of both facilities.

In order to prepare a feedstock for biostabilization [1], some activities have to be carried out within the facility including:

- Manual sorting of bulky items;
- Manual or automatic separation of recyclables;
- Magnetic separation of ferrous materials;
- Baling for the recyclables;
- Storage of baled materials; and
- Temporary storage of the process output stream.

The materials that are expected to be recovered are bulky items, cardboard, plastics, glass, aluminum and metals. There many different options for the feedstock processing that the designer can choose between depending on the characteristic of the raw materials and the desired results.

The current commercial scale market for the recyclable materials in the state of Khartoum is limited to the plastic, metals (ferrous and nonferrous) and paper. The state market analysis was obtained through brief interviews with waste pickers at the landfill and the transfer station visited in addition to the interview with the KSCA officials and plastic waste recyclers. It was stated that further sorting processes for recyclables (i.e. plastic resins) is unnecessary as waste recyclers purchase mixed plastic and sort different polymers independently. Refer to the table (25) for local market specifications.

Table 25: The market analysis of the recyclables in the state of Khartoum according to interviews with KSCA Officials. Source: Adapted from Dubanwitz, 2000, P. 11.

Material	Market Specification
Paper and cardboard	Baled or loose Clean or with some degree of contamination
Ferrous metals	Baled or loose Flattened or unflattened Labels not removed Some degree of contamination
Nonferrous metals	Flattened, shredded, baled or densified Some degree of contamination
Plastic	Baled, granulated or loose Mixed polymers With or without caps

KSCA future plans to introduce sorting lines at the already-existing and the planned transfer stations; the challenges identified by the KSCA that might hinder the implementation of such technologies are the marketing of the recyclables, secondary raw materials demand, and their ability of operating such facilities sustainably [6]. However, in Khartoum, as per interviews and observation, there is constant market demand for plastics and metals; whereas, the market for other recyclables such as glass, paper and cardboard requires further investigation.

4.3. The Design Process

The design process of the facility was divided into (1) the design of a mixed-waste processing facility (MWPF) for material recovery followed by (2) the design of an organic waste biostabilization facility. The treatment facility is planned to be served with compaction machines in order to accommodate any seasonal or future increase in the incoming amount of waste.

4.3.1. Facility Siting

This facility was located adjacent to the transfer station in Khartoum city. The drives for selecting this site are:

- The Khartoum locality produces the largest amounts of waste compared to the other localities, and hence treating the major part of it will be extremely beneficial.
- The landfill at the Khartoum has the smallest capacity compared to the other two landfills; therefore, treating some of the generated waste will help increase its lifespan.
- The transfer station is located to the south of the Khartoum industrial area.
- The presence of a deserted area adjacent to the transfer station of a minimum of 87,500 square meters.

- The other advantages that this site offers, as opposed to the landfill sites, are that they are served with utilities such as electricity, offices and public water network, road network, fencing, and security.
- Performing waste sorting and treatment near the central station means reducing the amount of waste to be transported to the landfills and as result cutting down on the transportation costs, fuel consumption, vehicle depreciation and carbon emissions. Moreover, treatment process rejects can be transported to the transfer station for secondary transportation.
- The organic waste treatment facility was sited adjacent to the sorting facility in such a way to ensure a smooth flow of the operations. This will eliminate the need to transport the organic material to a separate treatment site.

4.3.2. Mixed-waste Processing Facility

4.3.2.1. Facility Capacity

Based on the estimates made by the JICA team, the Khartoum transfer station was processing an average of 750 ton per day in 2016 [6]. The process is limited to waste compaction and loading onto larger truck for transportation to the disposal site.

The prediction for the year 2020 was 1,183 tons per day, which represents 70% of the waste generated in the Khartoum locality (the capital). Whereas the new transfer in Soba (Southern Khartoum) will be receiving the remaining 30%. This means the maximum capacity for the Khartoum station in currently is around 1,200 tons of waste per day.

The treatment facility was designed with a capacity of 600 tons per day for the next 10 years. An equivalent daily amount of waste, 600 tons, is directly compacted and transported to the disposal sites. Due to the large amount of waste treated, the facility is operated for 18 hours of hours per day divided into three (3) shifts of six (6) hours each in order to decrease the working load on the sorters. Hence, the process rate is around 33 tons per hour.

The amount of waste predicted in 2030 is 2,165 tons per day based on the unit generation rates (UGR) for the city of Khartoum. Future expansion of the treatment facility or the construction of other facilities the station should be designed to accommodate the entire amount of waste. The expected streams quantity according to the 2008 waste composition, are:

Table 26: Waste composition in Khartoum state as reported by the MOE (KSCA in 2008), the expected amount of waste incoming to the transfer station, and the amount of waste addmitted into the treatment facility (in tons per day):

Waste Fraction	Percentage (%)	Expected amounts to the TS	Feedstock to the MWPF
Organic material	49.5	594.00	297.00
Plastic	12.7	152.40	76.20
Paper and cardboard	11.8	141.60	70.80
Dust and ash	13.4	160.80	80.40
Metals	1.7	20.40	10.20
Glass	3.5	42.00	21.00
Cotton and jute	4.6	55.20	27.60
Wood	0.2	2.40	1.20
Leather	0.4	4.80	2.40
Couch	0.3	3.60	1.80
Other	1.9	22.80	11.40
Total	**100**	**1,200**	**600**

4.3.2.2. Selection of the layout

The processing of the incoming waste into valuable secondary raw materials can be achieved through different process equipment using the various physical properties of the different materials in the mixed waste stream. The recovered materials can be processed further depending on the market needs [1].

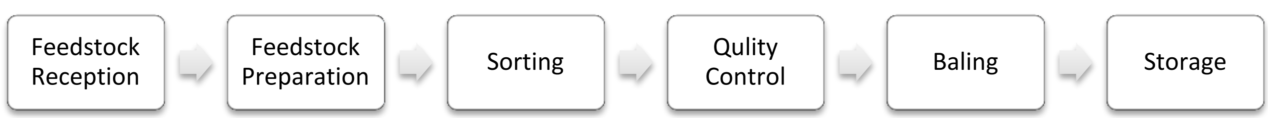

Figure 20: The main processes taking place at the waste sorting facility

The cost and sophistication of the facility depends on the waste sorting method selected and whether any of the materials recovered is to be processed further. The design process of the material recovery facility (MRF) depends on the waste sorting method put in use whether (i) manual (ii) semi-manual or (iii) automatic. Generally, manual separation results in lower treatment rates, costly and unsafe operational conditions, higher process residues, but higher quality material recovery [28]. Common unit processes used in a material recovery facility are listed in table (27):

Table 27: Common methods and equipment used for the processing or recovery of specific waste streams. Source: Tchobanoglous et al. (2000), P.8.17.

Unit Operation	Description
Manual sorting	Manual sorting employs human operators for the removal of specific items from the incoming waste stream. It can either be applied for the removal of bulky items and sorting of the different materials positively or negatively off of a conveyor belt system.
Automated sorting	Automatic sorting employs the physical characteristics of the different materials for separation such as the NIR for the separation of mixed plastic resins.
Size reduction	Unit operation used for reducing the size of materials either the incoming waste stream or a recovered waste stream.
Size separation	Through this unit operation, different waste materials can be separated using their size or shape. Typically, screens are used for this purpose.
Magnetic field separation	Unit operation used to separate ferrous or magnetic materials.
Densification (compaction)	Densification is used to increase the density of materials either to reduce the transportation costs or to make storage and material handling easier.
Material handling	Unit operations used for transporting and sorting the incoming waste stream or a recovered waste stream such as conveyor belts, loaders and trucks.

Recovery Factor Transformation Function (RFTF) Matrix

For the design and selection of the material recovery facility layout, the Recovery Factor Transformation Function Matrix (also known as the RFTF matrix) was used. The RFTF matrix, through the application of the concept of mass conservation, has factors specifying the fraction of each component of the waste; i.e. ferrous metal, nonferrous metal, glass, paper, plastic, fines, wood, and organic, retained in the primary stream and the amount of material remaining in the secondary stream after unit processing [29]. While the factors are to be determined based on field data, representative values of the RFTF matrix are reported in table (28); please note that the letter “D” refers to dry material whereas the letter “M” refers to the moisture content in the given waste stream:

Table 28: The factors of the RFTF matrix listed for different unit process. Source: Grosso, 2017.

Equipment	D&M	Ferrous metal	Nonferrous metal	Glass	Paper	Plastic	Fines	Wood	Organic
Bag opener	D	1	1	1	1	1	1	1	1
	M	1	1	1	1	1	1	1	1
Primary shredder	D	1	1	1	1	1	1	1	1
	M	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Drum screen (fine)	D	0.8	0.8	0.2	0.85	0.9	0.25	0.5	0.25
	M	0.8	0.8	0.2	0.85	0.9	0.25	0.5	0.25
Drum screen (coarse)	D	0.41	0.37	0.01	0.69	0.62	0.02	0.2	0.11
	M	0.41	0.37	0.01	0.69	0.62	0.02	0.2	0.11
Air classifier (shredded waste)	D	0.1	0.8	0.7	0.98	0.98	0.2	0.7	0.7
	M	0.41	0.37	0.01	0.69	0.62	0.02	0.2	0.11
Air classifier (nonshredded waste)	D	0.1	0.5	0.02	0.98	0.98	0.15	0.4	0.4
	M	0.09	0.45	0.018	0.882	0.882	0.135	0.36	0.36
Magnetic Separator	D	0.2	1	1	0.98	0.98	1	1	0.95
	M	0.2	1	1	0.98	0.98	1	1	0.95

Equipment	D&M	Ferrous metal	Nonferrous metal	Glass	Paper	Plastic	Fines	Wood	Organic
Secondary shredder	D	1	1	1	1	1	1	1	1
	M	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Ballistic separator	D	0.1	0.8	0.7	0.98	0.98	0.2	0.6	0.6
	M	0.1	0.8	0.7	0.98	0.98	0.2	0.6	0.6
Eddy-current separator	D	0.9	0.1	1	0.98	0.98	0.95	0.98	0.98
	M	0.9	0.1	1	0.98	0.98	0.95	0.98	0.98
Densifier, extruder, pelletizer	D	1	1	1	1	1	1	1	1
	M	1	1	1	1	1	1	1	1

The factors of the matrix were multiplied by the incoming stream to each unit process in order to obtain the average values recovered by each equipment. The coefficients reported in the matrix can be applied on both day matter and moisture content [30].

For the design of this treatment plant, in order to estimate the moisture losses resulting from the deployment of some of the MBT equipment; typical moisture content values were obtained from [31]. Also, the municipal solid waste composition reported by the KSCA were adapted to the fractions listed in table (28) in order to calculate the moisture losses of the different MBT equipment employed; the resulting values are listed in the table (29). It should be noted that in order to adapt the waste composition to the reported waste fractions, the assumptions below were made:

1. Bulky waste (cardboard, leather and couch) were assumed to be presorted with a high efficiency rate along with the “other” waste stream.
2. Both cardboard and nonferrous metals were assumed to be 46.64% and 25.66% of the “paper and cardboard” and the metal streams respectively.
3. Fines are comprised of the “dust and ash” waste fraction.
4. Organic waste fraction is made up of “organic waste” and “cotton and jute”.

The values reported in the columns named “moisture content” were calculated by simply multiplying the moisture content percentages by the incoming waste quantity. The “dry material” values were then obtained by subtracting the resulting moisture values from the initial amounts reported in the first column.

Table 29: Adapted waste fractions and typical moisture content values (in tons per day).

Waste Fraction	Rate	Moisture Content (%)	Moisture Content	Dry Material
Ferrous metal	7.58	3.00%	0.23	7.36
Nonferrous metal	2.62	2.00%	0.05	2.56
Glass	21.00	2.00%	0.42	20.58
Paper	37.78	6.00%	2.27	35.51
Plastic	76.20	2.00%	1.52	74.68
Fines	80.40	25.00%	20.10	60.30
Wood	1.20	20.00%	0.24	0.96
Organic	324.60	70.00%	227.22	97.38
Other	11.40	30.00%	3.42	7.98
Total	**562.78**	**45.39%**	**255.47**	**307.31**

Multiple layouts were examined for the recovery of recyclables and produce a mainstream of mainly organic fraction for the subsequent treatment process. All of the examined treatment layouts were preceded by a manual separation process for bulky items and hazardous waste and were concluded by a size reduction step in preparation for the aerobic treatment.

The different layouts examined both semi-manual and automatic sorting lines. Fully-automated mechanical sorting lines can be used for the production of compost; yet, shredding waste prior to the removal of contaminants such as metal and glass will result in the production of poor-quality compost. Alternatively, manual separation of recyclables off a conveyor belt prior to shredding can be used for the production of compost feedstock [1]. Therefore, automated sorting lines were eliminated from comparison not only for the compromised quality of compost but also for the higher energy consumption and capital cost required for setting up a fully-automated plant for mixed waste processing. The summary of the different layouts are reported in the table (30):

Table 30: Comparison between the different layouts of the material recovery facility (amounts in tons/day) and energy consumption in (MWh/year).

