REPUBLIC OF CAMEROON
Peace-Work-Fatherland

Department of Environmental Engineering

REPUBLIQUE DU CAMEROUN
Paix-Travail-Patrie

Department of Civil, Architectural and Environmental Engineering

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REMEDIATION OF LANDFILLS USING LANDFILL MINING WITH RESOURCE RECOVERY AS TECHNIQUE

CASE STUDY: NKOLFOULOU LANDFILL, YAOUNDÉ

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Engineering (MEng) in ***Environmental Engineering***

Presented by:

NDIFORNGU ATEH SUH NKWEKEU

Student Number: ***15TP21012***

Supervised by:

Prof. Roberto RAGA

Academic year: **2019/2020**

DEDICATION

This work is dedicated to all researchers and engineers in the field who believe in sustainability and would use this work as a reference or guide.

ACKNOWLEDGEMENTS

This work is a result of inputs from so many people. It is with profound gratitude that I extend my appreciation to these persons:

- My Supervisor, **Prof Roberto RAGA** for his huge support, patience, concern, positive energy, motivation, encouragement, counsel, corrections, understanding and consistent follow-up which he gave throughout the research period. These all contributed a long way to keep me going and finally pull through.

- The Director of the National Advanced School of Public Works, **Pr. NKENG George ELAMBO**, as well has the Head of Department for Environmental engineering Pr. **TALLA André,** for providing a conducive working environment and for their reminders and academic follow-up throughout my cycle in this institution.

- My Field Supervisors, **Mr. NOUTAT Steve and Mr. NKOSU Yannick**, for their hospitality, corrections, concern, availability, advice and mentorship throughout my period of field work. Their leadership skills and work atmosphere contributed to the success of this work and I'm so grateful.

- My Work Colleagues, **Mr. NANA Stephane** and **Mr. TCHANGA Simplice** who assisted me and gave me all they could do in their power to make sure I was able to do my work successfully as well as the entire HYSACAM staff at the landfill for their hospitality.

- My Course mates for their great encouragement towards each other and all other manner of support.

- My Lovely parents, **Mr. NDIFORNGU Abraham** and **Mrs. NDIFORNGU Gladys** for their all-weather support morally, spiritually, physically and financially. They powered me together with my siblings and friends and enabled me not to give up when things were tight and very difficult. Their encouragement made me ride on to attain this level.

- The **Almighty GOD**, my source, the giver of all good things, the one who brought me thus far and placed all these people in my life, the one through whom I can do all things as he enables. You made everything possible and even more. I'm very grateful for these and all others I'm yet to behold.

LIST OF ACRONYMS AND ABBREVIATIONS

PAH : Polycyclic Aromatic Hydrocarbons 37
PCB : Polychlorinated Biphenyls 37
PCE : Tetrachloroethene 40
RCRA : Resource Conservation and Recovery Act 18
RDF : Refuse Derived fuel 28
SITRAM : Engineering, works and Maintenance company (Société d'Ingénierie, de travaux et de Maintenance) 43
SOCAVER : Cameroon Glassware Company (Société Camerounaise de Vererie) 25
SOFAMAC : Construction Material and plastic Manufacturing Company (Sociéte de Fabrication des Matériaux de Construction et Plastique) 26
SVOC : Semivolatile Organic Compounds 37
SWA : Solid Waste Analysis 57
TCE : Trichloroethene 40
TOC : Total Organic Carbon 39
UNESCO : United Nations Educational, Scientific and Cultural Organization 2
US EPA : United Stated Environmental Protection Agency 2
VFA : Volatile Fatty Acid 51
VDP : Paris Tipper Truck (Ville De Paris) 58

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ABSTRACT

Developing countries such as Cameroon face a lot of challenges managing Municipal Solid waste landfills which are inherent feature in most cities. These usually pose threats to the environment and consume valuable land which could rather be optimized and the waste converted into a revenue generating asset. A city like Yaoundé with an increasingly huge population and rapid urbanization rate is a typical example facing this challenge. This study was an attempt to evaluate the potential advantages of mining out waste from the Nkolfoulou landfill as both remediation technique, a means of gaining airspace and a means of recovery of deposited material thus increasing the flow of secondary resources. The study had as specific objectives, assessing; i) the limitations of the current emission management ii) the recovery potential of materials by both open-dump mining and landfill mining iii) the possible gain in airspace, the economic and the environmental impact of mining out waste from the landfill. Waste sampling and characterization largely based on an adapted version of the MODECOM which is the French standard for Characterization was carried out for six districts (Yaounde1-Yaounde 6). The results obtained revealed the non-effectiveness of the current emission management, that open dump mining would yield a potential of roughly 22% of recoverable material and 29.2% gain in airspace per hectare which is more significant than the 1% average recovery potential and gain in airspace from the present recovery system. This would consequently prolong the lifespan of the landfill by two additional years. Also, the landfill mining possesses a recovery potential of 19% but to address the current state of the landfill and economy, feasibility for pretreatment of waste by open dump mining proved very beneficial and would be advised as a primary barrier and preferred to landfill mining.

Key Words: *Recovery potential, open dump mining, landfill mining, characterization, airspace.*

RESUME

Les pays en développement comme le Cameroun font face à de nombreux défis dans la gestion des décharges ménagers et assimilés, qui sont inhérentes dans la plupart des villes. Ils constituent une menace pour l'environnement et consomme de terres précieuses qui pourraient plutôt être optimisées et les déchets transformés en un actif générateur de revenus. Une ville comme Yaoundé avec une population de plus en plus importante, donc taux d'urbanisation rapide, est un cas typique face à ce défi. Cette étude a été une tentative d'évaluer les avantages potentiels de l'extraction des déchets de la décharge de Nkolfoulou à la fois comme technique d'assainissement, moyen de gagner de l'espace aérien et un moyen de récupérer les déchets ainsi augmenter le flux de ressources secondaires. L'étude avait pour objectifs spécifiques: l'évaluation (i) Les limites de la gestion actuelle des émissions, ii) le potentiel de récupération des matériaux par l'exploitation minière à ciel ouvert et l'exploitation minière des sites d'enfouissement iii) le gain possible dans l'espace aérien, l'impact économique et environnemental obtenu de l'extraction des déchets de la décharge. L'échantillonnage et la caractérisation des déchets, largement basés sur une version adaptée du MODECOM qui est la norme de caractérisation Français, ont été effectués pour six communes d'arrondissement (Yaoundé 1 – Yaoundé 6). Les résultats obtenus ont révélé l'inefficacité de la gestion actuelle des émissions, que l'exploitation minière à ciel ouvert donnerait un potentiel d'environ 22 % de matières récupérables et un gain de 29,2 % dans l'espace aérien par hectare, ce qui est plus important que le 1% potentiel moyen de récupération et de gain dans l'espace aérien du système de récupération actuel. Cela prolongerait donc la durée de vie de la décharge de deux années supplémentaires, Aussi, l'exploitation minière des zones déjà exploitées, possède un potentiel de récupération de 19%, mais pour faire face à l'état actuel de la décharge et l'économie, le prétraitement des déchets par l'exploitation minière à ciel ouvert s'est avérée très bénéfique et serait conseillé comme barrière primaire et privilégiée à l'exploitation minière des sites d'enfouissement.

Mots clés: Potentiel de récupération, exploitation minière à ciel ouvert, exploitation minière des sites d'enfouissement, caractérisation, espace aérien.

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GENERAL INTRODUCTION

The rising population in the world today is faster than any time recorded in history and has led to so many challenges, one of which is the problem of Solid Waste Management. A lot has changed from the 1 billion people that lived on the planet in the 1800 to todays 7.8 billion and a projection of about 11.2 billion by 2100 (UN, 2019). Around the world, waste generation rates are rising. In 2016, the total amount of solid waste generated by the world's cities was estimated at 2.01 billion tons, amounting to a footprint of 0.74 kilograms per person per day. With rapid population growth and urbanization, annual waste generation is expected to increase by 70% from 2016 levels to 3.40 billion tons in 2050. (The World Bank Group, 2021)

In developing countries, cities are more severely impacted by unsustainably managed waste. Over 90% of waste is often disposed in unregulated dumps or they are usually openly burned. These practices create serious health, safety, and environmental consequences. Poorly managed waste serves as a comfortable breeding ground for disease vectors, contributes to global climate change through methane generation, and can even promote urban violence. Therefore, managing waste properly is essential for building sustainable and livable cities, but it is still a big challenge for many developing countries and cities. Effective waste management is expensive, often comprising 20%–50% of municipal budgets and operating this essential municipal service requires integrated systems that are efficient, sustainable, and socially supported (The World Bank Group, 2021).

Another global challenge on the rise caused by this population rise, is meeting up with the demand for minerals which was estimated to rise by 25% between 2000 and 2050 (E Kesler, 2000). This has a direct impact of on the extractions of mineral, as pressure for exploitation mounted over the years for example; copper whose production rate has increased from 700 tons in the 1900 to 20,000 tons in 2017 and Nickel, was estimated to have 15 remaining life years as of 2012 (Statista, 2019). This statistics imply that just as the production rate for the minerals increases due to high demand, the quantity in mines are quickly depleting. Obviously this could have been perceived considering the fact that as valuable as minerals are, they are finite and non-renewable. While trying to manage the problems related to massive extraction of minerals, environmental studies have portrayed that even the mining activities generates a lot of waste which needs to be properly handled if not could be of potential harm to humans, animals and the entire ecosystem at large (UNESCO, 2015). According to Lottermoser (2010), mine waste constitutes the greatest amount of waste produced by an industrial operation, in the range of millions of tons per year for solid wastes alone. The various problems associated to mineral extraction and production would have to be addressed in one way or the other.

Circular economy has proven beyond reasonable doubts as a measure to accommodating and managing these global challenges. The concept is based on three principles: I) design out waste and pollution; ii) keep products and materials in use; and iii) regenerate natural systems (Ellen MacArthur Foundation, 2019). The model has as aim to provide a better alternative to the dominant economic development model known as the Linear based or the "take, make and dispose" (Ness 2008), as it embraces so many dimensions including the lifecycle of products, from when they are made, consumed, essentially handled, discarded or brought back to a second life. The negative effects caused by the linear are threatening the stability of the economies, and the integrity of natural eco systems responsible for human survival (Ellen MacArthur Foundation 2012; Preston 2012). By circulating these materials instead of discarding them, the hope is that the availability of resources, especially the non-renewable resources like minerals will not only be secured on the long run but that it also brings environmental and economic benefits while doing so (Ellen MacArthur Foundation 2013).

Based on EPA factoids, the recycling of steel and tin cans saves between 60 and 74 percent of the energy used to produce them from raw materials while at the same time, it saves the energy equivalent of 3.6 barrels of oil and 1.49 tons of iron ore over the production of new steel; recycling aluminum uses less than 5% of energy required to make the original product; plastics recycling requires only two-thirds of the energy required to manufacture it from raw materials; recycling glass will require 30% less energy than producing from virgin material and paper recycling requires just about 60% of energy used to make from virgin wood pulp (US EPA, 2016).

Generally circulation practices are regarded as more labor intensive than the resource intensive mining sector (Ayres, 1997), which implies that logically, circular economy is expected to be more economically beneficial in creating new work opportunities. It is estimated that by 2030, the number of additional jobs would exceed 75 000 in Finland, 100 000 in Sweden, 200 000 in the Netherlands, 400 000 in Spain and half a million in France. This is due to the fact that an economy favoring repair, maintenance, upgrading, remanufacturing, reuse, recycling of materials and product-life extension, is more labor intensive than both mining and manufacturing of a linear economy (Wijkman and Skånberg, 2017).

An essential cornerstone of circular economy is waste management, which is the area where it has been most implemented. However, in African cities as in many other developing countries, waste management had been simplified to collecting and dumping in landfills and to an extent, some form of landfilling is practically the only way solid waste is being treated and disposed. But in recent times, land around cities is being exhausted by the building of settlements to accommodate the growing population thereby making it increasingly more expensive and siting of new landfills becomes more cumbersome. As a consequence, the road of integrated solid waste management has to be taken and new treatment and disposal techniques developed in order to suit the changing economy (Fredrick, 2013).

Problem Statement

In Cameroon, Towns and cities face lot of challenges in managing their waste as perceived in most developing countries and these poor solid waste management services in towns and cities in Cameroon is attributed to several factors including inadequate financial resources, lack of a concise legislative framework on waste management, low level of enforcement of regulations and poor governance. These have contributed significantly to reducing standards of living and led to environmental degradation of the town. Waste treatment is being handled at the level of the various city councils. These have signed contracts with private companies and individuals thereby delegating responsibility to them of which the leading enterprise for managing solid waste in the nation is HYSACAM (Hygiene and Sanitation Cameroon). The process of managing the waste runs from collection, transportation to treatment which is mainly landfilling.