Layout	Recovered recyclables	Rejects to be disposed	Remaining to be composted	Compostable material	Compostable (%)	Avg. Energy Consumption
Layout 1	107.05	74.57	359.14	348.18	96.95%	1763.84
Layout 2	109.43	86.82	344.98	334.84	97.06%	1781.47
Layout 3*	122.69	16.56	400.28	386.81	96.64%	1896.36
Layout 4*	128.34	16.46	394.74	385.39	97.63%	1874.39
Layout 5*	129.10	10.21	400.02	390.24	97.56%	2006.35

*Each treatment layout includes a two-stage manual sorting process

It can be noted from table (30) above that the different layouts can be compared in many areas including the amount of recyclables recovered and the amount of material rejected; in which layout (5) is the best performing. Conversely, it consumes more energy compared to the other available options. On the other hand, layout (4) offers a relatively high amount of recovered material as compared to the each of layouts 1, 2 and 3 and it is performing relatively well in terms of energy consumption in comparison with the other designed layouts. Thus, layout (4) was selected as for the design of this facility. The detailed description of the layout and the design steps are detailed in following section.

Selected semi-manual material recovery facility layout

1. Receiving area (manual separation of bulky items and other items)
2. Bag opening (bag breaker)
3. Manual separation of recyclables (elevated conveyor belt)
4. Sieving (drum screen)
5. Manual separation of recyclables (elevated conveyor belt)
6. Ferrous metal separation (magnetic separator)
7. Size reduction (primary shredder)

The manual sorting process of the marketable waste materials is carried out in three different stages, over the receiving area (the tipping floor) mainly for the removal of bulky items. The second stage following the bag opening process and the last following material sieving. Manual sorting takes place along conveyor belts whereas recyclables are collected in bins that placed below the conveyor in order to be stored temporarily for sale. It should be noted that compaction and baling of recyclables is not a market requirement; nonetheless, they should be carried out for easier handling and transportation of the secondary materials.

Following this stage, the resulting stream is expected to mainly contain organic material. Downstream the conveyor belt, a ferrous metal separator is installed followed by a primary shredder for material size reduction for the production of a more homogeneous material and the enhancement of the organic treatment process. The organic waste stream is to be transported directly to the biostabilization pad using loaders (windrows construction machines).

1. Receiving area/tipping floor (primary manual sorting process)

The mixed-waste is delivered to the facility straight from the collection trucks into the receiving area where the manual presorting activities are to take place before the waste is loaded through inclined conveyor belts to the first unit process operation. The presorting activities taking place at this stage are intended for the removal of bulky items (e.g. lumber, white goods, cardboard, and broken furniture and oversized items) [1]. The amount of materials that is expected to be recovered at this stage of the process is about 37.22 tons per day. It comprises mainly cardboard, leather, and couch based on the waste composition in the state. According to the waste composition presented by the EWASCO in 2013 (reported in table 8) the cardboard represents 46.6% of the "paper and cardboard" stream. This percentage is used here to estimate the amount of cardboard recovered at the facility. It is also assumed that the "other" waste fraction is separated at this stage of the process, which amounts to 11.4 tons per day.

The receiving area, also known as the tipping floor, is designed to accommodate and temporarily store a 2-day amount of fresh waste. The bulk density in Khartoum state is 0.5 tons per cubic meter according to the JICA [20] while according to the study carried out by the Energy and Waste Treatment Services Company (EWASCO) in several quarters which value varied between 0.124 – 0.191 tons per cubic meter [24]. However, due to the study limitations mentioned previously, the density reported by the JICA was adopted (please refer to section 2.3.4. for study limitations). The size of the tipping floor was calculated based on the following equation:

$$\frac{\boldsymbol{Rate\ of\ feedstock\ delivery}}{\boldsymbol{Waste\ density}} = \frac{\mathbf{600}\ (\boldsymbol{ton/day})}{\mathbf{0.5}\ (\boldsymbol{ton/m^3})} = \mathbf{1,200}\ \boldsymbol{m^3/day}$$

$$Receivng\ area\ volume\ (m^3) = volume\ of\ feedstock\ \left(\frac{m^3}{day}\right) \times numberof\ days\ (days)$$

$$= 1,200(m^3/day) \times 2\ (days) = 2,400\ m^3$$

The receiving area should be enclosed to limit the offensive odor generation. Front-end loaders are used to load the waste material into conveyor belts for successive process unit operation.

2. Bag Breaker

The function of this machine is to rip the bags open and free the waste material for subsequent operations. It offers an advantage of high throughput of the material and low energy consumption of (2 – 4 kWh/ton) [30]. Bag breakers are placed upstream the process instead of shredders so as to reduce the damage to the to the incoming waste for an easier manual separation process and in order to increase the recovery rates and reduce the contamination of the organic fraction with broken glass.

Table 31: The amount of input and output from the bag breaker:

Waste Fraction	Ferrous	Aluminum	Glass	Paper	Plastic	Fines	Wood	Organic	total
Input	7.58	2.62	21.00	37.78	76.20	80.40	1.20	324.60	551.38
Dry matter	1	1	1	1	1	1	1	1	-
Moisture content	1	1	1	1	1	1	1	1	-
Output	7.58	2.62	21.00	37.78	76.20	80.40	1.20	324.60	551.38

Alternatively, rotary (trommel) screens with blades can be installed in order to eliminate the need for placing a bag breaker upstream; thus cutting down on the energy consumption as well as the capital and operational costs of the treatment site. The rotating drums are found in different lengths, diameters and speed, and mesh dimensions between 5 – 20 centimeters. The waste is loaded on the higher end of the cylinder and carried to the other end by gravity. The rotary movement of the drum increases the contact between the waste and the inner surface of the cylinder resulting in an enhanced screening process. The small-sized particles fall off through the drum mesh while the coarse material continues to the other end. A clogged trommel screen can be cleaned through an air jet [30]. This option was eliminated due to the damage it can cause to the waste stream.

3. Conveyor Belt (secondary manual sorting of recyclables)

According to [1], the widespread conveyor belts system is elevated belts with sorters and storage bins on the sides and ensuring a suitable distance between one sorter and another. In addition, the belt speed should be set to a suitable value in order to enable sorters to achieve higher recovery efficiency without considerably compromising the overall speed of the process. The other two factors that would influence the sorting quality are the sorter skills and worker fatigue. Training can be provided for the sorters in order to ensure better quality while and working conditions improved to reduce or eliminate worker fatigue.

Following bulky items removal, the material is then loaded into the conveyor belt system using font-end loaders. At this stage, marketable recyclables such as paper, plastic, metal, and aluminum and tin cans are positively sorted from the waste stream by human operators (also known as sorters) and deposited into bins leading to large material storage containers. The sorting efficiencies reported in table (32) were applied to estimate the amounts of recyclables recovered. It should be noted that glass waste has no proven market in Sudan but it must be removed in order to reduce contamination of the organic material. Therefore, additional sorters can be recruited for the negative sorting of glass and other contaminants from the organic waste stream.

Plastic polymers are to be sorted and collected in a mixed manner because of the flexible market requirements as well as the aluminum and tin cans. Since there is no reported market for glass, it is to be separated and transported to the disposal site along with other process rejects.

Table 32: Manual material sorting expected rates in (ton/person/day) and efficiencies. Source: Tchobanoglous et al. (2000) [1] [32]

Material	Range	Average	Recovery Efficiency
Mixed Paper	8.36 – 13.05	7.58	60 – 95 %
Mixed Glass	1.02 – 16.11	8.28	80 – 98 %
Mixed Plastics	0.60 – 3.21	1.60	80 – 98 %
Aluminum and tin cans	1.21 – 17.53	6.06	85 – 95 %

The daily quantity of the incoming is expected to be 551.38 tons of waste; whereas the amounts recovered amounted to 2.22, 16.80, 22.67, and 60.96 of aluminum cans, glass, paper and plastic respectively totaling 102.65 tons. The length of the conveyor belts can be based on the incoming waste quantity and the number of staff needed. Additionally, parallel conveyor belts should be installed with enough space between them. The energy consumption of conveyor belts falls between 0.3 – 0.9 kWh/m, according to [30].

4. Drum Screen (fine)

The resulting stream, which is expected to contain mainly organic materials, was passed through a screening step. The incoming waste screening was carried out using a rotating drum screen. This step is deemed necessary in order to eliminate the other undesired impurities such as small-sized pieces of plastic and glass, etc. The rotating drums are found in different lengths, diameters and speed, and mesh dimensions between 5 – 20 centimeters. The waste is loaded on the higher end of the cylinder and carried to the other end by gravity. The rotary movement of the drum increases the contact between the waste and the inner surface of the cylinder resulting in an enhanced screening process.

The small-sized particles fall off through the drum mesh while the coarse material continues to the other end. A clogged trommel screen can be cleaned through an air jet [30].

Table 33: The input and output streams from the drum screen.

Waste Fraction	Ferrous	Aluminum	Glass	Paper	Plastic	Fines	Wood	Organic	total
Input	7.58	0.39	4.20	15.11	15.24	80.40	1.20	324.60	448.73
Dry matter	0.8	0.8	0.2	0.85	0.9	0.25	0.5	0.25	-
Moisture content	0.8	0.8	0.2	0.85	0.9	0.25	0.5	0.25	-
Primary stream	6.07	0.31	0.84	12.84	13.72	20.10	0.60	81.15	135.63
Secondary stream	1.52	0.08	3.36	2.27	1.52	60.30	0.60	243.45	313.10

The mainstream resulting from the sorting process is passed through the second stage manual sorting process for the separation of recyclables mainly plastic and paper. The remaining stream is sent to a ferrous metal removal step along with the secondary stream.

5. Conveyor Belt (tertiary manual sorting of recyclables)

Similar to step secondary manual sorting, the estimation of the amount of recyclables sorted was obtained by applying the recovery efficiencies reported in table (32).

The incoming waste quantity to the secondary manual sorting step is 135.63 tons of waste. The sorted cans, glass, paper, and plastic amount to 0.27, 0.67, 7.71 and 10.97 tons consecutively totaling 19.62 tons of recyclables per day.

6. Magnetic Separator

The mainstream exiting the drum screen together with the remaining stream from the secondary manual sorting process are fed to a magnet separator for the recovery of ferrous metal. Magnetic separation is the most common technology for ferrous metal removal through a permanent magnet or an electromagnet with a very high recovery efficiency reaching up to 97%. The recovered amount of ferrous metal expected is:

Table 34: The input and output streams from the magnet separator:

Waste Fraction	Ferrous	Aluminum	Glass	Paper	Plastic	Fines	Wood	Organic	total
Input	7.58	0.13	3.53	7.40	4.27	80.40	1.20	324.60	429.11
Dry matter	0.2	1	1	0.98	0.98	1	1	0.95	-
Moisture content	0.2	1	1	0.98	0.98	1	1	0.95	-
Primary output	1.52	0.13	3.53	7.26	4.18	80.40	1.20	308.37	406.58
Secondary output	6.07	0.00	0.00	0.15	0.09	0.00	0.00	16.23	22.53

The recovered amount of ferrous metal with a removal efficiency of 80% is 6.07 tons per day recovered in the secondary stream; the remaining of which is sent to disposal along with other process rejects. The remaining amount of ferrous metals in the main stream amounts to around 1.52 tons per day (0.37%). The mainstream resulting from the magnet separator is sent to the following process unit operation.

7. Shredding

Shredding plays a key role for the enhancement of the biodegradation process [8]. Size reduction is also deemed necessary as the incoming waste comprises yard waste and wood, which serve as structuring material, and they are as well essential for achieving a required level of porosity.

A primary shredder, specifically high-speed hammer mills, offers an advantage of a high input of the material, whereas the output can be around 30 – 300 mm and around 7 – 15 kWh per ton of energy consumption [30]. In practice, however, there is a minimum size below which it is exceedingly difficult to maintain an adequate porosity in a composting mass. The particle size of the greater part of a fresh green plant mass, such as vegetable wastes, fruits, and lawn clippings, should be no less than 50 millimeters. On the other hand, depending upon their overall decomposability, their maximum particle size can be as large as 0.15 meters or even larger [1]. Size reduction is necessary for green waste; however, it is also crucial for ensuring the homogeneity of the organic mass.

Table 35: The input and output streams from the primary shredder:

Waste Fraction	Ferrous	Aluminum	Glass	Paper	Plastic	Fines	Wood	Organic	total
Input	1.52	0.13	3.53	7.26	4.18	80.40	1.20	308.37	406.58
Dry matter	1.47	0.12	3.46	6.82	4.10	60.30	0.96	92.51	169.74
Moisture content	0.05	0.00	0.07	0.44	0.08	20.10	0.24	215.86	236.84
Dry matter	1	1	1	1	1	1	1	1	-
Moisture content	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	-
Output	1.51	0.13	3.52	7.23	4.18	79.40	1.19	297.58	394.74
Dry matter	1.47	0.12	3.46	6.82	4.10	60.30	0.96	92.51	169.74
Moisture content	0.04	0.00	0.07	0.41	0.08	19.10	0.23	205.07	224.99

The RFTF coefficients have been applied to the incoming waste stream to the primary shredder in order the estimate the moisture losses taking place at this stage of the process. Moistures lost is estimated to equal 11.84 tons of moisture. The resulting stream 394.74 tons of waste, of which 97% (around 358.39 tons) is compostable, is sent to the organic waste treatment facility.

4.3.2.3. Summary of the sorting process

The overall material recovery process can be summarized as follows:

Table 36: The table provides the summary of the sorting facility:

Overall Sorting Process			Recovered Material			To Aerobic Treatment		
Recovered material	128.34	23.28%	Organic	385.39	97.63%	Metal	8.56	6.67%
To aerobic treatment	394.74	71.59%	Metal	1.64	0.42%	Glass	17.47	13.61%
Process rejects	16.46	2.99%	Glass	3.52	0.89%	Paper	30.37	23.67%
Moisture loss	11.84	2.15%	Plastic	4.18	1.06%	Plastic	71.93	56.05%
Total	**551.38**	**100.00%**	**Total**	**394.74**	**100.00%**	**Total**	**128.34**	**100.00%**

4.3.2.4. Material balance of the facility

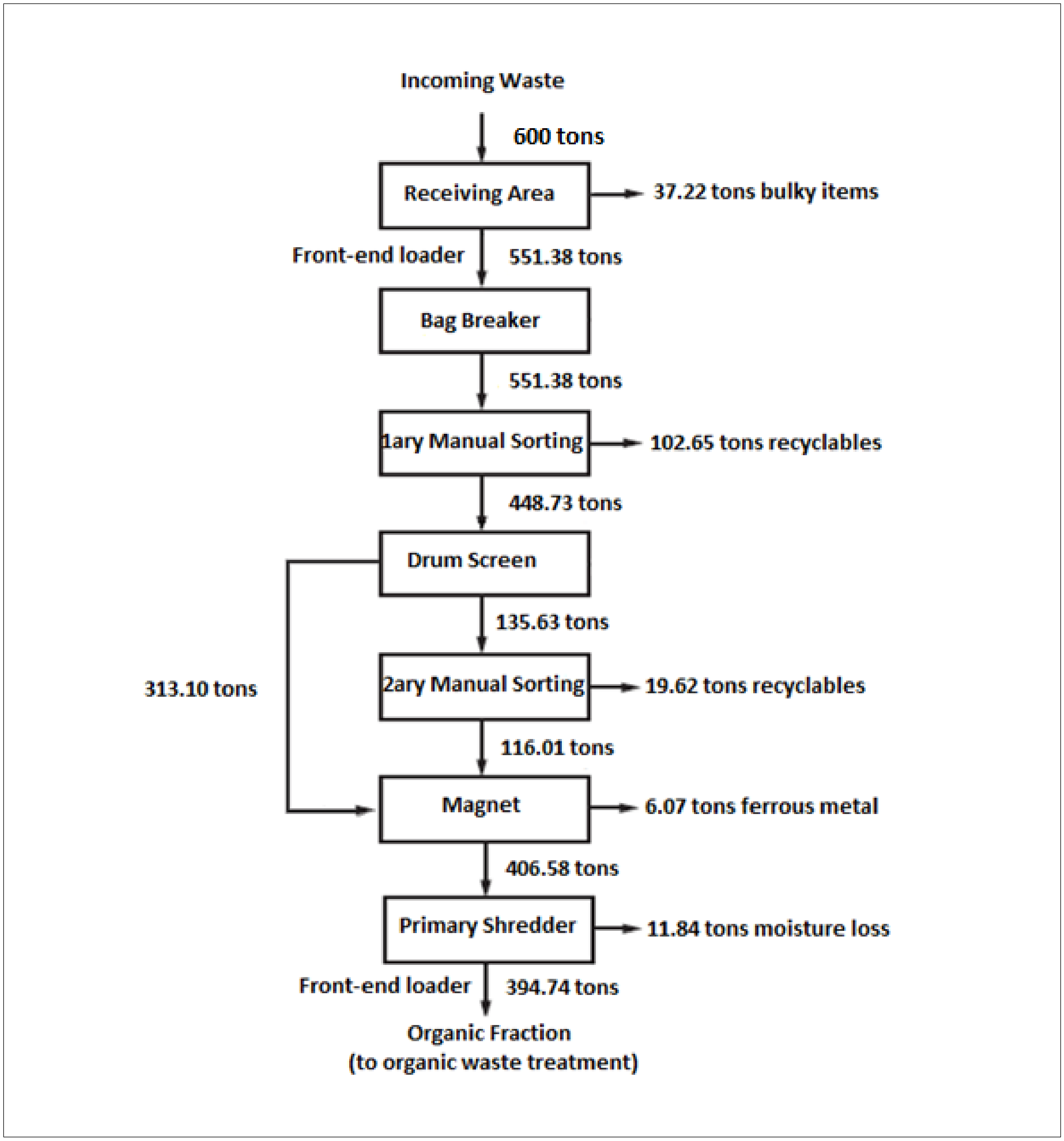

Figure 21: Flowchart of the mixed-waste processing facility (MWPF)

4.3.3. Organic Fraction Treatment Facility

This study suggests focusing on the treatment of the organic waste stream through the design of a large-scale biostabilization plant in the Khartoum locality to divert the largest waste stream as well as material recovery. The biostabilization process is considered one of the most affordable technologies of waste treatment and one of the least complex processes.

4.3.3.1. Selection of the Biostabilization Technology

Overview of the biostabilization process

Polprasert [33] defined the biostabilization treatment process as the biological decomposition of organic materials in the presence of oxygen (air), producing carbon dioxide (CO_2), Ammonia (NH_3), water (H_2O) and heat. This process is preferred to anaerobic treatment due to the amount of heat (thermophilic level temperature) produced that can treat larger amounts of organic materials at a faster rate. The system, in general, is also easier to operate; hence it represents a feasible option in the developing countries [33].

To regard the process in terms of mass balance, a single (1) ton of feedstock is expected to contain 10 – 20% of residues from sorting and screening activities while the finished compost will amount to 35 – 40% of the process input. The remaining 40 – 55% is equivalent to the weight loss due to the degradation of the organic matter, the loss of moisture through evaporation, and, lastly, from the gaseous emissions [10].

The biodegradation process can be expressed using the chemical equation below which means that the organic material will breakdown with the presence of oxygen and microorganisms to and carbon dioxide, water, and heat will be released; as a consequence, the material will be stabilized, sanitized and mineralized [34].

$$[CH_2O] + O_2 \rightarrow CO_2 + H_2O + \text{ENERGY}$$

Biostabilization proceeds in three main stages; namely, (1) lag phase, (2) active phase, and (3) maturation (curing) phase. Different processes that take place within the waste heaps characterize the phases of the composting process; but in practice, they are marked by the rise and fall in the heap temperature. The temperature profile would result in a curve that is similar to that of the biological activity (growth curve) [1].

The very first phase of the process is the lag phase, which starts shortly after the favorable environment for the microbes' growth is set. The microorganisms start breaking down the organic materials in the waste to release the nutrients essential for its growth, and as a result, the temperature increases. The lag period is remarkably brief, especially with the presence of highly putrescible materials as well as porous ones, i.e., yard waste.

The second phase is the active composting (ACT) which is characterized by the increased microbial activity and mass and the consequent a rapid increase in the temperature within the heaps. The temperature will only start decreasing when the easily decomposable materials are decreased; the temperature can rise to up to 70°C unless otherwise controlled by the operators. The duration of this phase can be somewhere between a few days to a few weeks depending on the environmental and operational conditions and feedstock characteristics. Thus, in order to shorten the ACT duration, the feedstock and the operational conditions need to be amended. The two most critical operating conditions for this phase would be the moisture content and the oxygen supply.

Lastly, maturation phase is marked by a slow microbial activity, or in other words, a decreased oxygen consumption rate. In practice, the temperature is sharply decreased until ambient temperature is reached. Again, the duration of this stage of the process depends on the substrate and the environmental and operational conditions, meaning that it can be as brief as a few weeks or longer. It is worth mentioning that this phase is less demanding in terms of process control [1][34].

The environmental factors adjusted through the employed technology (or the choice of control parameters) affect the course of the process. In addition to that, the process can also be hindered or slowed down by specific factors, e.g., toxins; the process can be restarted by eliminating these factors. The factors that render the composting process risk to the environment include the feedstock of the process (green wastes as well as animal products and wastewater sludge) and the location of the facility; however, the proper design and operation can be manipulated in such a way to reduce the associated negative impacts.

Polprasert et al. [33] cited that a large-scale composting is a multifaceted process that requires appropriate design and management and defined a well-designed composting process in seven steps:

i. Feedstock recovery;
ii. Feedstock preparation;
iii. Composting;
iv. Stabilization;
v. Curing;
vi. Refining; and
vii. Storing.

The first step of the design is the separation of the compostable material from the incoming waste stream. The preparation of the feedstock is to mix and shred the separated compostable stream from the into a smaller particle size so as to enhance the biological activity; moreover, this step provides a more homogenous feed in terms of nutrients and moisture content. After this step, the operator should achieve a particle size of around 5-25 mm, C/N ration of 30 to 45, and a moisture content of 60 to 65% [33]. The three following steps of composting, stabilization, and curing are the stages during which the operator should control the operating condition in order to guarantee the biological degradation is taking place to ensure the stabilization or the slowing down of the microbiological activity. The refining process simply means the removal of any undesired contaminants such as screening and metal separation in preparation for the final step of packaging and storing. Polprasert et al. added that the poor sizing or design of the composting facility lead to the commonly faced challenges of a poor-quality product, high operation cost, operating below or above design capacity, and offensive odor nuisances [33]. Also, Salvato et al. highlighted some of the major issues related to the composting processes, which are (1) the generation of odors, (2) presence of pathogens in the finished product, and (3) heavy metals and (4) constituents of compost. The odor generation can become problematic to the process if control measures are not put in place, especially in a windrow composting facility. The critical factors in odor control are the location of the treatment plant, proper design process and operation, and odor management system [8].

Composting is performed in several ways; however, central commercial plants are classified as off-site composting as the process involves the collection and transportation of feedstock to the treatment site. In addition, depending on the operation mode, it can be classified as manual or mechanical composting. For such a scale, and due to the incoming waste quantity, it is recommended to operate an aerobic process to reduce the process duration and land use [33]. Over the past century, over 50 different composting technologies have been developed; however, the most basic and standard processes [8] [1] are:

- Static windrow piles;
- Aerated static piles; and
- In-vessel composting process.

1. Static windrow piles

In this step of the process, the waste is piled in 1 – 2 meters high and 2 – 5 meters wide rows that are placed far enough (spaced) to allow the movement of the operators and any required machinery. The windrows are usually placed in the open subjected to air and is turned mechanically with an adequate frequency such to ensure aerobic conditions in a pile throughout the active composting phase. The decomposition process can be enhanced by increasing the frequency of turning. The process takes somewhere between two to six (2 – 6) months to finish. Offensive odors can be generated as a result of the development of anaerobic conditions within the piles [8].

2. Aerated static piles

The name of this process comes from the type of mechanical aeration system in use. Mostly, the organic waste piles are placed on a cemented pad, which is equipped with a grid of pipes that inject air into the static waste piles. Wood chips are placed before the organic waste to ensure uniform aeration as well as a cover of finished compost to serve as an external layer. Lastly, the expelled air is typically passed through a bio-filter for odor control [8].

3. In-vessel composting

The composting process is carried out in an enclosed reactor or a container that can theoretically have any desired shape. In-vessel composting can categorize as plug-flow or dynamic operations depending on whether the process is batch or continuous. This technology enables the operators to have better control of the process conditions as well as odor control. Due to the possibility of controlling temperature and airflow, the composting process is typically faster, and the detention period falls in the range of one to two weeks of active composting [8].

In conclusion, the first technology (static windrow piles) was selected for the design of this facility due to the reportedly lower investment costs and the lower technical demand.

4.3.3.2. General Design Considerations

Such a large facility should be operated with a relatively high degree of mechanizing (automation) and instrumented adequately in order to ensure the sustainability and the feasibility of the process. According to Salvato et al., composting facilities should comprise an enclosed building with concrete floors, enclosed composting reactors, and an enclosed facility for the curing phase of the process in addition to machines for packing as well as a good marketing plan for the finished products [8].

The composting pad should be designed with a slight slope so as to allow the drainage of the liquid discharges from the waste piles and the possible rainfall in addition to and a small basin for leachate collection as it is not expected to be produced as stated earlier. Moreover, the pad area can be roofed to prevent rainwater from accumulating between the compost piles, as flooding can create anaerobic conditions, which will contribute to the problem of odors and the elongation of the composting period as a result of the increased humidity; also, flooding can impede accessibility and consequently cause operational difficulties. Most importantly, covering the composting/curing pad (roofing) offers an economic benefit of decreasing the amount of leachate to be treated at the facility level [35]. This applies to the receiving, composting and curing and storage areas.

The access roads within the facility should be designed in such a way to facilitate the movement of heavy equipment and allow their backward movements. Protection should also be offered to the equipment, for example, a fenced area or 24-hour security watch when they are not operational or broken-down.

4.3.3.3. *Process Flow*

The aerobic digestion plant consists of four main steps, including (1) pre-treatment, (2) active composting, (3) maturation, and (4) post-treatment. Some of these steps comprise a few processes; a detailed process flow is depicted in figure (22) below. Additionally, the facility should include other additional areas such as offloading area, storage area, and facility offices.

Figure 22: The layout of the biostabilization facility designed for organic waste treatment in the Khartoum locality.