In Yaoundé, though the waste treatment by landfilling is recognized to meetup with standards given that structures have been put in place to manage emissions (gas and leachate), the topic is still being subjected to a lot of debates based on a lot of studies as per its low efficiency, hence huge environmental impacts. There could be a huge potential for circular economy as majority of these waste could be mined and recycled but lack of proper infrastructures to enable these have led to continuous increases in the amount of waste which ends up buried in landfills.. The general influx of waste also contributes to accelerate the filling up of the landfill hence increasing the need to speed up findings for a new site which would be subject to another dose of pollution. Considering the fact that the town has experienced significant changes in its land use since the 1990s and this is attributed to intensification of agricultural activities and urbanization, siting a new landfill becomes a problem and leaves us with no option than finding alternatives such as remediating the landfill.

RESEARCH QUESTION

Bearing in mind these challenges faced in dealing with solid waste management in Yaoundé, the state of the economy and the current situation of the landfill:

“Could mining out waste with resource recovery from landfills avail as an effective economic and environmentally beneficial remediation technique for the Nkolfoulou landfill?”

Objectives

- Main Objective:

  These thesis had as main aim, to mine waste from the Nkolfoulou landfill and characterize so as to reveal the environmental benefits, assess the resource potential and gain of landfill airspace.
- Specific Objectives:

i. To examine the current management of emissions and bring out its limitations

ii. To assess the resource potential of material in the landfill, its reusability and recyclability by both open dump mining and landfill mining.

iii. To estimate the possible gain landfill in airspace, the economic and the environmental impact of mining out waste from the landfill

Scope

This study was limited to waste produced from municipal Landfills and so any waste from mining or metallurgical processes, waste from construction and demolitions as well as hazardous waste and biomedical waste were excluded and the focus source were households, markets, offices, schools, other institutions and non-hazardous waste from enterprises. The reason landfills were chosen as an area of focus is because they are found almost everywhere; in regions, towns and even some villages and so if these dumpsites could be recognized as "local mines", a lot of potential could be withdrawn and consequently, development would be fostered to the benefit of not only man but the environment as well. Several categories of waste could be found in a landfill such as plastics, glass, metals, textiles, combustibles. However the first three will be emphasized because they have proven to carry significant recovery potential not only in our case study, but also in real life projects to suit the world of today with its many environmental problems and also, they are potential secondary resources which could bring employment and revenue to the economy. Nevertheless other materials will be recognized given that a variety of materials could be recovered from landfills.

My main focus during this research was studying how to reduce the impacts of our modern landfills on the environment while bringing out the importance of recovering materials from landfills. In as much as the theme highlights landfill mining, waste composition was studied for both fresh (open dump mining), and old waste (landfill mining). Considering previous landfilling activities for the past decades, potentials of landfill mining would be assessed as a tool for future use either for rehabilitation of landfills or as preliminary barrier in case the mass of waste could be re-landfilled elsewhere or even as a means to further recover material.

The Structure of the Research work

The thesis is comprised of four chapters. A short description is given on the various chapter content below:

This thesis begins by an introduction which outlines the problem and question this research addresses. It is followed by the first chapter which gives definitions of keywords and important concepts used in this work, a presentation of the study area, review of literature on solid waste management, landfills, the chosen remediation technique chosen and its applicability thus far. Then a brief presentation of other remediation techniques is done at the end of the chapter. The Second chapter describes the methodology; the methods and material used to carry out this research work. The third chapter follows suit with the presentation of results and analysis then the recommendations and proposals are brought forward just before a general conclusion closes the work.

CHAPTER 1

BACKGROUND AND LITERATURE REVIEW

1.1. Definitions of Concepts and Key words

1.1.1. Waste

Waste is a term used to describe any material which is has lost its marginal value in the eyes of the owner. According to the UK government, waste is defined as any substance or object which the holder intends or is required to discard. Waste could exist in many forms;

- Liquid waste which encompasses wastewater, fats, oils and grease (FOG), used oils, fluids, sludge and hazardous household liquid (Waste Disposal Inc, 2019).
- Gaseous waste are oxides of carbon, sulphur dioxide, oxides of nitrogen, hydrocarbons, aerosols, carbon monoxide, methane, Green house gases like chlorofluorocarbon (CFC) etc. Due to the increase of factories, industrial areas and the number of vehicles, a large amount of gaseous wastes go up to the atmosphere.
- Solid waste are waste which are any discarded or abandoned materials usually generated from human activities. They either be solid, liquid, and semi-solid or containerized gaseous material (New York State, department of environmental conservation (www.dec.ny.gov).

Waste could be further broken into categories such as;

- **Hazardous waste:**

This is waste which is dangerous or potentially harmful to our health and environment (www.calpaclab.com). In order for a material to be classified in this domain, it must first be a solid waste (EPA, 2019). Solid waste is hazardous if it meets the criteria for hazardous waste. Some of this criteria involve; ignitability, corrosivity, reactivity and toxicity (www.epa.gov).

- **Industrial waste:**

  Industrial waste is solid waste generated by industrial or manufacturing process that is not a hazardous waste following the regulations under the subtitle C of Resource Conservation and recovery act (Laun, 2017). Industrial waste can be divided into hazardous and non-hazardous waste but generally, industrial waste refers to non-hazardous industrial solid waste (www.waste.zendesk.com).

- **Construction and demolition waste:**

The department of Energy and Environmental Protection of the state of Connecticut defines this waste as waste to be generated from construction, renovation, repair and demolition of houses, large building structures, roads, bridges, piers and dams (www.ct.gov)

- **Municipal waste:**

  The European commission considers municipal waste as waste collected by or on behalf of municipal authorities. The waste stream originates from household or similar waste sources such as commerce, offices and public institutions. This is bulky waste excluding waste from municipal Sewage Networks and municipal Construction and demolition waste. According to the United States, municipal waste can still be referred to as municipal solid waste consisting of items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint and batteries (EPA, 2013). The Organization of Economic Cooperation and Development (OECD, 2015) presents municipal solid waste as waste collected and treated on behalf of municipalities.

- **Biodegradable waste:**

Biodegradable waste is waste typically originating from plant or animal sources which can be degraded by other living organisms (microorganisms). They can be commonly found in Municipal solid waste such as green waste, paper waste and biodegradable plastics. Other biodegradable waste include human faeces, manure, sewage, slaughterhouse waste (www.byjus.com).

Non-biodegradable waste:

This is waste which cannot be decomposed by biological processes. Non-biodegradable waste which can be recycled are known as "recyclable waste" and those which cannot be recycled are termed "non-recyclable waste" (www.byjus.com)

- **Biomedical waste:**

Biomedical waste or medical waste is any kind of waste that contains infectious material. This includes waste generated by healthcare facilities like physician's offices, hospitals, dental clinics, laboratories, medical research facilities and veterinary clinics (MedproDisposal, 2018). The Medical waste Tracking Act of 1988 defines medical waste as waste produced during medical research, testing, diagnosis, immunization or treatment of either human beings or animals.

The Cameroonian decree of 2012 defines medical and pharmaceutical waste as all waste which is produced as a result of diagnostic activities, the follow up and preventive treatment with curative or palliative motives in the domain of human or animal health.

- **Agricultural waste:**

These are all waste produced as a result of agro-pastoral activities.

- **Inert waste:**

Inert waste is any waste which is inflammable, non-biodegradable which neither reacts physically nor chemically, it doesn't contain dangerous substances liable to generate nuisances.

Waste management is the application of techniques to ensure an orderly execution of the various functions of collection, transportation, processing, treatment and disposal of waste (Debabrata 2019).

1.1.2. Landfills:

A landfill is a site built up for waste disposal either onto or into land. Generally, landfills are classified into three different categories;

- Hazardous waste landfill,
- Non-hazardous waste landfill,

- Inert waste landfill

Landfilling one of the final control measures through which waste is disposed and treated. It consist of collecting the waste, compressing it and burying it in sites reserved for the purpose.

1.1.3. Remediation:

This is every action taken in step 'to rectify, to make good' (Bradshaw, 2002) or 'action taken at a site following anthropogenic disturbance to restore or enhance its ecological value' (Emu Ltd., 2004), hence emphasizing the action or process rather than the end-point reached (Bradshaw, 2002).

Landfill remediation is every action put in place for the continuous abatement of the negative impacts of waste on the environment and natural resources. The goal is to reduce detrimental impacts on the environment during the entire life cycle of the landfill, especially the pollution of surface waters, ground waters, soil and air (the emission of greenhouse gases), to reduce the risks on human health which could arise from poor management of waste and to sustainably prolong the life span of the waste landfill, i.e. the goal is to bring waste landfills to an environmentally acceptable state (Environmental Protection and Energy Efficiency Fund, 2021)

1.1.4. Landfill mining:

Landfill mining is defined as a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground (Krook, 2012). It involves the excavation and processing of solid waste which had previously been landfilled. It is a remediation technique with multiple benefits; the reduction of environmental impact, landfill airspace recovery as well as recovery of useful fractions and recyclable material.

1.1.5. Open dump Mining

This is a waste management method that could significantly reduce the environmental and socio economic impacts of landfills through the withdrawal and recovery of waste having a resource potential before any final capping is done. It equally presents benefits such as materials and energy recovery and land reclamation.

1.1.6. Resource Recovery:

It is using waste as an input material to create valuable products as new outputs, with main aim to reduce the amount of disposed waste, thereby reclaiming landfill space and optimizing the values created from the waste. It delays the need to use primary raw materials in the manufacturing process. This greatly reduces production costs and is a potential economic strategy and has great environmental benefits.

1.2. Presentation of Study Area

This study was carried out in Yaoundé, the capital and second largest city in the nation (68.953 square kilometers). It is found in the Centre region which is further divided into ten divisions among which is Mfoundi division is one and Yaoundé is capital. The Mfoundi division is further divided into seven districts, numbered Yaoundé 1 to Yaoundé 7. Yaoundé possesses the biggest Municipal landfill in the nation. The present state of the population in this town is approximately three (3) million inhabitants. On daily basis, its Municipal Landfill records an average of 1400tons of waste deposited at the landfill. This could be seen as a result of the nature of the town (size), the population increase which is still on the rise and the many economic activities which flood the town. This ranks it the second highest daily waste collection in the country.

Location and description of Study Area

I. Location

The Municipal landfill of Yaoundé known as "Centre de Traitement des déchets" (CTD) is located 16km from the city center at the North eastern part between Yaoundé and Soa, in the Nkolfoulou I village (in Mefou and Afamba division, in the Sub divisional council of Soa) between longitudes 11.20^0-11.40^0E and latitudes 3.45^0-4.00^0N. (See Fig.1)

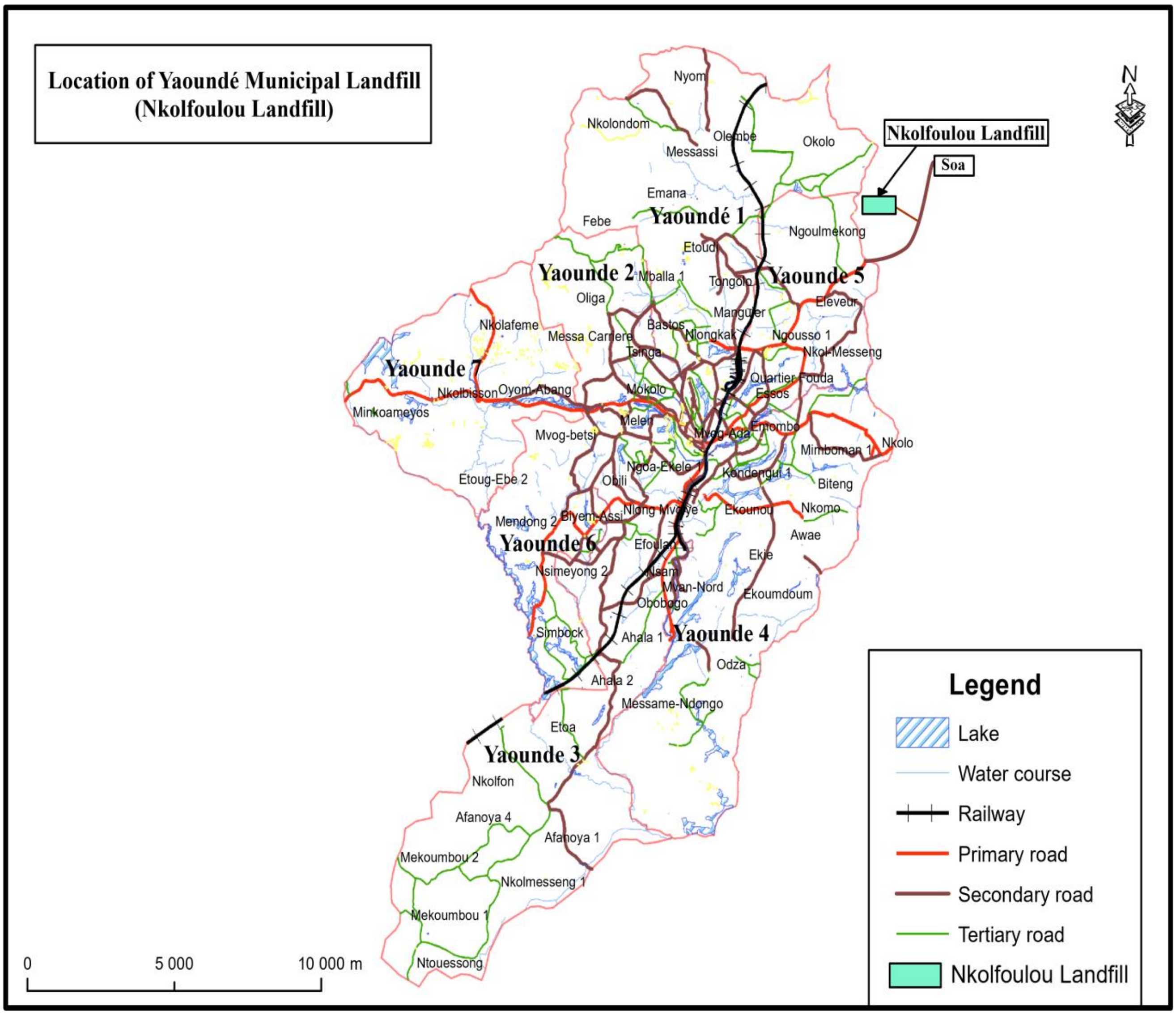

Fig 1: Location of Nkolfoulou Landfill

(Source: ArcGIS, 28/04/2021)

Other neighboring villages to the landfill are the Nkolfoulou II and the Nsan. This piece of land is located in the valley of the Foulou River which is a receptive medium for liquid waste from the Nkolfoulou landfill as well as runoff from diverse origins (MINMEE, 2004), and has a surface area of 56 hectares which is equivalent to 560,000 square meters of land. The Nkolfoulou village displays similar trends in climate and geology among many others as the observed in Yaoundé town.

II. Description of Study Area

The figure below shows the site topography and distribution of various service zones within the landfill area following an operational plan.

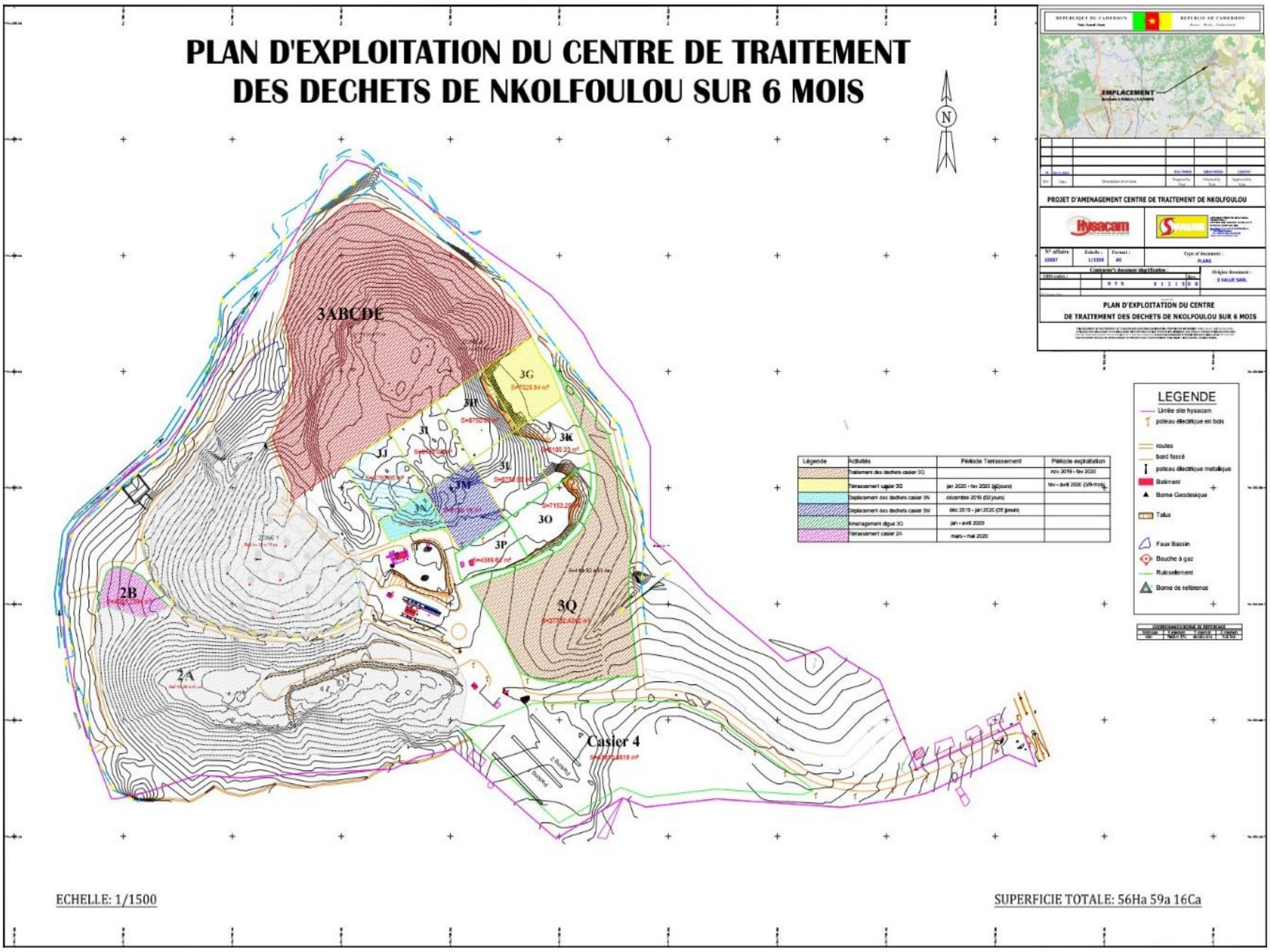

Fig 2: Operational plan of Nkolfoulou Landfill

(Source: Nkolfoulou landfill)

- **Climate**

This site in found in an equatorial zone characterized by four seasons, (long and short dry season alternating with long and short rainy season) with the rainy season covering a longer period of 8 to 9 months with an average precipitation of 1727mm registered as at 2021 (climate-data.org).

- **Air quality**:

Air quality in Cameroon is not a parameter that is thoroughly studied and as a result the highest criteria used to qualify air is land use. The activities which have the most significant effect on the air quality in the area of study are: emissions from vehicles transporting students and business people to Soa and beyond aside all other normal road users and waste trucks to and from the landfill; agricultural burning for purposes of managing waste, disease control and soil enrichment; burning of wood as a home based combustible and lastly biogas released from waste in landfill. Therefore, this area is likely to have a lower air quality index as compared to other parts of Cameroon.

- **Geology**

The geomorphology in the eastern and western parts of the city is mainly composed of para- derived migmatites and so is the case for the Nkolfoulou village. Ortho-derived migmatites which are very dark gneiss, massive and are basic gabbrodiotic in nature. They are composed of biotites, alkaline feldspar and plagioclase and are found in river beds such as the Foulou river as well as hillsides. (ABUHNGIENDO, 2004).

Soil and water investigations in 2003 by the geological sections of the design office revealed that the treatment center is located in an area consisting of;

- A slightly sandy clay approximately 1.8to 2.5. thick
- A reddish laterite breastplate approximately 0.7 to 1.5m thick
- A lateric breastplate of approximately 3m approximately 3.2 m to 8m followed by decomposed a rock layer.

The presence of clay gives the soil a certain degree of permeability and the characteristics stated above portray a small proportion of sandy soil but it does not affect the impermeability of the soils. The first layer of "Centre de Traitement des déchets" CTD is waterproof. In the second, the laterites are well structured and permeable. Underneath the clay, the breastplates found which are impermeable. However the breastplates are generally discontinuous in space and leave pockets that allow water to infiltrate. If the CTD of Nkolfoulou is on a continuous part of the breastplate, it will be perfectly waterproof. However, no information was available on the continuity of these layers in the CTD.

Generalities concerning the landfill

This site was negotiated in the 1980s between the Yaoundé city council and the village people of Nkolfoulou and came to effective use in the 1990s. It came to replace the old sites at Ngousso and Nkolewoe. The Treatment center is managed by Cameroon Urban Hygiene and Sanitation Property (HYSACAM) which is the leading waste management company in Cameroon. This was established by a contract in the late 90s which was signed by the Yaoundé city councils and the Cameroon Government. It stipulates the kind of waste to be collected which are: waste from households, public roads, paths, markets, public institutions such as schools, hospitals, small businesses, artisans and offices. The contract excludes waste from exploitation of public works, factories and industries, construction and demolition, commercial, anatomic or infectious waste from hospitals and clinics i.e. hazardous waste (CUY: "Communauté Urbaine de Yaoundé et al, 1998).

In addition to Municipal solid waste collected by the company, the landfill also receives waste from some partners such as smaller NGOs who do door to door collection as well as non-hazardous waste water and specific waste from institutions such as SECA (Services Camerounais D'Assainissement). Aside the collection and treatment of waste, the company is equally responsible for the daily manual and mechanized routine of sweeping of some streets, avenues and boulevards; public places and markets in the Yaoundé city area.

The major characteristics of the site which were the reason for attraction towards it are as follows;

i. Its Location: As afore mentioned, the landfill is situated 16 km (road length distance) from the city center and at least 1km away from residential areas.
ii. The Large size: The site is 56hectares allowing use for twenty years and above
iii. The Gentle slope which gives way for a suitable flow of leachate by gravity and a lastly the presence of a heavily rich clay soil whose permeability has been studied and attested

to be appropriate for use (as a barrier beneath and as a cover above the waste) in the landfill.

Entry into the facility is controlled at a gate 2 km away as seen in fig above which presents the topography of the site as well as the distribution of the various zones within the landfill area. However the structure of the landfill was modified a little due to the introduction of the "Mécanisme du Développement Propre" (MDP). The site receives an average amount of about 1400tons of mixed solid waste per day. The waste collection system is very well planned and efficient given that the company is paid with respect to the quantity of waste treated. This collection system is such that the site is opened 24 hours and the workers do their work in shifts of 7 to 8 hours (6a.m-2p.m, 2p.m-10p.m and 10p.m-6a.m). The drivers of the trucks which collect waste, equally work in shifts, each having a minimum amount of rotations to make and waste to have carried before the end of his shift. The landfill can boast of close to 120workers presently.

The staff is comprised of members from various departments (which are; the various controls at the weighing bridge, the maintenance, the MDP, the truck ushers and the Construction department) who work together in order to make sure the landfill processes are kept at optimal performance. We also notice scavengers who go about moving in the dump, sorting out items which are of significant economic value to them in the market such as plastics, metals, textile, glass, paper and cardboard, and tires, for either reuse or recycling. The presence of the scavengers as well as the activities they carryout is risky and not so formally authorized but it is however permitted since their activities are beneficial for the landfill and the environment at large.

1.3. Trends of Solid Waste Management

In the US and in Europe, waste was primarily disposed by dumping within cities until the 1800 when a link was identified between poor environmental conditions and disease (National Solid Waste Management Association, 2008). This was due to the geometric increase in population which reflected directly on waste generation of domestic and industrious waste.

The continuous piling up of waste gave birth to odors, disease breakout and contamination of water supplies. These lead to the death of about seventy five million people and it was termed Black Death. In attempt to mitigating this spread, waste management techniques sprouted and materials began being reused. The approach where materials were reused over and over was referred to as the "cradle to cradle system".

Back here in the African milieu, history has shown that the human existence was a peaceful and harmonious one as a result of what could be seen as proper waste management. In the ancient times (10000BC to 4000AD), given that the western world is always more advanced to Africa by 20-30 years, the major constituents of waste here in Africa were wood, food waste, vegetables, faecal waste etc. Waste was basically domestic and so generally biodegradable reason being that there were very few industries and the population was low. The little waste that was generated was separated into two portions, the portion which was still edible was given to animals and the other was simply allowed to decompose and it was a beautiful cycle. As population kept increasing and urbanization kept expanding, there was need for an effective and efficient waste management system.

A time came called the Industrial revolution in the western countries and so there was rapid growth and development in areas of trade, skill acquisition, product innovation and machinery development which was encouraged by the availability of raw materials was there coupled with good labor force. There after came the age of Sanitation which had as aim to prevent impending problems associated with improper management of disposal sites. Waste collection and disposal at designated sites was in operation. All these were aimed at maintaining public health, after which it was adopted and implemented in Africa due to colonization. Till now, environmental sanitation has remained a practice in most African countries (Bello et al., 2016). The sustainable management of solid waste streams is imperative to minimize environmental and public health risks around the world (ISWA, 2002; Fletcher et al., 2003; Ball, 2006).