1. Pre-treatment

The pretreatment of the organic waste stream is size reduction taking place following the recyclables recovery process. At this initial stage of the composting process, feedstock preparation can take place such as seeding, nutrient addition, and addition of bulking agent [8].

2. Active composting area

The area of the active composting depends on the type of the composting process. For this case of turned windrow composting method, around 0.8 square meters is sufficient to accommodate a single cubic meter of raw material [35] with an additional buffer to accommodate any fluctuations in the incoming waste as well as for the operating equipment. It is advised to carry out the active composting phase in an enclosed area [34].

The composting process can be accelerated if the waste windrows are turned over every few days. The heaps need to be turned every two days in order to meet the Environmental Protection Agency's (EPA) requirements of waste sterilization. Under typical operating conditions, the windrows are turned every other day [8][1].

3. **Compost curing area (Maturation)**

The curing period (also called the maturating phase) is when the organic matter starts turning into humus-like materials. The stage can be performed at the same place as the composting; however, there should be enough space between the two in order to prevent cross-contamination of the roughly done material with the incoming raw waste; moreover, this process can be carried out in an open space unlike the previous [1][34].

4. **Post-treatment**

Once the biological processes are finished, and the final product is ready, a few further steps are required in order to make it safe for use. A magnetic separation step might be necessary for the removal/reduction of ferrous metals existing in the feedstock, followed by a screen and an air classifier [8].

The unwanted residuals from the screening processes at the composting facilities, as well as from the sorting facility, are to be transferred to the Khartoum landfill (Tayba Elhasanab LF) for disposal whereas the finished compost is to be transferred to the next step of storage.

The biostabilization facility layout should include an enclosed area for the storage of the finished product, and it should be constructed in such a way to allow ventilation.

4.3.3.4. Biostabilization Facility Sizing

In order to calculate the land area to be occupied by the treatment facility, many factors have to be considered, such as areas required for pretreatments, feedstock and product storage, composting, maturing, post-treatment and facility offices; also, more land area is required for the operation of these processes. On the other hand, the land area required for the actual composting process is influenced by many factors including the volume of the feedstock, the space the windrows are to occupy, additional space to accommodate the material handling equipment, and lastly the total area occupied by the composting plant as a whole [1]. Thus, the first step is to calculate the total volume of the incoming waste. For this, the following equation is used:

$$= \frac{[\boldsymbol{retention\ time\ (days)} \times \boldsymbol{rate\ of\ waste\ delivery}\ (\frac{\boldsymbol{kg}}{\boldsymbol{day}})]}{\boldsymbol{bulk\ density}\ (\frac{\boldsymbol{kg}}{\boldsymbol{m^3}})}$$

The biostabilization facility receives mainly an organic fraction of 394.74 tons a day, which is expected to be contaminated by dust, ash, broken glass, small metal parts, and other small-sized contaminants that attach to the organic matter and paper fractions. The facility was designed in order to accommodate up to 132,237 tons annually of compostable waste. The waste composition at the composting facility (CF), based on the prior sorting process, is as follows:

Table 37: The composition of the incoming waste (tons per day) to the composting facility is expected to be as follows:

Waste Fraction	Expected amounts	Percentage (%)
Ferrous metal	1.51	0.38%
Nonferrous metal	0.13	0.03%
Glass	3.52	0.89%
Paper	7.23	1.83%
Plastic	4.18	1.06%
Fines	79.40	20.11%
Wood	1.19	0.30%
Organic	297.58	75.39%
Total	394.74	100.00%

It should be noted that the density of the feedstock is expected to be higher than that of the fresh waste (0.5 ton/m^3) due to shredding; a value of 0.6 ton/m^3 was used for the entire process. Therefore, the volume of the incoming waste is calculated according to the following equation:

$$\frac{\boldsymbol{Rate\ of\ feedstock\ delivery}}{\boldsymbol{Waste\ density}} = \frac{\mathbf{394.74}(\boldsymbol{ton/day})}{\mathbf{0.6}\ (\boldsymbol{ton/m^3})} = \mathbf{658}\ \boldsymbol{m^3/day}$$

1. **Feedstock receiving area**

The storage area was located downstream of the MWPF to enable the storage of waste in case of an emergency or periodic cease of operation at the facility. The volume of the waste can be used to calculate the size of the receiving area to ensure that it is large enough to accommodate a few-days' volume if necessary. However, since it is not recommended to accumulate organic waste as it likely to lead to undesired decomposition especially in such hot climate conditions; therefore, a single day of storage was considered in this case in order to allow for temporary storage while constructing the windrows.

$$\boldsymbol{Receivng\ area\ volume}\ (\boldsymbol{m^3}) = \boldsymbol{volume\ of\ feedstock}\ (\boldsymbol{m^3/day}) \times \boldsymbol{numberof\ days}\ (\boldsymbol{days})$$

$$= \mathbf{658}\ \ (\boldsymbol{m^3}) \times \mathbf{1}\ (\boldsymbol{day}) = \mathbf{658}\ \boldsymbol{m^3}$$

The dimensions of the storage bay will be 25x35 square meters with a possibility to store the material higher than one (1) meter to allow for more storage space and easy movement of waste handling equipment. As mentioned previously, at this initial stage, feedstock conditioning can take place such as seeding, nutrient addition, and addition of bulking agent [8].

2. Active composting pad

The composting pad sizing is estimated using the selected duration of the active composting process, which in this case is set to 4 weeks (30 days) and the daily input of the process while the number of windrows is estimated based on the geometry of the cross-section. This is, of course, valid when there are no strict limits on the land area to be used. A rough estimation of the area needed or composting of organic waste, according to [36], can be calculated with an assumption that around 0.8 square meters of the land area is sufficient to accommodate a single cubic meter of raw material:

$$\boldsymbol{Composting\ area\ needed\ (m^2) = 0.8\ (m^2/m^3) \times 658\ \left(\frac{m^3}{day}\right) \times 30\ day\ =\ 15{,}792\ (m^2)}$$

Using the resulting daily volume of the raw materials, we can calculate the area required by the windrows; first, we calculate the volume of each windrow using the following equation:

$$\boldsymbol{Windrow\ volume\ (m^3) = cross - sectional\ area\ (m^2) \times length\ of\ windrow\ (m)}$$

The windrows' dimensions are determined based on the aeration requirements, the land area available, and the characteristics of the material to be composted; whereas, the geometry of the windrow should be considering the climatic conditions and the area available for the windrows; however, the most important determining factors in practice is the constructing and turning equipment used. The organic waste fraction of the height is between 1.5 to 1.8 meters, and it goes a little higher with green waste, but again in practice, it depends on the machinery used for compost pile aeration. Alternatively, the width of the pile is determined by convenience, and a suitable measure is between 2.4 to 2.7 meters. In this case, a larger width was used where the turning equipment can turn the piles in two passes in order to reduce the working area needed between the windrows [1].

The area of the composting pad was calculated based on different windrow configurations following the steps below (trapezoid cross-section is used as an example). The following equation is used to calculate the cross-sectional area of the windrow, where b and h are the widths and the height of the windrow, respectively:

$$\boldsymbol{Windrow\ cross - sectional\ area\ = \frac{(a+b)h}{2}\ (where\ a\ \approx 0.5b)}$$

$$= \frac{(2.5+5)\times 2}{2} = \mathbf{7.5\ m^2}$$

Hence, the volume of a single windrow is equal to:

$$\boldsymbol{Windrow\ volume\ = 7.5\ m^2\ \times 80\ m =\ 600\ m^3}$$

Meaning that a single windrow equals roughly the daily amount of incoming volume of waste. Now, to determine the number of the windrows, the incoming waste volume is used according to the following equation:

$$\boldsymbol{The\ number\ of\ windrows = \frac{total\ volume\ of\ feedstock\ (m^3)}{volume\ per\ windrow\ (m^3\ per\ windrow)}}$$

The total volume of the feedstock refers to the volume of waste that occupies the active composting pad for the total period of the process, it can be estimated using the retention time of four weeks (30 days) of the composting piles in the windrow pad, and the daily volume of the incoming waste previously calculated:

$$\boldsymbol{The\ total\ volume\ of\ the\ feedstock = retention\ time\ (days) \times daily\ volume\ of\ feedstock\ (m^3)}$$

$$\boldsymbol{= 30\ day\ \times 657.89\ \frac{m^3}{day} =\ 19,736.84\ m^3}$$

Hence, the number of windrows on the pad is obtained from the following equation:

$$\boldsymbol{The\ number\ of\ windrows = \frac{19,736.84\ \ m^3}{600\ m^3} = 33\ windrows}$$

Whereas, the area occupied by the windrows alone can be obtained using the volume of the single windrow multiplied by the footprint of each windrow:

$$\boldsymbol{Area\ occupied\ by\ the\ windrows = (5 \times 80)\left(\frac{m^2}{windrow}\right) \times 33\ windrows =\ 13,200\ (m^2)}$$

Lastly, an additional land area is needed for the operation of the construction and the turning equipment between the compost piles thus it depends on the machinery used; however, a four-meter (4 m) distance is considered safe, and the same distance was applied around the perimeter of composting pad. Hence, the total length of the composting pad equals the length of the windrow in addition to the distance around the pad totaling 88 meters.

On the other hand, the width of the pad can be calculated using the width of a single windrow (5 meters), the number of windrows (33), the maneuvering space between the windrows (4 m), the number of spaces (33 – 1 = 32) and lastly the twice the length on the sides (8 m). The calculations result in the total area of the active composting pad that is 88 x 301 meters:

$$\boldsymbol{Total\ area\ required\ for\ AC\ pad = 88\ m \times 301\ m = 26{,}488\ m^2}$$

It should be noted that the shrinkage due to the pretreatment of the organic waste was considered by using a bulk density of 0.6 tons per cubic meter. However, the overtime shrinkage was not considered, meaning that the waste volume treated is expected to drop to around half of the initial volume due to the loss of volatile matter and moisture; therefore, the resulting value is the maximum area requirements [1] [36]. However, a volume loss of 60% was adopted for the sizing of the curing pad in the following section [36].

Table 38: The different windrow-configuration design specifications for the selection of the active composting pad:

Component	Rectangular	Semicircular	Trapezoidal	Triangular
Windrow volume (m^3)	800	502.65	600	400
Windrow footprint (m^2)	400	320	400	400
Volume/footprint ratio	2	1.57	1.5	1
Number of windrows	25.00	40.00	33.00	50.00
Windrow surface area (m^2)	740.00	515.22	592.36	871.63
Total composting pad (m^2)	20,152.00	27,994.63	26,488.00	39,430.94

It can be noted that the rectangular configuration offers optimal design specifications; however, the construction of such windrow geometry is deemed unachievable in practice and hence was eliminated when comparing the different designs. Moreover, the triangular configuration is also eliminated due to the high area requirement and the low volume to footprint ratio. Alternatively, the trapezoidal and the semicircular configurations offer more or less similar specifications but the trapezoidal is favored due to the lower area requirements [1].

In conclusion, the active composting pad area is 26,488 square meters, with 88 x 301 meters dimensions and 33 windrows in total.

3. The maturation/curing pad

The curing stage is characterized by slower decomposition rates hence longer process duration compared to the active composting phase. It is also characterized by lower oxygen consumption and generally less requirement of process control. Thus, the compost piles are usually let sit for a few weeks or months without any kind of intervention unless deemed necessary. The term "cured" describes the level of readiness of the compost for the intended purpose, i.e., the end-use. It is necessary to note that after the curing stage, the product will have to meet quality requirements [34][36].

The process can be carried out aerobically (through passive aeration) with no need for active aeration or turning due to the low oxygen demand at this stage of the process, the porosity of the compost heaps should be adequate, and the size should be smaller compared to that of the active composting phase. The maturation pad hence is expected to as well be smaller compared to the composting pad because there is no need for the working space between the windrows (maneuvering space) [36]. Moreover, the mass balance of the composting process indicates that the organic waste piles experience volume loss during the process, and most of it takes place during the active composting phase. It was assumed that the waste volume loss will amount to 60% of its initial volume [36]. The design considerations for the sizing of the maturation pad are:

- The process duration was set to 8 weeks (60 days).
- Volume loss were assumed as 60%, meaning that volume received is 40% of the initial value.
- The dimensions of the windrows were set at 3, 5, and 88 as height, width and length, respectively.
- The windrows were placed adjacently with no spaces in between. The working space around the curing pad is 4 meters.

The input of the curing stage is the product of the active composting process (ACT). The ACT is characterized by a rapid biological degradation process because of the active aeration and the presence of readily biodegradable materials; therefore, the volume received at the maturation pad is expected to be less than the raw material volume.

The calculation of the maturation pad area was carried out similarly to the active composting pad land area, with a reduced process input and the removal of working spaces between the windrows. The results of the calculations are tabulated below:

Table 39: The different windrow-configuration design specifications for the sizing of the maturation pad:

Component	Rectangular	Semicircular	Trapezoidal	Triangular
Windrow volume (m^3)	1200	1130.97	900	600
Windrow footprint (m^2)	400	480	400	400
Volume/footprint ratio	3	2.3562	2.25	1.5
Number of windrows	13.00	14.00	18.00	27.00

Windrow surface area (m^2)	910.00	1159.25	742.50	639.82
Total maturation pad (m^2)	6,424.00	8,096.00	8,624.00	12,584.00

As per the results tabulated in the table (39) above, it can be noted that the rectangular and the semicircular configurations hold the best performing design specifications in all areas compared. Of course, in practice, the selection was based on which of the profiles is easily constructible. The design selected in this case was the third option (the trapezoidal) due to the larger windrow volume and surface area compared to the triangular configuration and the significant land area difference.