1.4. Landfills as tools for Solid Waste management

The first ever landfill dates back to 3000BC, about 5000 years ago in Knossos (Crete) which is today known as Greece where large holes were dug and filled with refuse. The waste dumped were mostly wood, bones, ash from fires and vegetables and much attention or control wasn't needed since the effects of those holes couldn't have been as dramatic as in recent times. The simplicity and effectiveness of Landfilling made it probably the most ancient and organized mode of waste management dating from at least to ancient Athens (Mumford, 1961).

Since then, even with the introduction of other modes of managing waste (such as incineration and recycling), it has remained the most dominant mode of waste management (Kollikathara et al, 2009; UN-HABITAT, 2010). In 1937, the Circa 1937 Fresno Municipal Sanitary landfill was considered to have been the first modern sanitary landfill of its kind. This development came along with so many environmental disasters such as leaching of contaminated liquid into the soil and ground water, the release of overwhelming amounts of methane in air. In 1976, the Resource Conservation and Recovery Act (RCRA) defined the legislation for MSWM practice in America. It requested the closure of open dumps nationwide around 1980-1990 (Louis, 2004) and prescribed landfills to be lined with plastic, clay or both, thus effectively wiping out the idea of "dumps" or the old school trenches, thus the creation of landfills.

In South Africa, for general and hazardous waste, landfilling is the dominant waste treatment with an estimate of 90% of all waste generated disposed of in Landfills (Godfrey & Oleofse, 2017). This is typical of waste management in many developing countries, where waste disposal is often in uncontrolled dumpsites. A number of environmental impacts and human health issues prompted the government to develop policies and regulations aimed at improving the designs and operation of landfills with time. This was marked by the Environmental Conservation Act (Act 73 of 1989) and the Minimum Requirement Document series published by the Department of water affairs and Forestry. (DWAF) in 1994, which provided technical guidance for waste handling, classifying and disposal. The minimum Requirements were later replaced by the "National Norms and Standards for the Assessment of Waste for Landfill Disposal" and the "National Norms and Standards for Disposal of Waste to Landfill". Today the Bissar Road in Durban, South Africa is one of Africa's largest landfill sites opened for business in 1980 under the apartheid regime (Bond & Shafire, 2009).

Another danger that could arise from poor management of a Landfill is Landslides. In Addis Ababa, Ethiopia, the Kioshe landfill has been the only Landfill for over half of a century. As the city expanded, the landfill became part of the urban landscape sprawling over an area covering the size of 36 football pitches. Earlier in 2017, a landslide on the dumpsite was reported to have killed 114 people, prompting the government to declare days of mourning (United Nations Environment Program, 2017). Also, in Guatemala City in the Philippines, the slide of Landfill rubbish caused by Garbage pickers and scavengers who unknowingly destabilized the piles of waste while picking up materials from the base, caused the death of at least 50 people (Petley 2008). In the Mozambican capital, Maputo, in 2019, seventeen people were killed and several others injured in a landslide in a garbage dump due to heavy rain (www.xinhaunet.com). It is most likely that such landslides that often kill a few people are common but the majority undoubtedly goes unreported.

These dangers therefore provoked the addition of the concept of sustainability in creation of landfills. The 1987 report of the World Commission on Environment and Development defined "Sustainable development" as a development which meets the needs of the present generation without compromising the ability of the future generations to meet their own needs. This concept of sustainability lead to a new definition of Landfills by ISWA in 1992 as "the engineered deposit of waste onto and into land in such a way that pollution is prevented and after restoration, the land provided can be used for another purpose".

Therefore a sustainable landfill is one that, within a limited period of time, reaches a state in which the wastes no longer pose a potential threat to the environment (Huber-Humer and Lechner, 2013). This kind of landfill is one in which the waste materials are safely assimilated into the surrounding environment in way so as to manage leachate, gas and odor problems so as to minimize environmental impact as much as possible. Today we have much more of contained landfills i.e. landfills with both soil liners and top covers although with time, the liners wear out and so the escape of the products of waste degradation is inevitable. Hence, on the long term, usually has been proven to present more devastating effects as compared to what we call open dumps or traditionally old landfills.

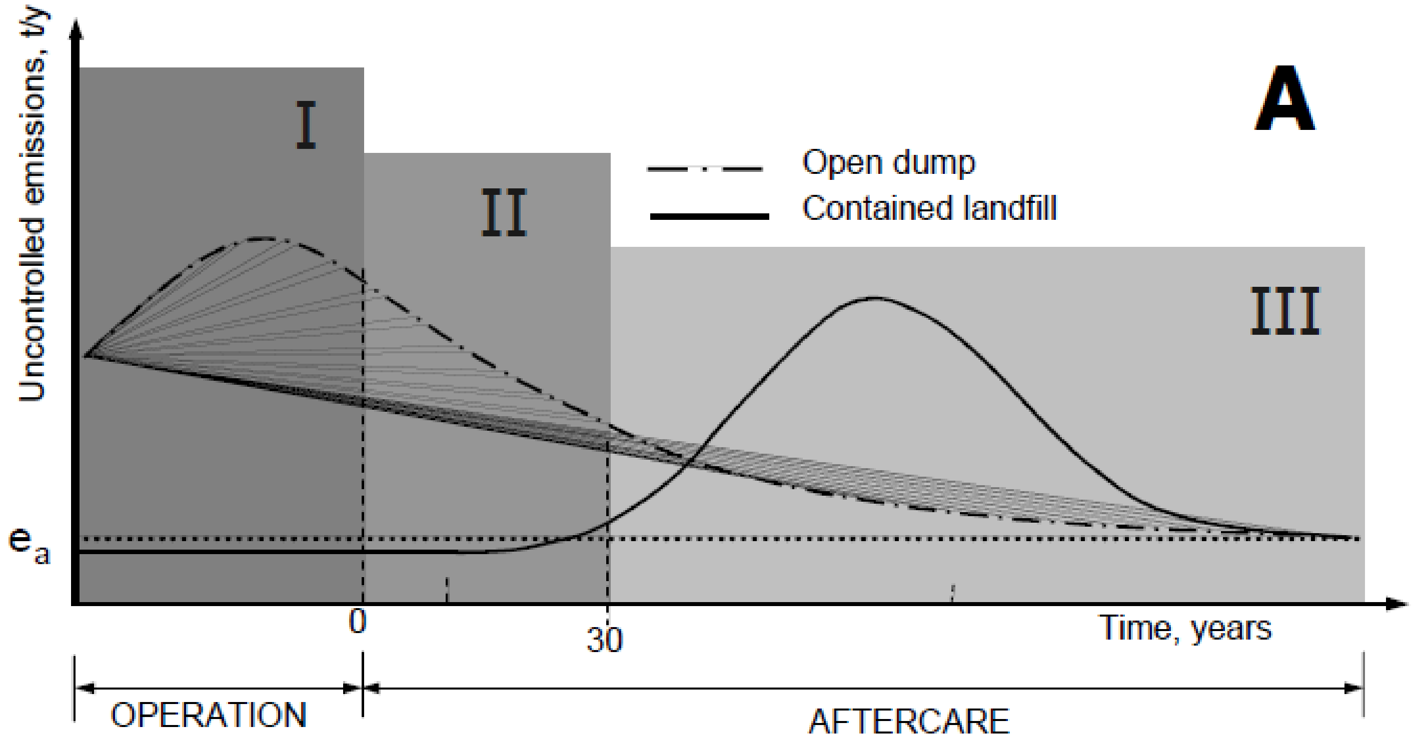

Fig 3: Uncontrolled emission patterns for open dump and contained landfills in different phases (I=Operation, II= Active aftercare, III= Passive aftercare

(Source: Cossu, 2005)

A secure or contained landfill is basically a bathtub in the ground and there are four critical elements which ensure its security namely: a bottom liner, a leachate collection system, a cover and a system for capture of biogas as described by Scott, 2003.

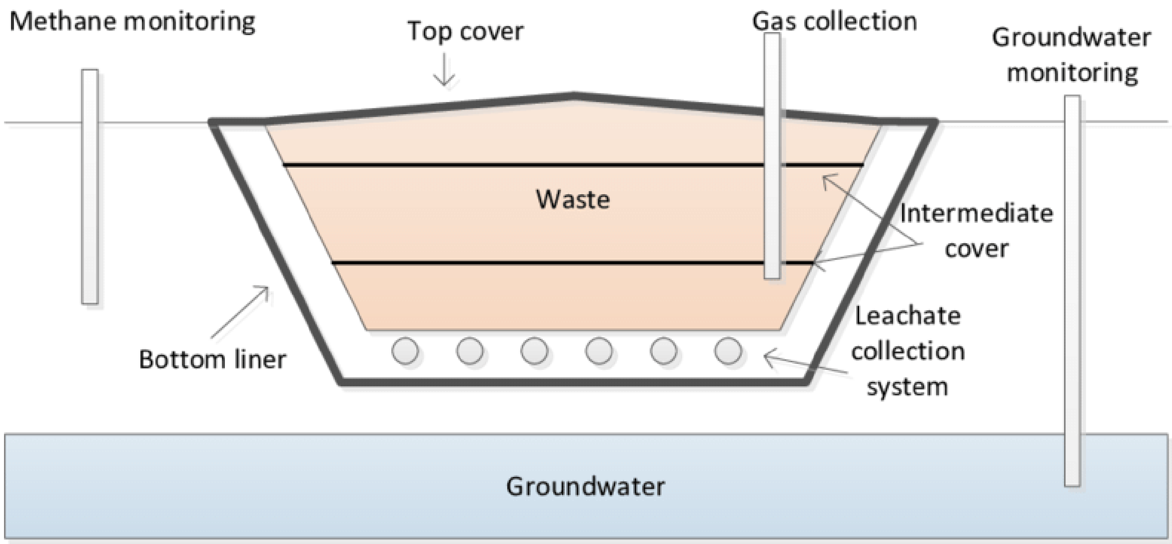

Fig 4: The major design components of a landfill based on Vesilind et al. (2002)

Limitations of components of a Sanitary or Contained landfill

- The liners which could be clay, plastic or composite on the long term eventually give way; for natural clay liners, it is often fractured or cracked and so diffusion will move organic chemicals like benzene and some other chemicals through a three foot thick clay landfill in approximately five years given that no compacted clay is totally impervious or immune to chemical reactions of various types. The very best liners today which are made of a tough plastic film called high density poly ethylene (HDPE). A number of household chemicals and stuffs such as margarine, vinegar, ethyl alcohol, shoe polish to name a few, will degrade HDPE permeating it, making it loose its strength, softening it, or making it become brittle and crack. Composite liners are made up of both plastic liner and compacted soil (usually clay) and will be slightly permeable to liquids and gases thus a certain amount of permeation should be expected
- The leachate collection systems can clog up in less than a decade from silt or mud. They could also clog up due to growth of microorganisms in the pipes or chemical reactions leading to the precipitation of minerals in the pipes. This weakens the pipes greatly and they could be crushed by the tons of garbage piled on them.
- The cover acts like an umbrella that keeps water out to prevent leachate formation. It consists of several sloped layers: clay or membrane liner, overlain by sandy or gravely soil and then

vegetative soil. Erosion by natural weathering can occur, vegetation can root to stabilize, burrowing animals, insects and reptiles could destroy the cover, subsidence due to settlement and even human activities (fires) could contribute to making tears and cracks on the cover, rain will consequently enter the landfill resulting to build up of leachates, overflow by the sides and pollution to the environment.

- The biogas extraction system could have basic infrastructure problems such as leakages due to gas pressure or loss of material due to human activities. (Zohaib et al, 2020).

Contained landfills (and even more critically dry tomb landfills) maintain a very low level of uncontrolled emissions during the operation and active aftercare phases in coincidence with the efficiency of the physical barriers they are equipped. But when the barrier expires and liners fail, water infiltrates, gas is generated and leachate leakage occur, this uncontrolled emissions will be higher than in the open dumps, as the emission potential of the waste was preserved and the waste degradation/attenuation barrier was very low ("mummification effect", Cossu, 2005). Results from an experimental work on small rural old landfills (lined and unlined) showed proof of this theoretical considerations (Allgaier et al, 2001).

This implies that, appropriate site selection, design and management/maintenance are crucial to attain a more sustainable waste management (Westlake, 1996). According to the EU legislation, (Directive 99/31), any amount of solid waste must be subjected to treatment prior to landfilling in order to reduce the organic load and consequently the environmental impact from landfilling operations. When MSW is landfilled without pretreatment, emissions occur during and after landfill operations in the form of approximately 150m3/ton of biogas and 5m3 of polluted leachate depending on the composition and climatic conditions (Mavropoulos & Kamariotakis, 2009). Also, due to the biological degradation process, important settlings take place (between 20 to 25 % of the height of the landfill) which may damage the barriers of the landfill (Mavropoulos & Kamariotakis, 2009). The use of all these bottom liners and top covers as well as leachate treatment and biogas flaring plants represent great expenditures; at the level of the construction and maintenance for leachate and biogas treatment systems and the liners and covers have an operational lifetime of only three decades maximum as seen on the table below.

Table 1: Landfill's barrier duration X= Available (Mavropoulos & Kamariotakis, 2009).

Duration(years)	**10-20**	**20-30**
Geological barrier	X	X
Geomembrane	X	
Drainage	X	
Clay liners	X	X
Leachate treatment plant	X	
Biogas Treatment Plant	X	
Top cover	X	X

The figure presents the fact that emissions cannot be totally prevented in a landfill and so measures need to be taken to make sure that the environmental and financial cost in the management of these landfill operations aren't transferred to the future generations. The basic principles of a sustainable landfill as suggested by Mavropoulos & Kamariotakis (2009), are such that, the solid waste degradation has to be accomplished within the service lifetime of the landfill's barriers such that at the end the landfill doesn't represent a risk for the environment and public health which is really good but not quite feasible considering the current economy trend and urbanization rate in the world.

Herein comes the importance of remediation techniques as a tool to rectify the evil which has already been done by attempting to restore or restitute the ecological value of the site and also somehow adapt the today's landfills to current living standards. As the risks with landfills emanate from the deposited material, the recovery of those materials into resources has been proposed, similar to remediation, as a way to manage problems associated with landfills (Cossu et al., 1996; Hogland, 2002). Potential materials like minerals (metals, plastics, glass etc.) could be recycled and organics composted which would lead to reducing the leaching potential. Resource recovery could be integrated with remediation measures whereby, the extraction of disposed material will not only bring resources to the surface but also upgrade the landfills infrastructure to suit the current regulatory standards.

1.5. Integrating resource recovery with landfill mining as an innovative remediation technique for Landfills

1.5.1. Resource Recovery

Resource recovery, has as aim, to use waste as an input material so as to create valuable material as new outputs. These action contributes to reduce waste found in landfills and optimizes value from waste. It is a part of circular economy and it takes place at different levels in the waste management cycle depending on a lot of factors such as the policies, markets, regulations and the available structures. The concept could be viewed from several angles among which in collabo with landfill mining forms a powerful remediation technique in landfills. These will contribute to reducing future remediation costs and seeks to move waste upwards from the bottom of the solid waste hierarchy, to **recovery, recycling/composting** which have been ranked by the EPA government as **more preferred** to treatment and disposal wherein landfilling is the most common form. This is illustrated in the figure below

Fig 5: The US EPA Waste Hierarchy diagram

In Cameroon presently, there is no existing policy for waste separation or even recycling. However some recycling is done at source by some households, some at open dumps and skips and some equally done at the level of the landfill. The figure below illustrates a recovery flow diagram for Yaoundé

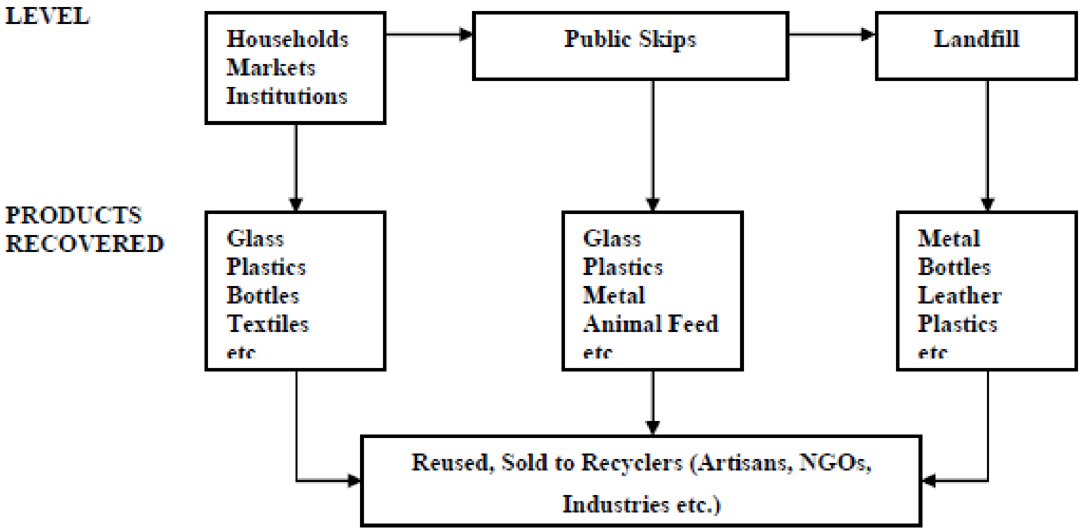

Fig 6: General waste recovery flow diagram for Yaoundé

(Source: Achenkang, 2004)

Recycling, is an undeniably important component of the waste management hierarchy yet it is not an activity on the fore front of the Central African countries but it is becoming increasingly implemented. Though it began with things done in a very informal way where some waste items were transformed by artisans such as household utensils from smelting aluminum, some thermoplastics into recycled plastic material, paper and carton into news print and reusing tires to flower pots, furniture or recycling into shoes and ropes, with time, structures (small and medium size enterprises) have risen so as to better process secondary raw materials.

In Douala, for example which is the heart of recycling in the country, the general recycling rate has increased from about 14% to 28% over the past decade. The leaders of Glass recycling which is SOCAVER has an estimated production of 105 tons of glass per day. Metal recycling enterprises are equally established with commodities for both domestic and international markets. Recycling aluminum requires less than five percent of the energy and emits only five percent of the carbon dioxide emissions when compared with primary production, according to the Ministry of Mines. The metal can be recycled indefinitely because reprocessing does not damage its structure. Aluminum is also the most cost-effective material to recycle and reduces the waste going to landfill. “Recycling 1 kg of aluminum saves up to 6 kg of bauxite, 4 kg of chemical products and 14 kWh of electricity, enough energy to light many homes for several hours. Each ton of steel that is recycled can save 1.5 tons of iron ore, 5 tons of coal, 40 percent of the water used in production, and 75 percent of the energy needed to make steel from raw material. It also saves 1.28 tons of solid waste and reduces air emissions by 86 percent and water pollution by 76 percent, compared to making steel from raw material (Monde Nfor, 2014).

Several private initiatives have erected with respect to plastic recycling in Cameroon; SICA, CIPRE, SOFAMAC, POLYPLAST, NAMe Recycling etc. In Yaoundé, a few formal NGOs emerged with time, some of which went out of operation due to the lower efficiency coupled with high competition from the brand new goods and ignorance on the part of the population on benefits of this practice. This is further discouraged with the absence of transfer centers and as a result of this, much ends up in landfills and so maximizing recovery by mining out waste here would avail very beneficial.

However, total reliance on recycling under the canopy of circular economy as a tool to solve the problems associated to mineral extraction and production has shortcomings such that as long as the consumption of resources increases and are held in use for a considerable period of time, the waste streams will always be smaller than the rising resource demands. Georgescu Roegen, (1971), asserted that, as consumption increases, recycling cannot meet the demand for the resources. Also, complete recycling is impossible as there will always be losses in the form of abrasion, oxidation or dilution.

1.5.2. Landfill Mining

Mining has to do with extraction of valuable resources from "mineral rich deposits". If the focus could be shifted from what is conventionally referred to as mineral rich deposits in discussions concerning mineral availability and sustainable development to the unseen reservoirs, then there could be an increase in recycling rate. This will counteract what was asserted by Graedel et al., (2011) whereby he mentioned the fact that the recycling rate of base metals in some countries is already too high and cannot know any significant increase. Waste deposits are unseen but highly potential resource reservoirs. About 300 million tons of copper for instance, is currently located in landfills and other waste repositories around the world (e.g. tailings and slag heaps), corresponding to more than 30 percent of the remaining reserves in known ores (Kapur and Graedel, 2006). Furthermore, landfills typically contain significant amounts of combustibles and earth construction materials (Cobb and Ruckstuhl, 1988; Obermeier et al., 1997; Hogland et al., 2004; Kurian et al., 2007).Given the evidence of this much potential which is buried in landfills all over the world, there is need to put in place strategies to recover these resources.

Landfill mining has been proclaimed as an innovative strategy whereby resources can be recovered, it has been proposed as a source of net addition of raw materials (Krook et al, 2012; Jones et al, 2013) both in terms of earth construction materials, metals and energy recovery from combustibles. Aside the Energy recovery and reuse of recovered materials, landfill mining is a remediation technique which could be of multiple benefits which are listed as follows;

- ✓ Elimination of potential contamination source
- ✓ Conservation of landfill space
- ✓ Rehabilitation of dump sites
- ✓ Reduction in waste management costs
- ✓ Redevelopment of landfill sites (Hogland et al, 1997).

According to an article written by Stephanie A 2019 published on SciDev.Net, there has been an increase in methane emission from Sub-Saharan Africa between 2010 and 2016. This increase has been related to human activities having waste management featuring amongst the prime sources. Given that these risks emanate from the materials that were previously deposited in the landfill in the first place, mining and recovery of these materials would serve to manage these problems associated with landfills (Cossu et al, 1996; Hogland, 2002). Materials having a potential recovery value such as minerals, could be recycled, organics composted and combustibles incinerated.

Aside reducing risks, another “resource” recovered in the process of landfilling is the landfill air space that is defined as the volume of space on the landfill site permitted for the disposal of Municipal Solid Waste (MSW). As the waste is excavated and material removed, the total volume of waste reduces and so the lifespan of the landfill increases. Landfill mining is equally quite feasible when projecting urban development because with rapid urbanization taking place, even the sites reserved at the outskirts of the town for landfills are beginning to stand in the way since free exploitable land is getting scarce and regulations concerning the creation of new landfills are also making things more difficult.

Therefore excavating and recycling of dumped material will create more space for more material to be dumped and postpone the closure of the present or recreation of new landfills (Spencer, 1990; Dickinson, 1995; Cha et al., 1997). The extraction of waste from disposal sites for recovery of valuable material is not an unprecedented ideology or concept. Far from that, landfill mining a practice that is actually widespread and relatively known and has been carried out so many countries over the last six decades with focus mainly on expanding the lifetime of the landfill and consolidating the material to facilitate closure and remediation of the sites. LFM projects (Savage et al., 1993) and the drivers have spanned from regaining landfill capacity to recovering valuable materials such as organic material for soil improvement purposes, refuse derived fuel (RDF) and metals (Hogland, 2002). This was confirmed in 2012 by Kroko et al where most initiatives involved some level of recovery mainly soil cover and in some cases waste fuel, the recovery of materials for recycling have often been secondary. The recovery of the land and materials, together with the aim of reducing surface- soil and groundwater contamination by remediating the landfill represent important drivers for LFM (Marella & Raga, 2014). This could also contribute to reduction of after care costs and other pollution-related costs.

Thus landfill mining in a way, internalizes materials previously externalized by the markets (Nils Johansson, 2016) and is believed to therefore limit the problems associated with mining of primary materials by creating an alternative stock of resources, while addressing the main problems of emissions in landfills which come as a result of the dumped waste. This does not in any way cancel the fact that the excavation and material valorization process could also lead to additional costs and impacts (Hermann et al., 2016). According to the Flemish Public Waste Agency in Belgium, the cost for landfill remediation (Landfill mining in this case) goes up as far 100 billion to1trillion euros. Moreover the challenges faced by this strategy are not minimized as they have led to low amount of high quality or high-value materials coupled with the high cost for its implementation the increasingly stringent regulation in waste management sectors as well as rising standards in the production industry (Krook et al., 2012). This is the reason why appropriate studies should be done before engaging in projects as such.

1.5.2.1. Global initiatives of Landfill mining over time

The first case was reported in Israel in 1953, whereby fertilizers were extracted from a Tel Aviv landfill using excavators and sorting equipment (Savage et al., 1993). In the 1990s interest in the practice grew in the United States, with one of the important divers for this interest in landfill mining during the 1990s being stricter environmental legislation such as the so-called Subtitle D regulations on management of non-hazardous solid waste. When stricter regulations were introduced and made permits for landfills harder to obtain, the landfill owners were forced to think innovatively and this lead to the exhumation of landfills and utilization of materials to increase the life span of the landfill, obtain valuable landfill space and postpone the expensive final cover (Spencer, 1990; Richard et al., 1996; Dickinson, 1995; Reeves & Murray, 1997; Cha et al., 1997). In Europe and Asia, the trend was similar but the drivers for landfill mining were primarily, the increased need for remediation of contaminated landfills and removal of landfills in the way of urban development (Cossu et al., 1996; Hogland et al., 1995; Hylands, 1998). In the city of Helsingborg, Sweden several cases of landfill mining have been carried out to create space for urban development and the remediation of leaking landfills (Hogland et al., 1995).