The maturation pad was situated in line with the composting pad to ensure a seamless flow of the process. A minimum distance that it is large enough to house two-way direction of travel must be considered; a space of ten (10) meters is deemed sufficient, which includes the margins of both the composting and the curing pads of eight (8) meters. Moreover, additional space is left unoccupied to enable the operators to store the finished product temporarily in case of emergency or periodic cease of the post-treatment equipment. A two-day storage space equivalent to 526 cubic meters is used.

In conclusion, the active composting pad area is 8,624 square meters, with 88 x 98 meters dimensions with 18 windrows.

4. Post-treatment (ferrous metal removal and screening)

The final process unit before the product is finally ready for delivery is refining. Refining is carried out through screening or air classification, the first being used for achieving a desired particle-size whereas the latter for separating any remaining contaminants. However, it should be kept in mind that there is an optimal moisture content range of 40 – 45% below which there is an increased dust generation and above which it will be challenging to carry out the process efficiently.

Different finished product sizes have different end uses; for instance, a commonly-used 9-millimeter screen's product can be utilized by different sectors, including the horticultural sector and land reclamation purposes, whereas a finer product can be used for gardening and coarser material for mulching. Nonetheless, agriculture, particularly organic farming, could be the most significant user in the future [37].

For this composting facility, an electromagnet for ferrous metal removal and a two-stream, mono-stage fine-screens of 9.5 mm were installed as the unique post-treatment process, where fine particles are to be transported to the "storage and packaging" area while the larger-sized are separated from the mainstream is rejected. The residues of the screen are expected to amount to 5 – 10% of the product weight [34]. The magnet is place over a conveyor belt that loads the finished onto the screen and it consumes 0.6 – 1.0 kWh/ton, whereas the screen occupies an estimated area of 25 square meters and consumes 0.5 – 1.5 kWh per ton of waste.

5. Packaging and storage

The finished product's packaging and storage area was as well located near the maturation pad to eliminate the need for material transportation. At this stage, because no further processing is required, the product can be piled in much larger units before being packed for sale. The finished product is stored in larger piles compared to those of the composting and the curing areas because no further treatment is required [36]. Typically, the compost is shipped in bulk. The economical range of transportation is usually considered within 80 kilometers. Bagging the product increases the range and usually brings in higher remuneration for the product [37]. An estimated area of 4312.00 square is used for material packaging and storage.

Thus, the total land area that is estimated for the aerobic treatment facility is roughly 40,107 square meters excluding the area needed for offices and vehicle parking within the facility premises. Therefore, the area needed for carrying out the biostabilization process represents 45% of the available land area at the proposed site as detailed previously.

4.3.3.5. Material balance of the composting facility

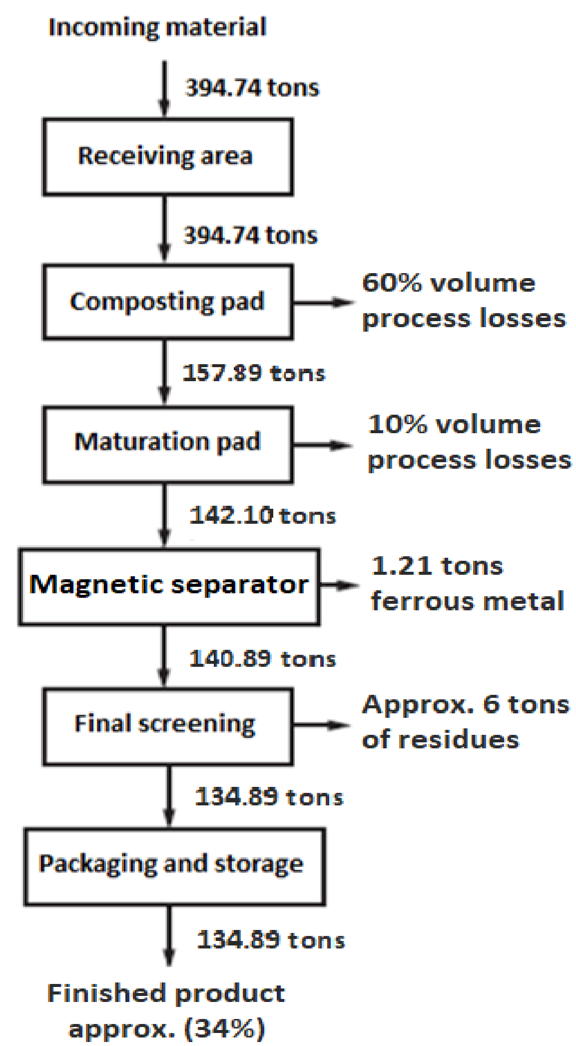

Figure 23: The material balance quantities in (ton/day) for the composting process

4.4. Facility Electric Energy Consumption

4.4.1. The material recovery facility (MWPF)

The electric energy consumption of the sorting facility is calculated using the average energy consumption of every machine employed for 330 days a year and 18 hours per day.

Table 40: The energy comsumption of the mixed-waste material recovery facility in mWh per year (335 day per year):

Equipment	Consumption (KWh/ton)	Material rate (ton/day)	Min. Annual Consumption	Avg. Annual Consumption	Max. Annual Consumption
Bag breaker	0.3 – 0.9	551.38	55.41	110.83	166.24
Drum screen (fine)	0.5 – 1.5	448.73	75.16	150.32	225.49
Magnetic separator	0.6 – 1.0	429.11	86.25	115.00	143.75
Primary shredder	7 – 15	406.58	953.43	1498.24	2043.06
Total	-	**551.38**	**1170.25**	**1874.39**	**2578.53**

4.4.2. The Biostabilization Facility

The electric energy consumption of the entire facility is calculated according to the minimum and maximum consumption rates of all the equipment installed. Certainly, additional electric energy will be consumed by the facility offices, the lighting of the entire facility and any other purposes. The calculations were made based on the assumption that the facility will operate 330 days per year. However, given the limited storage capacity at the site, the 35 halt days must be sporadic throughout the year.

The tonnage of material processed by each of the equipment was estimated based on the assumptions made previously (please refer to section 4.1.6.). The annual energetic consumption of the equipment installed at the facility is listed in table (41) below:

Table 41: The maximum and minimum energy consumption in (MWh/year) of the equipment deployed at the facility:

Equipment	Consumption (KWh/ton)	Material rate (ton/day)	Min. Annual Consumption	Avg. Annual Consumption	Max. Annual Consumption
Permanent magnet	0.2 – 0.4	142.10	9.52	14.28	19.04
Screen	0.5 – 1.5	140.89	23.60	47.20	70.80
Total	-	**394.74**	**33.12**	**61.48**	**89.84**

It shows from table (41) that the total energy consumption by the composing facility's equipment (post-treatment process) fall between 33.12 – 89.84 MWh per year with an average of 61.48 MWh/year.

The above calculations represent a preliminary design for the organic composting facility. In contrast, the final design of the site would include the preparation of final plans and specifications for the site construction, environmental plans, detailed cost estimates, and lastly, the procurement documents [1].

Lastly, the transfer station in Khartoum locality should be rehabilitated and expanded in order to accommodate an amount of ≥600 tons per day.

CHPATER (5): EMISSION SCENARIO EVALUATION

5.1. Tools

Version two (2) of the Solid Waste Emission Estimation Tool (SWEET) was utilized to determine the emission baseline scenario. The tool was developed in 2018 by the Abt Associates and the SCS Engineers on behalf of the Environmental Protection Agency (EPA) and the Climate and Clean Air Coalition Municipal Solid Waste Initiative (Waste Initiative). This tool helps in providing estimates of the annual emissions of pollutants with a focus on methane and black carbon. Additionally, it provides the opportunity to generate other emissions scenarios following different treatment scenarios and the effects they have on the emissions; however, the excel-based tool has some limitations including waste composition held constant throughout the years meaning that the values entered apply to all years during the period analyzed [7]. In order for the SWEET to generate different emissions scenarios, the user should input various data into the tool; in some instances, such data might not be detailed enough or available.

The various sources included in this tool are: (1) waste collection and transportation, (2) waste burning, (3) landfills and dumpsites, (4) waste handling equipment, (5) organic waste management facilities, and (6) waste combustion equipment. For the calculation of the emissions of the landfills and dumpsites, the tool uses disposal site data while it uses annual activity data and process emissions factors.

The tool helps in determining first-order estimates of annual emissions of methane, black carbon, and other emissions such as carbon dioxide, nitrogen oxides, and organic carbon. It also provides estimates of the total different emission in terms of carbon. The emission scenario in this chapter focuses on total emissions and methane emissions. The pollutants emitted by each sector are detailed in table (42):

Table 42: The pollutants emitted by each sector of the waste management. Source: SWEET User Manual 2018.

Sector	Pollutants							
	CO_2	NO_X	Black Carbon	Organic Carbon	CH_4	SO_X	$PM_{2.5}$	PM_{10}
Waste Collection & Transport	x	x	x	x	x	X	x	x
Waste Burning	x	x	x	x	x	X	x	x
Landfills & LFG Combustion		x	x	x	x		x	x
Waste Handling	x	x	x	x	x	X	x	x
Organic Waste Management					x			
Waste Combustion	x	x	x	x	x	X	x	x

5.2. Current Emission Scenario

To obtain the current emission scenario estimates for Khartoum state, the author made some assumptions that are listed below:

1. The last updated figure in the year 2013 is 65%; according to JICA 2014, the target collection rate according to the MP is 80% in the year 2028; therefore, the waste collection rate in 2020 assumed to be 72%.
2. According to the 2008 national enumeration census, Khartoum State had a percentage of 81% urban population out of total. Even though this percentage is outdated; however, it is the only available official figure.
3. The waste generation rate per capita per day in the rural population was assumed to be the same as the urban population as advised by the tool (0.78 kg/capita/day) as no data is available.
4. The future projection of the average annual growth rate (%) in the quantity of waste collected is assumed to be 1%, as it is required to achieve the targeted collection rate of 80% by 2028.
5. The average annual growth rate (%) in the quantity of waste collected based on historical data is 3% based on the JICA 2014.
6. The percentage of the waste collected that is generated outside the formal waste collection zones is assumed by 0%.
7. The available waste composition by the KSCA did not report some of the waste fractions required by the tool; thus, the values had to be adapted from the other studies that investigated the waste composition in the area of study. The data has mainly been drawn from the KSCA, and where data was missing/unreported (i.e., tires), the values reported composition by the EWASCO and the IRCC were used instead.
   i. "Green waste" was assumed to be included in the organic waste fraction and is set to 6.53% (EWASCO). Thus the organic waste fraction reported by the KSCA (49.5) was decreased to 42.97%.
   ii. "Textiles" waste fraction was assumed to be only "cotton and jute" with a value of 4.6%.
   iii. "Tires" fraction was neither reported by the KSCA composition nor the EWASCO. The reported value by the IRCC was 0.4%, and hence it was assumed as part of the "other" waste stream in the KSCA values.
   iv. The "other" waste stream was assumed to be the sum of the remaining amount in addition to the "dust and ash," "couch," and "leather," totaling 15.3%.
8. The baseline line scenario only accounts for plastic recycling of 29,200 tons per year (EWASCO).
9. The waste collection and transportation operational each year was set to 444 and 15 respectively according to the MP 2016; whereas the landfill operation equipment were a total of 33 according to the MP 2016 in addition to 6 new equipment procured by the JICA aid project (JICA 2017)
10. The percentage of waste burning is calculated based on the 2016 waste flow reported on the MP (refer to figure 4). Knowing that the waste that ends up uncollected, illegally dumped or recycled amounts to 2,013 tons per day. 320 tons per day is assumed to be illegally dumped after collection while 1,693 tons per day is either openly dumped or recycled (mainly plastic

amounting to 80 tons per day); therefore, waste burning represents 80% of the uncollected waste, which assumed for both for areas inside and outside the formal collection zones. Whereas, the percent of 1% was used for waste burning at the landfill/dumpsite.

As stated previously, the tools detail the emissions of different pollutants; however, the results shared here are focused on total emissions and methane emissions as it has a high global warming potential. Figure (24) depicts the total emissions by the waste management sector in terms of carbon equivalent. The curve shows that the emissions will continue increasing as waste production increases and no treatment plants are put in place reaching up to 2,942,434 metric tons of CO_2 equivalent by the year 2050. The same applies to the methane emissions (figure 25) that are expected to reach about 900,000 tons of CO_2 equivalent by the year 2050 should the current practices continue.