In the 2000s, landfill mining came this time with resource perspective as the main driving force, and about the same period, researchers began to study the flow of materials in a new way not as to predict future sources of pollution but as to identify where resources accumulated in the environment (Graedel et al., 2004; Sörme et al., 2001). Consequently several recycling actors have shown interest in the extraction of resources in landfills. Numerous excavation processes have been implemented today; in Germany (Franke et al., 2010), Italy (Zanetti & Goido, 2006), India (Kurian et al., 2003), USA (US EPA, 1997), Belguim (Jones et al., 2013) Denmark (Rosendahl, 2015) and Finland (Kaartinen et al, 2013), many of which are pilot scale investigations to explore feasibility of mining.

Although the waste mountains in Africa keep growing, formal waste mining remains a rare practice. However, sites are being assessed in some countries like Ghana, where the Oti landfill is being studied; Kenya, where the Dandora landfill is being studied (Eman El-Sherbiny, 2019) and in South Africa, where a trial mining operation in the Coastal park portrayed that enormous could be derived from mining landfills and described it as being viable (R Emery et al 2012). This new awakening whereby resource recovery becomes the starting point rather than a secondary issue, has pushed scientist to develop a holistic concept known as enhanced landfill mining (ELFM) which is defined by Jones et al., 2010 as "the safe conditioning, excavation and integrated valorization of landfill waste streams as both materials (Waste-to-Material) and energy (Waste-to-Energy) using innovative transformation technologies and respecting the most stringent social and ecological criteria and has been under development by the Flemish ELFM consortium since 2008 (jones et al., 2013). The "integrated" aspect refers to a maximum valorization of material and energy rather than some cherry picking approach. In this scenario, the technological innovation follows a value-chain approach from advanced landfill exploration, mechanical processing, thermochemical conversions and upcycling. This concept has as main goal to insert LFM in a circular economy context where most residues are upcycled and their presence in landfills minimized, thereby rendering landfilling sustainable.

1.5.2.2. Stages of landfill mining

Landfill mining takes place in two main stages mainly site exploration and material processing proper as described by Juan Carlos et al published on Detritus, journal for waste resources and residues in 2020.

a. Site exploration:

It has to do with the preliminary investigation on the physicochemical properties and material composition of the waste disposed in the landfill, from which economic, technical and environmental feasibility can be assessed. Information concerning the type of waste deposited in the landfill are not very evident and so usually, sampling or small scale excavations are usually done in order to determine the waste composition and characteristics while in worse cases, no previous analysis is done (Hernandez Parroddi et al., 2018). In case of invasive exploration, the excavated waste samples are classified according to material type and particle size which are used to determine the amount of material that might be valorized and the estimated remediation costs of the whole site (Bhatnagar et al., 2017; Cha et al., 1997; Garcia Lopez et al,. 2019; Hernandez Parrrodi et al., 2018b; Hogland 2012). However, with time the value of certain waste might diminish due to the degradation and contamination processes and so they may no longer be valorized.

From an ELFM perspective, geophysical methods such as the ones used for underground water or petroleum exploration, could be used to determine the material characteristics in a rough manner without the need of invasive, as well as to identify areas which could be rich with water content or certain materials, before carrying out the extraction of landfilled waste. The characterization of landfill subsurface using rapid and non-destructive means would greatly reduce exploration costs (Bobe et al., 2018) and be useful to develop a procedure to either discard or select the most appropriate sites for LFM according to specific criteria. The figure below represents the characterization of subsurface structures of a landfill from which information of the electric and dielectric properties are obtained. This type of analysis could enable types of material to be expected as well as the potential presence of metals or leachate level.

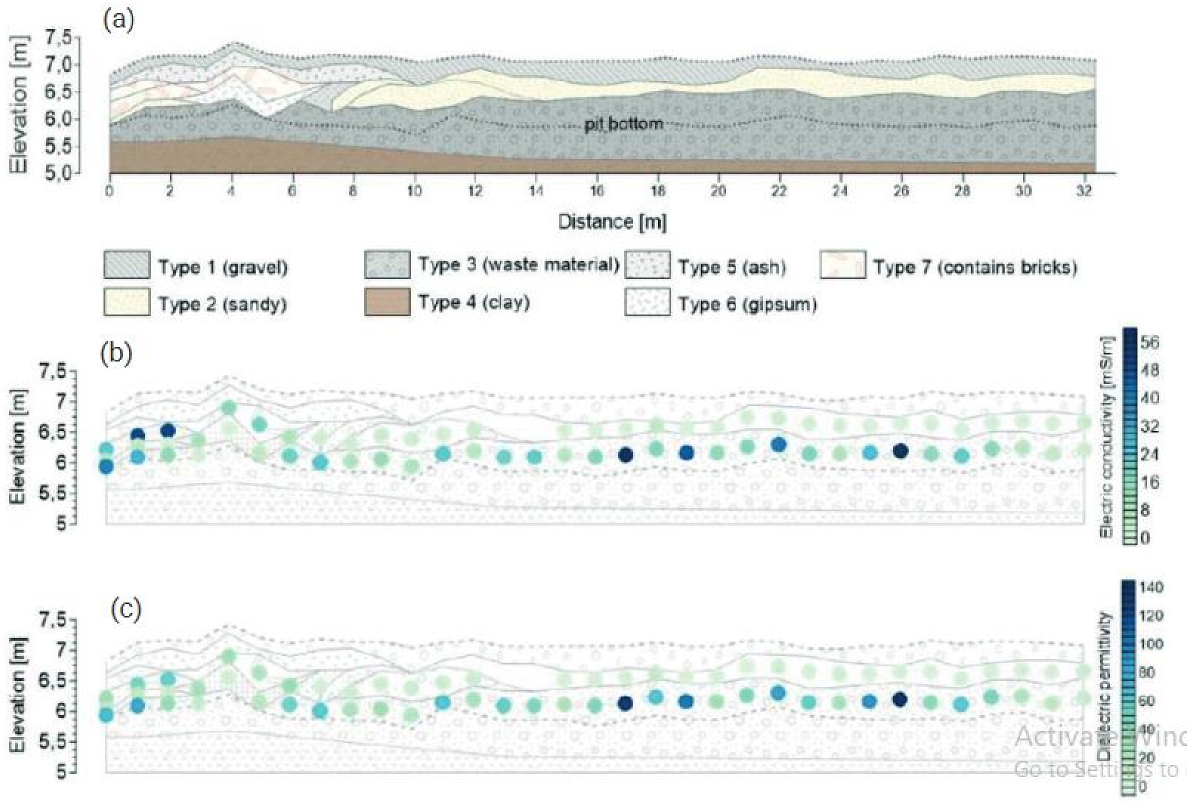

Fig 7: Schematic representation of the (a) profile description indicating the main types of material discriminated and (b) profile measurements of electric conductivity and (c) dielectric permittivity (Bobe et al., 2018).

b. Excavation and material processing:

This is the step which follows the site exploration and feasibility studies for the LFM. It is normally dune using bulldozers to remove the top cover and then the excavators dig out the waste which was previously landfilled and then load them in trucks which are then transported to the processing plant. The process which follows in the plant is mainly characterization and this activity has been facilitated with trommel sieving, magnetic separation and density classification, which some cases have shown marketable recyclables (Krook et al., 2012).

Moreover LFM has faced a lot of challenges over time, such as low amount of quality of high- value materials and increasingly high cost of implementation as well as stringent regulations in the waste management sector and rise of standards in the production industry over time (Krook et al., 2012). Nowadays, newer equipment's are being introduced and tested with promising results such as ballistic separators which can separate landfill waste into three different fractions, namely; three dimensional, two dimensional and an under screen fraction. This technology can be used to pre-process the landfilled waste directly after excavation and precondition the material for further mechanical processing (Garcia Lopez et al., 2019). Further processing such as drying, size classification, ferrous and nonferrous selection, metal separators, density separation methods and sensor based sorting could be used in order to sort landfilled waste into different material outputs (Hermamdez Parrodi et al., 2019; kuppers et al ., 2019) such as high calorific value materials (e.g. Plastics, woods, textiles, paper, cardboard etc.), ferrous metals, non-ferrous metals, inert materials (e.g. Glass, ceramics and concrete among others) and residual fractions which could be reintroduced into the economic cycle.

1.6. Other remediation techniques

Generally, remediation of Landfills and contaminated soils can take place either using the in situ or ex situ techniques. The key criteria for the technical solution of remediation are; The Environmental impact, the technical features of the location and the economic properties of the location. Other existing techniques have been outlined below.

1.6.1. Ex situ method.

This method implies moving the waste from its original location to another and subsequent treatment either onsite or offsite. Under this method, we have technologies that have been described by Saranya et al., (2016) as follows;

- **The pump and treat**:

  It is a method whereby contaminated ground water is pumped out and treated using granular activated charcoal. Generally it takes such a long time to achieve its remedial goals (50-100 years) which are never achieved in most cases (US EPA 1996). Moreover with time the contaminants could get recalcitrant and therefore render the technique somehow ineffective. Soil vapour extraction is a technique which could also be used in the case where vapour is extracted from a contaminated area and is treated before being released into the atmosphere.

- **Incineration**:

Incineration has grown over the past 20 years to equally be a serious technology to treat environmental waste. It is similar from combustion or chemical oxidation which involves waste being subject to temperatures as high as 1200ºC. Incineration is carried out in different experimental units like; infrared combustors (electrically-powered silicon carbide rods are used to heat up organic wastes to a temperature of 1010ºC via infrared energy); fluidized bed combustors (utilize high-velocity air with infrared as heat source; incineration occurs at temperature up to 850ºC); circulating bed combustors (high velocity air entrains circulating solids and destroys noxious hydrocarbons by creating a highly turbulent combustion zone at temperature up to 850ºC) and rotatory kilns (rotating cylinder that is slightly-inclined and refractory-inclined, with an afterburner that burns at temperatures up to 980ºC. Incinerators are very expensive both in the initial and operating costs. Their equipment require maintenance and is rather unreliable, supplementary fuels are often required to achieve target combustion temperatures which are all very expensive.

A major disadvantage with this practice is that it may cause drastic environmental impacts given that most waste combustion systems have gas or particulate emissions that are highly dispersed by wind (for example, flue gases composed of noxious fumes, nitrogen gases, carcinogenic hydrocarbons, carbon monoxide, hydrogen chloride, Sulphur dioxide and odors. It may also generate leachates that pose health risks given that heavy metals generated from these are very difficult to control (Sabas et al., 2003). Despite all these challenges, incinerators are still widely used in a country like the US but subject to series of regulations such as Noise control Act (NCA), the Clean Air Act, Toxic Substance Control Act as well as many others. The residues from this procedure equally need to be subject to a few treatment before final disposal.

- **Pyrolysis**:

Also known as arc technology is an emerging remediation technology whereby thermal energy is used to decompose hazardous materials chemically in the absence of oxygen, at temperatures above 430°C under pressure (Venderbosch et al 2010). It transforms target compounds into gas or a significant amount of solid or liquid residues containing ash and fixed carbon, it yields char organic liquids, fuel gas and water. Though a complete Oxygen free atmosphere is hard to obtain, this process is operated with an oxygen level which is less than the stoichiometric quantity. High pollutant cleaning efficiency is achieved using this method coupled with the fact that there are no CO_2 evolution during the course of the pollutant treatment, therefore combatting global warming. The operation is stable for a broad range of waste and emissions from here are well below regulatory limit values.

There are also efficient material recovery and energy production opportunities emerging from this system and its cost of operation is quite low and it doesn't require supplementary fuel for its operation as compared to incineration plants. However, CO, H_2 CH_4 and some other hydrocarbons are produced during the course of the operation which may require further treatment. Another limitation with this method is that it requires material to be very dry to achieve a low moisture content of < 1% before combustion, anything above will increase the treatment cost. Stabilization is needed as the treated medium is composed of heavy metals. The processor could be damaged in case of high abrasive feed. This technology is ideal in remediating organic pollutants from oily sludges and soils and s would not effectively destroy or physically separate inorganics from polluted zones

- **Landfill bioreactor**:

A landfill bioreactor as defined by Reinhart et al., 2002 and Pacey et al., 1999 is a sanitary landfill in which microbial processes are enhanced and stabilize the readily and moderately decomposable organic waste constituents within a period of 5-10years. It works such that leachate sometimes combined with additional fluids, is being added in a controlled manner to the mass of waste (often in combination with recirculating leachate), to bring the moisture of the degrading waste to at least 40% to accelerate the anaerobic biodegradation of the waste

(Townsend et al., 2008). Temperature, nutrient level and the pH are all parameters which need to be controlled. Landfill bioreactors work either in the presence or absence of oxygen, hence we have Aerobic and anaerobic Landfill bioreactors.