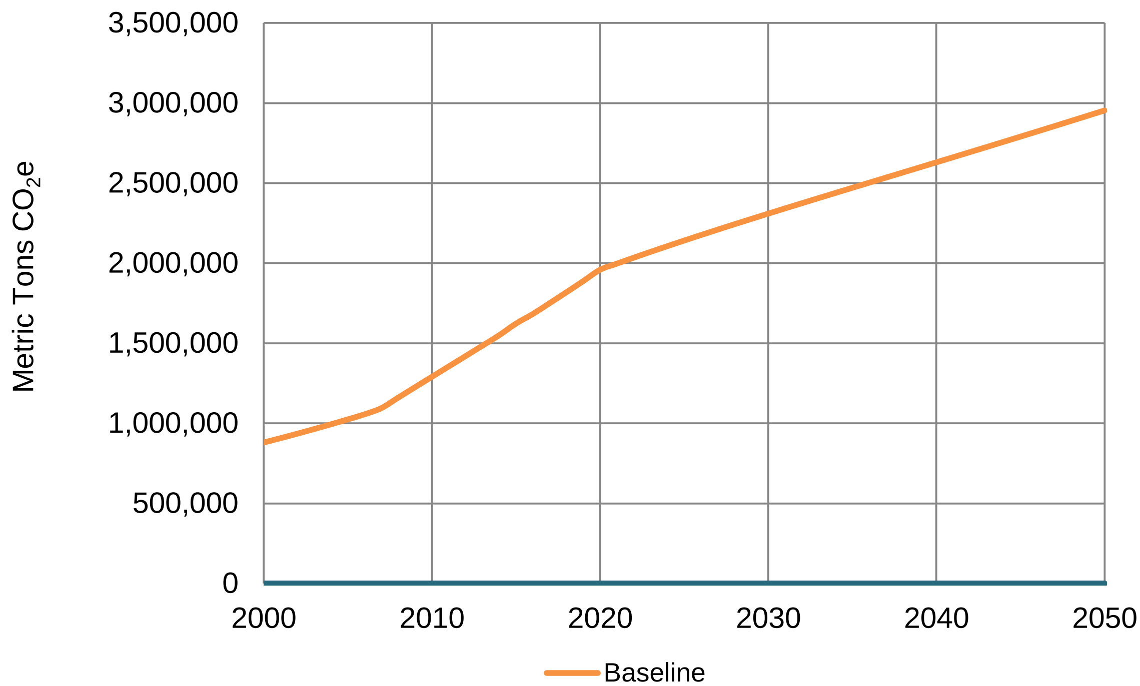

Figure 24: The current (baseline) total emissions including CO_2, NO_X, CH_4, BC and Organic carbon from the year 2000 to 2050 in Khartoum state. Source: SWEET.

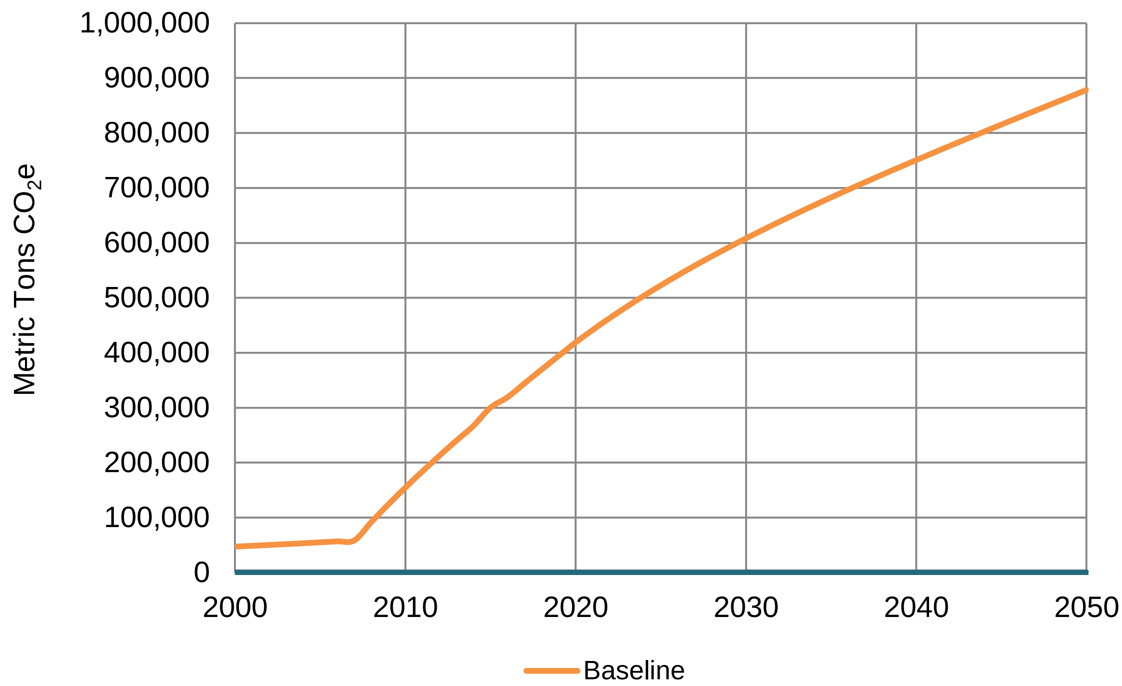

Figure 25: Methane emissions by the baseline (current scenario) from year 2000 to 2050. Source: SWEET.

On the other hand, Figure (26) shows the baseline emissions segregated by sector. According to the results, the major contributor to the total emissions is "waste burning", expected to exceed 2,000,000 metric tons of CO_2eq (2,123,766) by the year 2050. Followed by "landfills" 768,645, waste collection and transport 37,850 (assuming the same number of vehicles will be operated each year), and lastly, waste handling equipment 12,174 metric tons of CO_2eq with a total of 2,942,434 metric tons of CO2 equivalent by the year 2050 as mentioned above.

In reality, the emissions from waste collection, transportation and disposal (or waste handling equipment) should increase more rapidly as more vehicles and equipment are to be procured because of the increasing waste quantity. Moreover, the emissions from waste burning, according to the figure, will continue to increase proportionally to the increasing waste quantity because a specific percentage of waste is assumed to be burned; however, this percentage will decrease or increase depending on the waste collection services coverage and quality. As for landfills, the emissions can be decreased through the organic waste treatment or the upgrade of the landfills to sanitary landfills with methane gas extraction system.

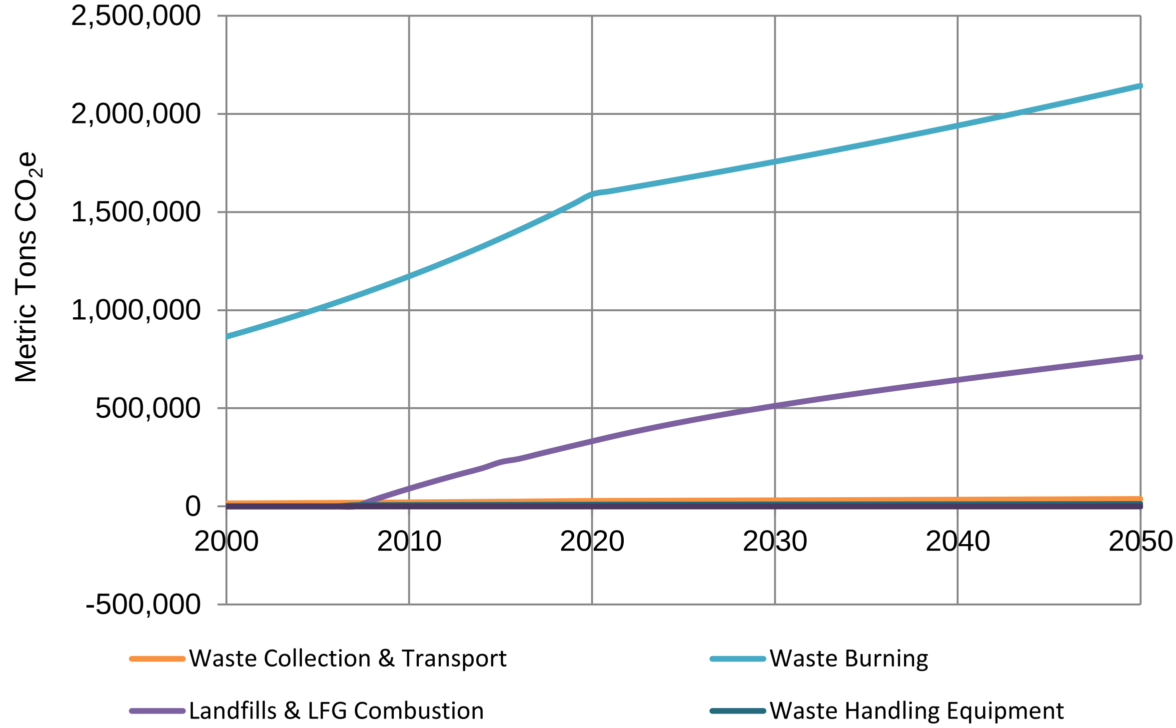

Figure 26: Total emissions in Khartoum state from the year 2000 to 2050 by sector. Source: SWEET.

The emissions by the four (4) disposal sites in the state is depicted in the figure below (figure 27). The operations at the Khartoum are expected to cease in 2040 due to the planned expansion of the site. As for the Bahri temporary disposal site, the site was reportedly closed in the year 2019. Therefore, the curves of both sites follow an ascending trend that descends at the closure year.

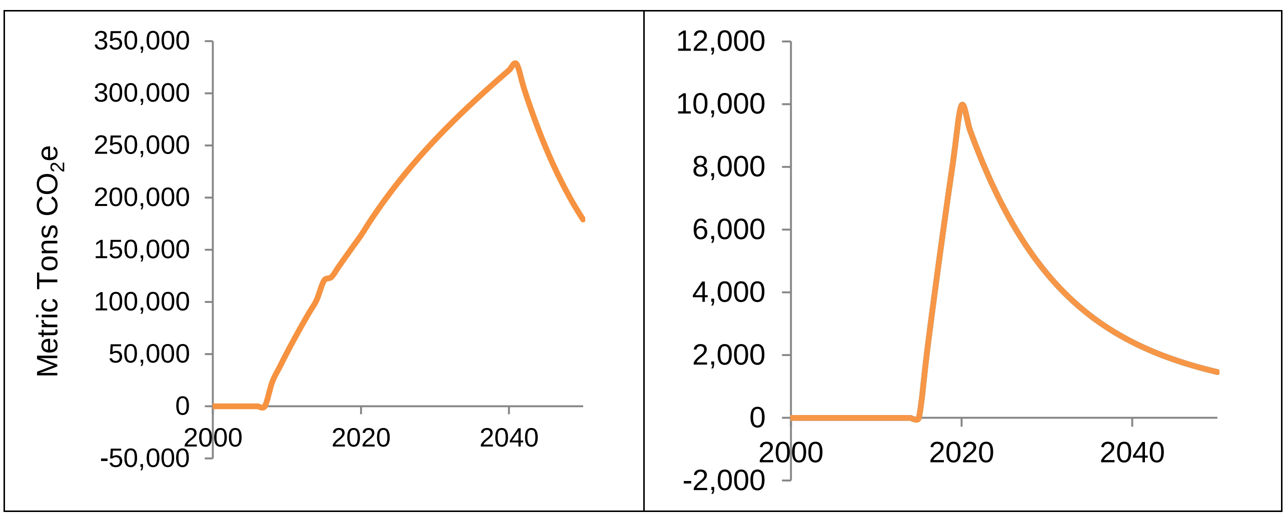

Figure 27: The figure shows the emissions from the Khartoum disposal site on the left and the Bahri temporary disposal site.

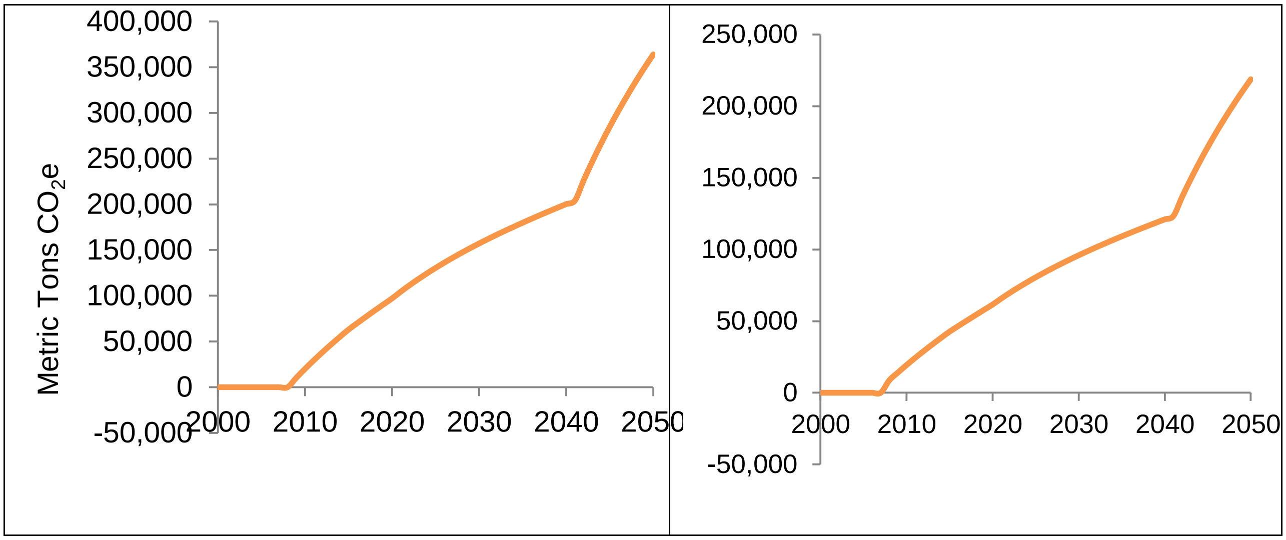

Figure 28: The emission scenario of the Omdurman and the Bahri disposal sites respectively

On the other hand, the curves follow the same ascending trend. However, the Omdurman landfill receives approximately double of the amount that is disposed at the Bahri site hence more emissions are produced compared to the other site.