- Anaerobic landfill bioreactors: in this kind of bioreactor, moisture is added to the waste mass in the form of recirculated leachate and other sources to obtain optimal moisture levels. The degradation occurs in absence of oxygen and so biogas is produces as a result.
- Aerobic Landfill bioreactor: this one is similar to the previous case but for the fact that in addition to the recirculation of leachate, we have horizontal or vertical wells through which air is injected to promote aerobic activity and accelerate waste stabilization.
- However there also exist cases of a **hybrid landfill** bioreactor which combines both aerobic and anaerobic conditions at different sections, in the upper and lower sections of the landfill respectively to be able to enhance degradation at the upper part of the landfill, yet collect gas at the lower part of the landfill.

The advantage landfill bioreactors have over sanitary landfills is that the increased waste settlement provoked by leachate recirculation will lead to recovery of airspace and this recirculation will call for improvement for in situ leachate treatment which is an advantage too. There will be more rapid production of biogas and maximization of its capture which may improve upon the economics of gas recovery (Barlaz and Reinhart, 2004) and therefore mitigate the release of landfill gases to the atmosphere. Landfill bioreactors equally minimize the time needed for stabilization of waste and this aids in better monitoring and reduce of efforts during the post closure period. The advantages offered by a landfill bioreactor were summarized in the table below and adopted from ITRC (2005).

Table 2: LFB primary and secondary advantages

Primary advantages	**Secondary Advantages**
Stabilization of waste in a shorter time	Optimization of waste emplaced in a landfill
In situ Leachate treatment	Reduced leachate handling cost
Enhanced LFG generation rates	Potential for LFG to be a revenue steam
Reduced post closure care	Reduced air and leachate emissions
Efficient utilization of landfill capacity	Consistency with sustainable landfill design

As many as the advantages may be, like other techniques, landfill bioreactors have concerns with regards to the leachate seeps, the slope stability, excessive temperatures, gas emissions and odor control.

- Seeps may occur when the liquids are added at high pressure or at a flow rate higher than the normal infiltration rate or absorption capacity of the waste mass.
- The slope stability may be tampered with where the liquids added may increase the internal pore pressure and reduce the shear strength of the waste which eventually leads to slope failures.
- Excessive temperatures of waste which is not controlled may cause fires which like odorous emissions are directly harmful to human as and to the environment at large

- **Soil washing technique**:

It is a technique which could be both in-situ and ex-situ. It is a water-based approach for treating soils and is extensively carried out in Europe. It uses coupled aqueous-based separation unit and physical separation operations to minimize the toxin levels of and age prone contaminated site to specific objectives. This technique doesn't significantly alter or detoxify the pollutant but it instead mechanically concentrated the hazardous waste into a much smaller mass or transfer the contaminant from soil into washing fluids for successive treatments (Dermont et al., 2008). Soil washing involves mechanical screening, crushing, physical processes (soaking, spraying and tumbling action scrubbing), treatment of coarse and fine-grained soil fractions and the management of generated residues.

Though it is considered as a stand-alone approach, it is combined with other remedial systems to complete the off-site treatment process. It is highly applicable to treat diverse array of pollutants like heavy metals, SVOCs, PCBs, PAHs, pesticides and petroleum as well as fuel residues (Parca et al., 2002). It permits recovery of metals from coarse soils. It is considered to be a very cheap procedure, reducing the volume of contaminated soil requiring further treatment and it is proven to be suitable for sandy or gravel solid (Urum et al., 2003). It however fails to treat soils with silt and clay (>40%) fractions, multicomponent soils with high clay and humic acid content where access of leaching solution to contaminant is restricted.

- **Land farming**:

This is a simple technique which is particularly used for remote sites due to minimal equipment requirement. Generally with this method, passive aeration is done by tilling or ploughing the contaminated soil in order to reduce contaminant levels (EPA, 2014). After which the waste material is deposited on large flat impermeable surface to increase interaction between the polluted soil and the atmosphere in order to improve aerobic microbial activity in the soil (Nedeef et al., 2012). Treatment is achieved through biodegradation and possible photo oxidation in sunlight (Rockne and Reddy, 2003). This method could be applied in in situ cases of shallow contamination (less than 1m below ground surface) whereas when contamination goes beyond 1.5metres, the soil should be excavated and treated in Special facilities (Kappusamy et al., 2016).

The simplicity and affordability of this method makes it highly cost competitive however, it equally has limiting factors to be taken into consideration before using this technology. These are; the area for treatment, production of leachate and volatilization of the compounds. Volatile constituents have the tendency of evaporating rather than degrading in the treatment process and this will result in air pollution problems which will increase treatment cost as a result. Landfarminig may not be effective in treating heavy hydrocarbons and so would be suitable for treatment of compounds including BTEX, petroleum hydrocarbons such as diesel, light lubricating oils, crude oils, PAHs, particularly lower ringed aromatic lighter compounds such as naphthalene, phenanthrene and phenolic compounds (EPA, 2014), in order to reduce contaminant levels (EPA, 2014).

- **Biopiles**:

This method is one which is used to treat soils contaminated with petroleum products using biodegradation. Biopiling is done by excavating the contaminated soil and placing it in hips or piles and then microbiological process are stimulated by aeration followed by the addition of water and nutrients besides controlling heat and pH (US EPA 2012). This system differs from composting and landfarming in the sense that, it provides control over the maintenance of optimum levels of moisture, temperature pH, aeration and nutrients favoring microbial survival and activity promoting rapid biodegradation (McCarthy et al 2004). This provides a better pollutant removal strategy since it makes provision for mas transfer efficiency of air and water in the piles. Materials like sand, straw, saw dust, wood chips and dry manure are used to ensure mass transfer efficiency. Biopiles generally attain a height of 0.9-3.1m and could be enclosed with an impervious lining to prevent runoff or evaporation or volatilization and to promote soil heating. Thus the efficiency will be poorer in clay soils as compared to sandy soils since contaminant mass transfer is quite difficult in clayey soils which have the tendency of forming agglomerates which limit soil permeability (Rezende et al., 2012).

- **Composting**:

This technique transforms organic contaminants like PAH into stabilized innocuous byproducts by microorganisms (under anaerobic and aerobic conditions). It is all about creating a suitable environment for microorganisms by mixing contaminated soil with organic carbon sources and this technique has been at the forefront of diverting and processing organic waste due to its relatively simple and robust process. It differs from landfarming in that it requires a thermophilic condition (50-65^{O}C) to suitable compost hazardous organic compound-contaminated soil. During composting, the pH (6-9) is also monitored as well as oxygen (10-15%), the moisture level (50-55%), the C-N ratio (30:1) and the porosity (1-5cm) (Semple et al).

It should be noted that land farming, biopiling and composting are all bioremediation ex-situ techniques mostly used in sited contaminated by petroleum compounds.

1.6.2. In situ Method

Unlike ex situ methods, these methods seek to treat the contamination in its place of origin, without having to remove the soil or groundwater from original location. Some of the techniques operating with this principle are;

- **Airflow System**:

Air flow system is a promising technique for shortening the long term impacts of municipal solid waste landfills. Based on the report given by Ritzkowski and Stegmann (2012), the airflow system can be classified amongst the low pressure aeration systems with simultaneous active aeration and off gas extraction. Following this principle, air is injected at low pressure in landfills giving way for aerobic conditions and biogas is then extracted. The aerobic condition render conditions suitable for the rapid degradation of organic load in leachate and on carbon transfer from leachate into biogas as CO_2. In situ aeration within an operation of 2-3 years results in a strong reduction of TOC and Ammonia in the leachate and methane generation and should be adopted any time the environmental problems from a landfill are associated with a significant residual presence of biodegradables in the waste mass (R Cossu, 2005).

In addition to this there is a pneumatic leachate extraction from the aeration wells in order to keep the leachate table low in the landfill and thus increase the volume of unsaturated waste available for air migration. It could be used as a pretreatment to ease the activity landfill mining as shown by Raga and Cossu, 2015 (Case study; the Modena Landfill). This method is a powerful remediation technique as it accelerates waste mineralization and stabilization thereby reducing the emission potential of the site. However, based on the findings of Mitali

Nag, 2016, optimization of O_2 concentration inside the MSW landfill is a key factor to control N_2O production. It was hypothesized that high airflow rate is a potential parameter of N_2O production because of nitrite accumulation and that the soil cover and regulation of temperature with controlled water are all thing to be considered when dealing with aeration in landfill since it increases the rate of degradation, consequently increasing temperature which favors the production of N_2O.

- We equally have passive actions such as encapsulation and capping, and natural attenuation methods which make use of natural processes such as biodegradation, dispersion, dilution, sorption, volatilization, radioactive decay and chemical or biological stabilization, transformation, or destruction of contaminants (Brown et al., 2007; Declercq et al., 2012; USEPA, 1999). However the usage of passive measures without being complemented are not very encouraged as it will serve to only postpone the environmental effects which will become more difficult and costly to attend to on the long run.
- Also, there exist technologies which combine both ex situ and in situ technologies such as reductive dehalogenation and oxygenation.

The benefit that in situ techniques have over ex situ is that contaminated soil doesn’t need to be transported or removed but comparatively, ex situ techniques require a lesser time to effectively get rid of contaminants and so tend to be more effective though their cost is higher and its more risky health wise due to the exposure to contaminants.

CHAPTER 2

METHODOLOGY

This chapter presents the steps used to attain the objectives of the study ranging from desk to field work on general and specific base. This also includes materials used at all levels and the difficulties encountered during the work.

2.1. Method.

The process for preparing this thesis and the methodological choices used are all reflected, presented and described below.

To answer the research questions put forward by this thesis, two main approaches were used. This involved desk study and a field study;

2.1.1. Desk study

This was done with the aim of finding out what had been already done so far with respect to the theme of study. The desk study wasn't really constrained to a particular direction, but from several dimensions so as to reveal much more potential benefits offered by the chosen technique. This was achieved though the consultation of past works, articles, reports from various authors and all legal documents within reach which lead to elaborating a literature review well suited for this work.

Materials: This consultations were gotten from the internet and from hardcopies. Access to internet was gotten using a phone and laptop. Books, pen and a pencils were used to jot down.

The advantage of this strategy was that most of these documents, if not all had undergone review before finding themselves on the various sites and locations, these therefore made the information from there reliable.

The locations maps were drawn using; the software Argus and from the landfill. They permitted us know the area of study as well as the structures bounding the landfill.

2.1.2. Field Study

In order to have an idea of what was already being done and to be able to perceive the limitations of the technology that currently exist, a descent was made to the site used as a case study where field work was carried out across interviews, personal observations and characterization procedures. The field study is of great importance as tangible contact is made with the work context and so any conclusions made would be relevant, having weight and more adapted to the case in question.

- ***Interviews***

These are tools used to assess some level of information which goes beyond what has been written in articles, reports etc. The type of interview used in this case were mostly informal face-to-face interviews given that the target people to be interviewed had a skeptical mindset about people approaching them with pen and paper.

- ***Survey and field work***

The survey was done by the use of sight to evaluate the daily activities carried out which pertain to the management of the landfill during tours. This was closely followed up with field work which involved engaging in day to day tasks in every department of the landfill and then diving into the work proper following a material flow approach, which was the quantitative method of estimating percentage composition of municipal waste by the manual characterization and quantification. This procedure was mainly sampling, sorting by hand-picking and weighing of the waste samples.

2.2. Landfill Layout and Functionality

- The landfill starts up with the first checkpoint which is the security office where control is done with regards to the persons and trucks which enter or leave the landfill. Only authorized persons and trucks are granted access.
- The trucks containing waste gotten from Yaounde, after being granted access to the landfill climb on the weighing bridge for the weighing of waste. The trucks coming in and leaving the landfill have to be weighed in order to get the net quantity of waste per truck and information about the driver and the zone to which he is affiliated to is equally noted. The

facility has two weighing bridges for this activity, one of which is made of metal and the other made of concrete. This two bridges are automatically synchronized to the computers through a software through which the detailed information is stored and an electric scale which reads the various weights.

- To permit a smooth mode of both collection and transport of municipal solid waste, the city was subdivided into two which group the various districts of the Mfoundi Department (Yaoundé) and further subdivided into circuits for collection. The administrative units, population density, standard of life and economies were all taken into consideration for this division to be effected. Due to this procedure, today the company's collection activity can boast of covering close to 70% of the town.
- On the 16th January 2019, a contract was signed between HYSACAM and the Yaoundé city council on the dispositions to limit the impacts of waste on the Nkolfoulou locality as much as possible and so in responds to this contract, SITRAM has a unit of workers at the landfill who ensure that the exploitation of the landfill is done following the norms established by this contract. In addition to this site verification, the make sure the content of the soil is solely municipal solid waste, not some other material which is not permitted. If the material carried contains some soil to an extent, based on their observations, they estimate the actual weight of municipal waste carried and that's what is submitted to the hierarchy. In case the waste composition is unaccepted, their controllers have the right to cancel the load weight to the corresponding vehicle.
- After the weighing exercise, the trucks are directed to a platform in the zone chosen to be exploited as the dumpsite at that point in time and they offload their waste there through the help of the truck ushers. Reorientation of the waste follows suit with the help of the bulldozer.
- The maintenance section consists of two fueling stations solely for the company's use and a garage whereby, in case of any breakdown or problem with any truck, the mechanics are there and also follow-up and ensure proper functioning of every truck and machine. They assess the need for particular machines or spare parts needed and place commands for them through the hierarchy.