5.3. Emission Scenario of the Treatment Proposal

In order to calculate the emissions of the suggested treatment scenario in comparison to the baseline scenario, the same assumptions previously listed in section 3.4. are applied into this section; in addition to the following:

1. The treatment scenario starting year is assumed to be year 2022.
2. Diverted waste composition is obtained from the total amount of waste that is recovered by the MSPF and the amount of waste sent to the composting facility.
3. It assumed that the site is operated by a total of ten (10) diesel vehicles, including front-end loaders, forklifts and windrow construction vehicles.

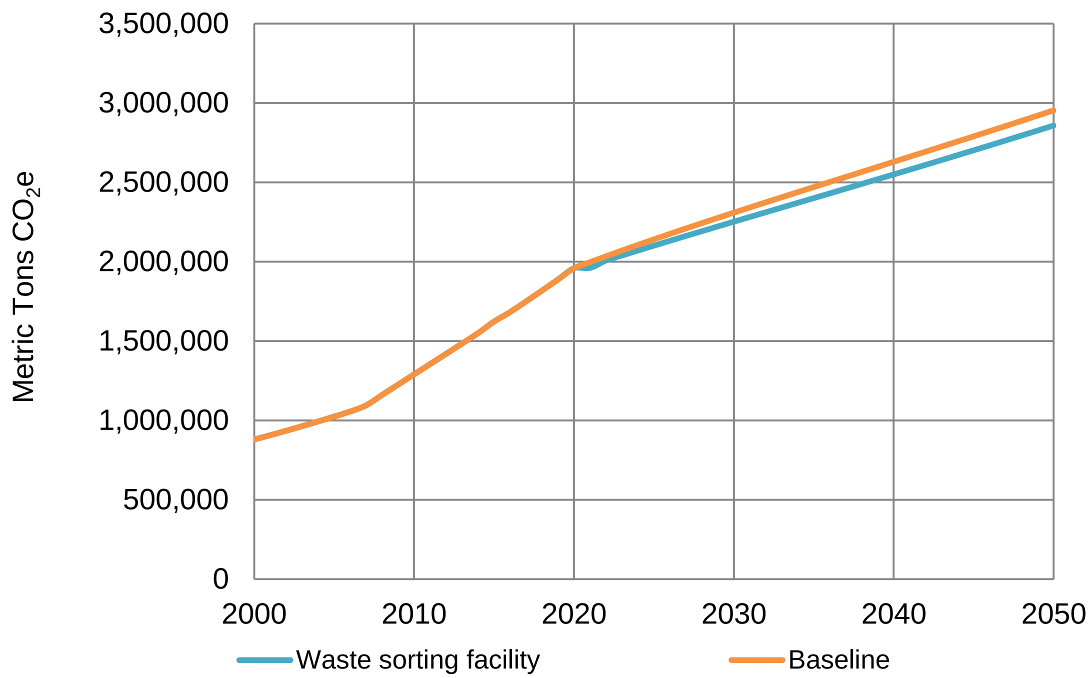

Figure 29: Total emissions (CO_2, NO_X, CH_4, BC and Organic carbon) by scenario including from the year 2000 to 2050. Source: SWEET.

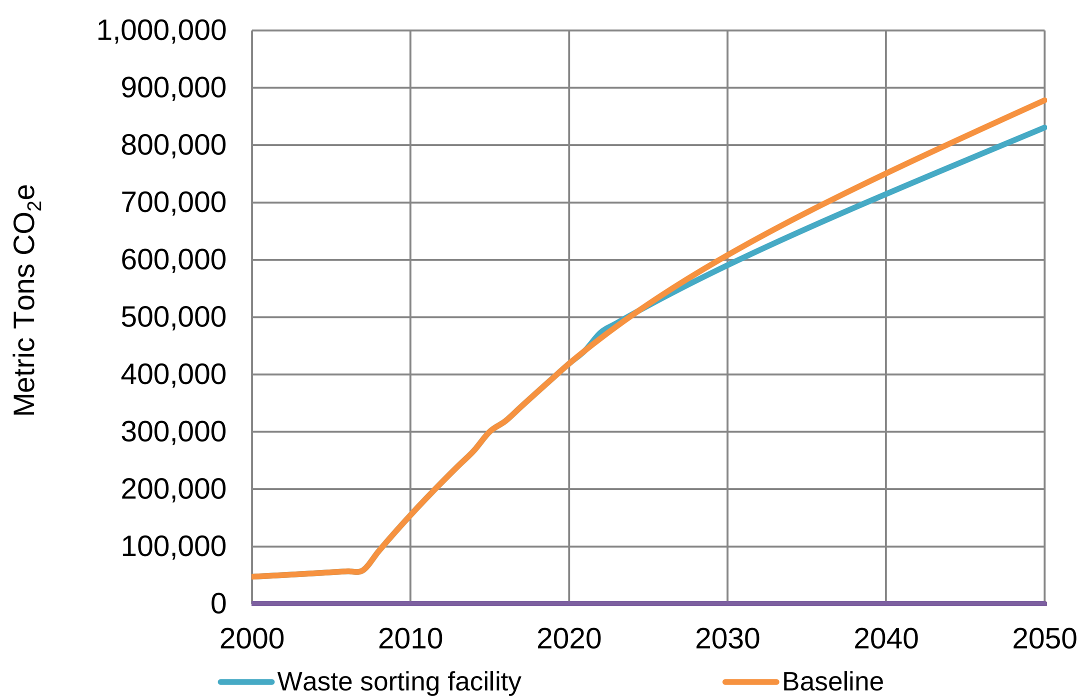

Figure 30: Scenario comparison of methane emissions over time from the year 2000 to 2050. Source: SWEET.

The suggested treatment scenario, blue curve, includes the entails the diversion of 58,896 tons of recyclables annually (including ferrous metal recovered at the post treatment of the organic waste treatment facility) and the treatment of 111,690 tons of compostable waste materials per year starting from 2022. It can be noted from the figures (29) and (30) above, that the introduction of a new treatment scenario will cause a consequent decrease on the total emissions and the methane emissions starting from 26,375 tons of CO_2eq in the year 2022 and up to 95,598 tons of CO_2eq in the year 2050. The treatment scenario will have a similar effect on the emissions from the landfill sites.

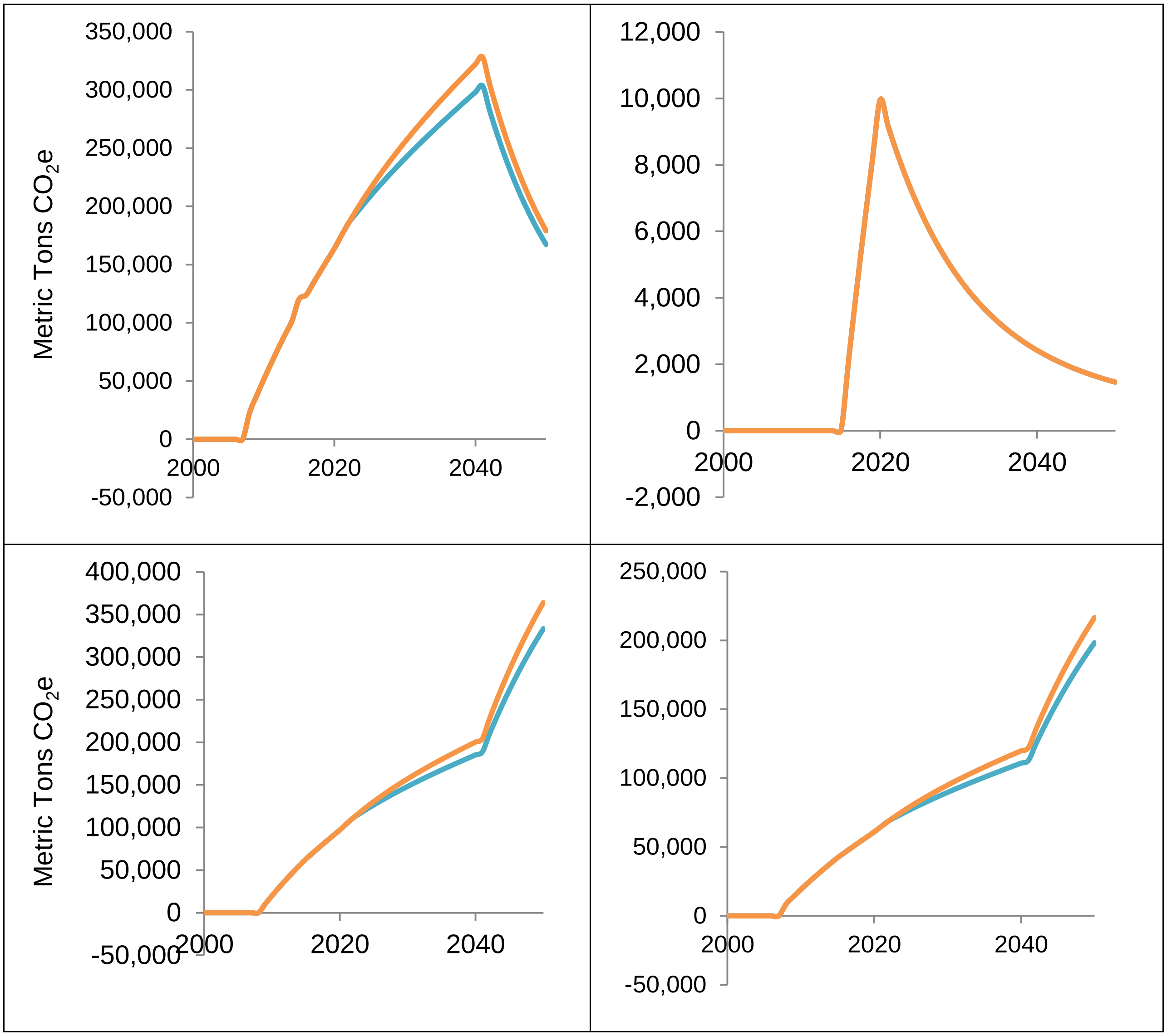

Figure 31: A comparison between the emission of the baseline (yellow) and the treatment (blue) scenarios for the different disposal sites in Khartoum state

CHPATER (6): ENVIRONMENTAL, PUBLIC, AND INDUSTRIAL HEALTH CONSIDERATIONS

The other design considerations at an organic waste treatment facility are environmental protection, public protection, and the industrial health and safety measures at the site. The operation of the facility poses major potential impacts on the environment and public health, including the operators. Preventive or remedial measures during the design or the operation process can be put in place in order to avoid or reduce any potential adverse impacts.

6.1. Environmental and Public Health

6.1.1. Water protection and leachate control

The water produced at the composting facility that requires attention is leachate and runoff. Leachate is generated only when the moisture content of the organic waste is higher than the optimal value for composting. Hence, moisture content control represents a key element to the leachate control process. Moreover, the material can be protected from increased moisture content due to precipitation. Additional measures would be installing impermeable surfaces and designing them in such a way to collect the leachate and send it for a nearby sewer for treatment or onsite treatment [1].

On the other hand, runoff can cause water to seep through the composting mass and get polluted by either pathogen, soluble organic, and inorganic compounds [37]. This situation can be avoided by protecting the areas where the material sits by either elevating surfaces or building ridges around the site and channeled to the treatment facility

Due to the low amounts of rainfall in Khartoum and deep groundwater table levels at the landfills on top of the dry weather, there is no fear of vast amounts of leachate water production or threat of leachate seepage to the groundwater [6]. However, in order to decrease the amount of leachate during the rainy season and reduce moisture evaporation and drying off the piles, the roofing of the working areas is recommended. Moreover, to prevent the accumulation of leachate, a gentle elevation and slope of the composting and maturation pads should be considered. A minimum slope of 1% and a maximum of 4% should be applied, the latter being the recommended slope. Nonetheless, Since the waste delivered may be high in moisture, the area should be slightly sloped (1%) to avoid leachate ponding. A drainage system collects leachate and cleaning water to be reused for watering composting windrows.

6.1.2. Air protection and odor control

The operation of a composting facility would lead to the release of dust and aerosols that most likely carries biological and non-biological agents that are believed to cause health issues such as respiratory tract infections and other organ infections according to [1]. Therefore, dust control measures at the different stages of the process should be put in place, e.g., mist sprayers can be installed in the working areas. A more sophisticated measure would be installing dust collection and particulate control devices, e.g., fabric filters [1].

A typical composting process is also accompanied by the generation of odorous compounds that come in many forms and odors depending on the feedstock, process conditions, and the ambient temperature, or weather conditions. According to [1], the odors generated by an organic treatment facility, even though it affects the air quality around the area, it, however, does not pose health hazards to human health unless they become very foul. Offensive odors, specifically, arise from the development of anaerobic conditions due to failure in sustaining aerobic conditions. The compounds that are most responsible for offensive odors include; reduced Sulfur compounds, volatile fatty acids, and ammonia and nitrogen-containing compounds.

The siting of the plant, as well as the proper management of the composting process, can affect the investment in the odor control system. Typically, if the composting facility is located far enough from the residential area or other facilities, odor control measures become less necessary. Instead, and through the understanding of familiar odor sources, the composting facility operator can eliminate or reduce some of the incomings of certain organic materials and perform frequent turning of the piles to ensure proper aeration (oxygen supply). Additionally, and as previously mentioned, feedstock size reduction and separation of contaminants that are non-compostable to minimize the potential odor problems [8][1]. In mixed-waste processing systems, the tipping floor areas can be designed with negative pressure to control odors [1].

The organic treatment facility, in this case, is located in an industrial area though not far from the residential area of Elrimeila. Hence, odor reduction measures should be put in place, including [8]:

- Ensuring a high efficiency of the sorting process (contaminants removal) and screening processes.
- Shredding the material in order to reduce its size and ensure it is mixed adequately.
- Conduct periodic turning of the windrows (every other day) during the active composting time.
- Adequate mixing of the windrows, ensuring all the parts are aerated.
- All turning equipment will be on standby. Additional equipment should also be available.

6.1.3. Noise Control

The sources of noise in a material recovery facility are the vehicles and the sorting equipment. Noise can be controlled through the operation of the facility equipment in enclosed areas.

6.1.4. Vector control

A site where there is organic waste represents an attraction for rodents and flies, especially when the raw material is stored for long at the receiving area due to the presence of food waste. Vector control can be avoided by enclosing the facility area. Other measures that would significantly reduce the intensity issue include the careful cleaning of the entire area, the shortening of the storage period of the raw material. Moreover, shredding of the raw material so as to destroy the flies' eggs and larvae to render the material less attractive for rodents, and, lastly, paving the surfaces to prevent the migration of fly larvae that survive the preprocessing and the early compost stages [1].

6.2. Industrial Health and Safety

6.2.1. Personnel Safety

Operators of the material recovery and the composting facility are exposed to many risks and health hazards. They include injuries from the process machinery, infections due to the dust suspended in the air in the site, and lastly, exposure to noise caused by the process equipment and lauders. It is noted that most of these risks and health hazards take place in the pretreatment phase of the composting process. The health and safety measures that can be put in place in this case, in addition to dust control equipment, are providing PPE, face masks, and ear protection, especially for prolonged periods of exposure. Moreover, during the manual sorting process, the height of the worker relative to the moving belt must be adjustable. Additionally, the facility should also have a controlled access where the so that the waste pickers, vendors and general public cannot access the facility [1]. Worker fatigue can be reduced by adjustment of environmental variables such as temperature control, lighting, and ventilation [24].

6.2.2. Fire Protection

Fires at the facility can be caused by two main reasons, which are the equipment maintenance activities or spontaneous combustion of the finished product. The size, surface area, moisture content, and composition of the piles of the finished product at the storage area can make them more or less susceptible to self-ignition according to [1]. The necessary control measures would be the avail of fire extinguishing equipment and constant water supply and the periodic monitoring for the finished product piles [1]. The climate of Khartoum is mostly hot and dry; therefore, the possibility of combustion is low.

CHAPTER (7): DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

The municipal solid waste management efforts by the state government in Khartoum are currently directed towards solid waste collection and disposal. Nonetheless, both processes are being carried out in an inefficient, inadequate and unsustainable manner; despite the involvement of both the public and the private sector in the waste collection area. Moreover, despite the foreign aid, the collection rate in the state is believed to be lower than the estimated percentage (65%) in 2018 according to an interview with the JICA Project Coordinator at the HCE. Waste disposal, on the other hand, is not carried out properly. Only a relatively a small percentage (39.3%) of the collected waste went through the transfer stations (TS) in 2016. Moreover, the waste disposal at the landfills (LF) does not follow the minimum safety and environmental requirements.

Notwithstanding the fact that the financial analysis of the waste management prepared by JICA and the state government was irrelevant due to the continuously deteriorating economy in addition to lack of information of market demand and secondary material pricing, the proposed treatment option is expected to show savings in the transportation costs and the avoided disposal costs. The revenues from the sales of the recyclables and the compost are expected to cover the operational costs of the facility provided subsidies by the state government are availed; without subsidies, the sustainability of the organic waste treatment in particular will be compromised.

The sorting facility was designed as semi-manual so as to minimize the reliance on human operators due to the large amount of waste treated. However, there will be a need for employing good management and technicians for the maintenance of the facility's equipment. It is worth mentioning that this facility design considers the minimum possible requirements for compost production. Three major constraints, which are; capital investments, energy consumption, and facility siting were considered when designing this facility. Different facility layouts can be altered in order to produce higher-quality products by methods, including more equipment in the design of the layout of the facility. Additionally, more products can be acquired by expanding the post-treatment stage. Nevertheless, treating the organic waste fraction resulting from a mixed waste stream is costly and linked to the production of poor-quality compost with low or no market value.

A material recovery facility plays a key role in a successful waste management system. This work is intended to form a basis for additional research and development. The design of any waste management system needs updated information on waste generation and compositions trends as well as the existing waste treatment options. More research is required for the investigation of waste recycling by the private sector in Khartoum for all the different waste streams that can be recovered and the financial analysis of the recycling sector in order the evaluate the profitability of the designed treatment facilities. Nonetheless, the non-monetary values of such facilities such as the protection of human health and the environment should be a priority by governments.

The following recommendations were determined based on the current situation of waste management and treatment in the state of Khartoum:

i. In order to ensure the feasibility of the facility, the sorting process has to be preceded by a reliable collection system, due to the heavy informal sorting activities taking place from the point of waste collection to final disposal (challenge: the informal sorting nature for mostly plastics and metals).
ii. The waste management and treatment efforts in the country as a whole and Khartoum state in particular need to be greatly strengthened in terms of investments, roles activation, and capacity building;
iii. Organization of awareness campaigns through different media outlets to spread awareness among citizens and promote proper waste disposal practices; this is in tandem with capacity building programs for personnel involved in the waste management system at different levels.
iv. The local policies and regulations on waste management and treatment need to be updated, disseminated, and enforced.
v. The Khartoum government should work to provide increased capacities of organic waste recycling in the state. The state government should study the feasibility of introducing source separation of organic waste and separate collection. The introduction of source separation organic waste and starting from the areas that will be/are served by organic fraction treatment facilities;
vi. Waste prevention activities should be promoted, adopted and developed to prevent littering and improper waste dumping;
vii. There is an urgent need for carrying out different studies related to solid waste management in Sudan in general and Khartoum state in particular and for availing updated and reliable information.

CHAPTER (8): BIBLIOGRAPHY

[1] G. Tchobanoglous and F. Kreith, *HANDBOOK OF SOLID WASTE MANAGEMENT*, Second. 2002.

[2] M. Bobeck and I. Assignment, “Organic Household Waste in Developing Countries decentralised technologies and strategies for sustainable management,” no. June, 2010.

[3] G. Review and S. W. Management, “A Global Review of Solid Waste Management.”

[4] C. Furger, “Impact on Health and the Environment,” *Live Cell Assays*, no. December, pp. 197–217, 2016.

[5] M. Alhadi *et al.*, “Investigating the Solid Waste Management Problems in Urban Area, Sudan,” vol. 3, no. 6, pp. 947–953, 2014.

[6] C. Agency, Y. Engineering, C. Agency, Y. Engineering, and C. Agency, “2017 Report Completion Project Completion Report 2017 Report Completion Project Completion Report,” 2017.

[7] “Solid Waste Emissions Estimation Tool (SWEET) User Manual,” no. February, 2018.

[8] J. A. Salvato and J. Wiley, *ENVIRONMENTAL ENGINEERING FIFTH EDITION*. .

[9] “Being wise with waste : the EU ’ s approach to waste management.”

[10] “Best Practice Municipal Waste Management,” 2018.

[11] S. W. Management, “Waste prevention : generalities and examples Waste hierarchy / 2 □ Waste prevention holds the most important role □ Before implementing a proper and efficient management strategy for the generated waste (which can ’ t certainly be disregarded), it is re,” pp. 1–30, 2019.

[12] M. Grosso, “Waste recycling Recycling and recovery Packaging waste : current management Plastic recycling Glass recycling Paper recycling Aluminium recycling Energy and environmental considerations on material recycling Directive 2004 / 12 / EC on packaging and packa,” pp. 1–34, 2019.

[13] G. A. N, “State of the Art of Emerging Solutions,” no. 642451, 2020.

[14] H. Saveyn and P. Eder, *European Commission, Joint Research Centre – Institute for Prospective Technological Studies - End-of-waste criteria for biodegradable waste subjected to biological treatment (compost & digestate): Technical proposals*. 2014.

[15] M. Hyman, B. Turner, and A. Carpintero, *Guidelines for National Waste Management Strategies: Moving from Challenges to Opportunities*. 2013.

[16] I. Adebayo Bello and M. N. bin Ismail, “Solid Waste Management in Africa: A Review,” *Int. J. Waste Resour.*, vol. 6, no. 2, 2016.

[17] L. Godfrey, M. T. Ahmed, K. G. Gebremedhin, and J. H. Y. Katima, “We are IntechOpen , the world

’ s leading publisher of Open Access books Built by scientists , for scientists TOP 1 % Solid Waste Management in Africa : Governance Failure or Development Opportunity ?”

[18] T. H. E. Solid, W. Management, P. In, and K. State, “THE SOLID WASTE MANAGEMENT MASTER PLAN IN KHARTOUM STATE REPUBLIC OF SUDAN CLEAN KHARTOUM MASTER PLAN 2 (REVISION),” vol. 2, no. December, 2016.

[19] I. Ali, “Waste Management in Sudan : A case of Waste Characterization in Khartoum Waste Management in Sudan : A case of Waste Characterization in Khartoum State,” no. December, pp. 1–8, 2017.

[20] C. Agency, “February 2014 japan international cooperation agency,” no. February, 2014.

[21] T. M. Ali, “Assessment of solid Waste Management system in Khartoum locality,” no. August, 2009.

[22] N. O. M. Elbaroudi, “Solid Wastes Management In Urban Areas : The Case of Khartoum State , Sudan,” 2015.

[23] E. H. A.-R. M. A. H. E. M. A. S. Alnagrabe, “Environmental Assessment of Polyethylene Bags: A Case Study in Khartoum State, Republic of Sudan,” *Int. J. Sci. Res.*, vol. 4, no. 3, pp. 383–388, 2015.

[24] “PROJECT FOR STRENGTHENING SOLID WASTE MANAGEMENT IN KHARTOUM STATE IN THE REPUBLIC OF THE SUDAN WASTE AMOUNT AND COMPOSITION SURVEY By ENERGY & WASTE TREATMENT SRRVICES COMPANY (EWASCO) Table of Content,” no. October, 2016.

[25] C. Production, B. Ismail, F. B. Sc, and E. E. Yassin, “Management of PET Plastic Bottles Waste Through Recycling In Khartoum State,” 2010.

[26] D. L. B. Road and S. Africa, “SECTION A . Description of project activity,” vol. 0022, pp. 1–81, 2015.

[27] S. A. Aziz Mohammed Yadi, “Assessment the Efficiency of Solid Waste Management Tayba Al Hasanab Landfill, Khartoum Municipality Sudan,” *Biomed. J. Sci. Tech. Res.*, vol. 10, no. 2, pp. 1–4, 2018.

[28] A. J. Dubanowitz, “Design of a Materials Recovery Facility (MRF) For Processing the Recyclable Materials of New York City ’ s Municipal Solid Waste by Master of Science in Earth Resources Engineering,” no. May, 2000.

[29] M. G. K. Charles R. Rhyner, Leander J. Schwartz, Robert B. Wenger, *Waste Management and Resource Recovery*. 1995.

[30] “Scuola di Ingegneria Civile , Ambientale e Territoriale Milano - Leonardo Master of Science in Environmental and Land Planning Engineering Lecture notes of Solid Waste Management and Treatment MECHANICAL-BIOLOGICAL TREATMENT TECHNOLOGIES MECHANICAL-BIOLOG,” pp. 1–30, 2017.

[31] V. Krishna and S. Chaurasia, “International Journal of Scientific Research and Reviews Assessment of approximate chemical formula and energy content by Modified Dulong formula of municipal solid waste of Allaha...,” no. November, 2019.

[32] Ministry of Housing and Urban Affairs, “Sorting and Material Recovery, Chapter 8,” India.

[33] C. Polprasert, *Organic Waste Recycling*, vol. 6, no. 0. 2015.

[34] M. Grosso, "Composting is carried out by microorganisms , such as : They already exist in the input waste , but optimal conditions for their survival and reproduction have to," pp. 1–21, 2019.

[35] D. J. L. Forgie, L. W. Sasser, and M. K. Neger, "Compost Facility Requirements Guideline : How to Comply With Part 5 of the Organic," no. March, 2004.

[36] S. Your and C. Pad, "Turned Windrow Composting Sizing Your Composting Pad," pp. 1–16.

[37] E. Epstein, *INDUSTRIAL COMPOSTING AND FACILITIES MANAGEMENT*. 2011.

[38] W. Management and F. Secondary, "Operational Manual on Composting for an Integrated Resource Recovery Center (IRRC)," no. March, 2012.