- The MDP is a block which consist of 2 offices controlling the biogas plant, a toilet joined to a checkroom for those working under this unit and a small shelter for the generator. The first office is attached to part of the biogas flare system. It contains the blower as well as some other pipes. The second office is the control room for the Biogas flare. It has the Biogas analyzer from where information is given concerning gas getting into the flare (Volume percentages of Methane, Carbon dioxide and Oxygen), followed by the exhaust gas analyzer where information about the gas which is being burned. The biogas flare is automatically controlled and followed up across the computer from the control room.

2.3. Waste treatment in the Landfill

The method of waste treatment adopted by the waste contractor HYSACAM is landfilling as in many other African countries. This method consists of burying the waste offloaded by the trucks into sockets or cavities specially dug for the purpose. After the various controls concerning the type, origin and weight of waste in question, the waste is transported and dumped directly on the ground without any barrier below with the justification that the soil dominant in the landfill is made of clay which has a permeable coefficient between 10^{-7}cm/s and 1.10^{-6} cm/s, thereby implying that the soil has a good impermeability and does not need any other barrier.

The waste is piled up with the help of the excavator and then the bulldozer does the process of compacting. The aim of the machine is to layout the waste in such a way that it attains a maximal angle of 33^0, which has been deduced as the perfect angle through which the layer of clay followed by the geotextile and geomembranes could be placed without running the risk of having waste sliding downwards. The layer of clay has a minimum thickness of 80cm and is carried from zones reserved for future exploitation. The Geotextile and Geomembranes are placed to prevent infiltration of rain water, migration of gaseous emissions, windblown waste, and presence of harmful fauna and the last layer of vegetative soil is placed having a minimal thickness of 70cm, all these with the help of the bulldozer, the excavator and trucks to transport the ground.

The reason why all this barriers are put in place is to prevent both air and land/water pollution which could happens as a consequence of biogas escape to the atmosphere or the latter, if the leachate is not well channeled and treated.

a)

b)

c) **d)**

Fig 8: Various machines and vehicles used for re-profilation and landfilling of the waste: a) Bulldozer; b) Front-head Loader; c) Excavator d) Truck (BE) (Source: Nkolfoulou landfill, February 2021)

2.3.1. Landfill emissions

Within the landfill, biological, chemical and physical processes occur and they all promote decomposition of waste and result in leachate and gas production. The landfill ecosystem is quite diverse due to the homogenous nature of waste and is strongly influenced by environmental conditions such as temperature, pH, the presence of toxins, moisture content and the oxidation-reduction potential. Waste stabilization process takes place in five distinctive phases (Vesilind et al, 2002).

i) Initial adjustment phase: This phase is associated with initial deposition of solid waste and accumulation of moisture within landfills. An acclimatization period is observed until sufficient moisture develops to support an active microbial community.

ii) Transition phase: In the transition phase transformation from aerobic to anaerobic environment occurs.

iii) Acid formation phase: The continuous hydrolysis of solid waste followed by the microbial conversion of biodegradable organic content results in the production of intermediate volatile organic acids at high concentrations throughout this phase.

iv) Methane fermentation phase: Intermediate acids are consumed by methanogenic bacteria and converted into methane and carbon dioxide.

v) Maturation phase: During the final state of landfill stabilization, nutrients and available substrate become limiting, gas production dramatically drops and leachate strength stays steady at much lower concentrations. Apart from landfill gas and leachate emission, wind-blown litter, vermin and insects are also identified as the minor emissions of the landfills, but emphasis usually is placed on the landfill gas and leachate as they are the most important causes for number of environmental and socio economic impacts.

a) Biogas Treatment

The major components of landfill gas are methane (CH4) with a percentage ranging from 45-75% and 25-50% carbon dioxide (CO_2) (Amini & Reinhart, 2011; Mescia and al., 2011), with a large number of other constituents at very low concentrations such as ammonia, sulphide and non-methane volatile organic compounds (VOCs). Methane and carbon dioxide are greenhouse gases but methane is a greenhouse gas with greater concern as its global warming potential is 25times that of CO_2 on a 100 year timescale (Foster et al., 2007). Life cycle assessments (LCA) studies on waste management have shown that landfill gases significantly contribute to the total GHG emissions from urban areas. It was estimated that landfills are responsible for 3-7% of total global CH4 emissions (Bogner et al., 2011).
Generally, landfill gas is controlled by installing vertical or horizontal wells within the landfills which are either vented or connected to a central blower system that pulls gas to a flare or treatment process.

In our case study the potential average production of methane from waste entering the site is 79 kgCH_4 per ton of wet waste and so on this basis, the cumulative emissions of methane are estimated at an equivalent of 1.9million tons of CO_2 between 2007 and 2030 (Emmanuel

Ngnikam et al 2012). A project known as the MDP was put in place for the extraction of biogas. Following the implementation of this project, extraction wells and pipes as well as the biogas flare were all installed in the landfill.

The landfill has a total of sixty extraction wells (installed both vertically and horizontally) which were drilled for the purpose of biogas extraction with the help of special drilling equipment. Thirty were dug in the first zone, twelve in the second and eighteen in the third zone for now. After the wells were drilled, HDPE pipes of sizes ranging from 90cm-160cm with crevices to permit the gas to be pumped out and channeled, were inserted into the wells. 20 of these wells were mixed wells and 40 were simple wells.

Mixed wells are the wells which contain pipes to pump out leachate as well as pipes for biogas while the simple contain pipes only for biogas extraction. After the pipes were inserted, a layer of gravel with diameters ranging between 25mm and 40mm were placed round the pipes to prevent blockages by waste and to ease the extraction of the gas. The head with diameter of 160cm were placed above. The simple wells are equipped with a manometer for the purpose of verifying the pressure with which the gas is pumped up in but mixed wells have in addition to that, a pneumatic pump to permit the withdrawal of leachate. This pumps are of mark Silex, and were specially designed to work inside charged up waters and difficult physical and chemical conditions.

However, with time most of these equipment have worn out and no maintenance done, so scrupulous follow-up such as verification of pressure is no longer done at the level of the wells but mostly just in the office.

Fig 9: Biogas Flare

(Source : Nkolfoulou Landfill Site, February2021)

a) **b)**

Fig 10: Some other parts of biogas plant: a) perforated pipe; b) head of a simple extraction well

(Source: Nkolfoulou Landfill Site February2021)

Fig 11: An example of a mixed well with manometer and pneumatic pump

(Source: Nkolfoulou Landfill Site February2021)

a) Leachate Treatment

Leachate is defined as any liquid percolating through the deposited waste and emitted from or contained within a landfill. As it percolates, it pics up suspended and soluble materials that originate from, or are products of the degradation process. The principal organic contents of leachate are formed during the breakdown process and its organic strength is measures in terms of BOD, COD and TOC (Crowley et al., 2003). This is another dangerous product of landfill that if not taken care of might lead to devastating short as well as long term effects to the people and the whole vicinity of Nkolfoulou. As afore mentioned, the mixed wells contained pipes for Leachate extraction as well. This Leachate is then channeled across pipes down into a lagoon which was dug to a height of about 3.5metres deep, primary decantation takes place at this level. The lagoon has a manual float with which circulation of leachate to the treatment basins can be controlled. From here, the leachate is channeled across pipes into a series of three basins with a capacity of $180m^3$ each.

The leachate treatment is done as follows;

- **Filtration**: Before entry into the first basin, the leachate flows across the pipes into filters of height, 1.1m composed of 40cm sand, 50cm gravel and 10cm saw dust (from top to bottom). Here the first form of treatment is done
- **Decantation:** When it gets into the first basin, which has a retention time of a month, dense particles decant after which the leachate is channeled to the second basin
- **Aeration:** At this level, air is forced through to remove VFA's by evaporation and biodegradation. It remains here for a period of one month too before being moved into the third basin.
- **Solar Radiation:** In the third basin, the leachate stays for a period of one month as well and the man treatment given at this level is exposure to sun as another form of treatment, however it should be noted that all the basins are exposed to sunlight and so this treatment with the sun takes place at all levels.

In recently exploited zones in the landfill, the leachate is channeled down into the lagoon by means of gravity taking into consideration the nature of the zone and its slope which could be thoughtful method but is however not very accurate. Around the basins, gutters have been constructed to drain and channel surface runoff to the river downhill, still it was observed that the possibility of leachate finding itself in those basins were very high.

The leachate basins are cleaned once a year and the procedure involves draining a basin at a time, allowing the sludge that previously settled to get dry and then scraping it off and then disposing of it in the landfill since no form of qualitative analysis have been carried out of it to know how if it could be valorized or not, meanwhile the leachate which has been treated is pumped out and discarded in the river or used to wet the already dried up waste. A study by Dr. Ngnikam et al in 2012 showed that an average amount of 450 m^3 of leachate is generated on the site per day of which only 54 m^3 is finally collected, then discharged into the river without any effective treatment. The leachate quality revealed COD load (700 to 2500 mg/l) and BOD (400 to 700 mg/l) and heavy metals to a lower extent, yet having visible impacts at a distance of 100m downstream from the discharge point.

a)

b)

c)

Fig 11: Leachate flow in landfill: a) leachate flow by gravity; b) lagoon (3,5 m deep)

c) Leachate treatment basins (Three compartments with volumes of 180 m3 capacity)

(Source: Nkolfoulou Landfill Site, February2021)

a)

b)

c)

Fig 12: Parts of the leachate treatment Basins; a) Gutter which captures surface runoff b) 1st basin into which leachate flows from lagoon c) local filter composed of sand, gravel and sawdust through which leachate passes before flowing into first basin

(Source: Nkolfoulou Landfill Site, February2021)

2.3.2. Material Recovery

The process of material recovering in most landfills in third world countries is known as scavenging. It is an instrumental tool in solid waste management and if this activity could be carried out in an appropriate, well-organized, and safe way, would be very profitable at all levels; socially, economically and environmentally

How it is done

Presently, it is unofficially handled by people termed scavengers or waste pickers who do sorting of waste and collect by handpicking, each for his own private interest. There is no official platform allocated for this activity and so the waste pickers find themselves walking inside the dump and picking what they deem reusable or recyclable. On several cases, they could be found right at the back of waste trucks set to pick up valuables (recyclable or reusable material) that had been perceived upon arrival of the trucks due to high level of competition amongst them. On other cases they are found in the waste mounts together with the bulldozers and excavators which are working on levelling the mounts so that space can be made for more waste. The materials of interest usually are; ferrous materials/metals, glass bottles and ceramics, textiles, rubber and materials made of plastic types (Polyvinyl Chloride, Highly Dense Polyethylene and Polypropylene). At the end of the day, each waste picker ties up what he got, carries and looks for a place in the landfill and keeps there, with the exception of tires which are displaced to be kept only using trucks given their weight. When the stores of valuables become voluminous to an extent, arrangements for trucks to come in are made, the various items are weighed and then then transported to the various clients or purchasers and enterprises concerned.

It should be noted that this is not done on regular basis however, a track record is made at the end of every month by the landfill coordinators to have an idea of what leaves the landfill. Given that it is an activity somehow beneficial to the landfill, access to the landfill in granted to them and no amount is levied on the scavengers but no pay is given to them since it is assumed they make gain from the items they gathered.

The waste pickers usually show up at haphazard times, since they are not under any work constraints, some come early and others later in the day based on each person's convenience. Upon arrival, they change into their work clothes and get to the dumpsite and work till they are satisfied and then call the day off and return to their various homes.

a) **b)** **c)** **d)**

Fig 13: categories of waste sorted at Nkolfoulou landfill: a) plastic; b) metal; c) glass; d) tires

(Source : Nkolfoulou Landfill Site February2021)

Fig 14: Bag used by waste pickers to store up materials

(Source : Nkolfoulou Landfill Site, February2021)

2.4. Waste Characterization

Knowing the composition of MSW is a key element to managing waste. MSW composition varies from place to place depending on the season, administrative district etc. The results usually gotten from the sampling and analysis would help take important decisions with respect to risk assessment, treatment, protective measures etc. European countries have developed several methods for characterization of MSW; ARGUS in Germany, SWA in Austria, IGBE in Belguim, EPA in Ireland and MODECOM in France.

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2.4.1. Protocol for waste sampling:

a) Method

Given that no specifications for waste characterization has been established nationally, the protocol of characterization used was based mostly on the French approach introduced and carried out by ADEME in 1993, the French Environment and Energy Management Agency. This method is known as MODECOM, the Method for Characterization of Domestic Waste, which has been transcribed as the standards for AFNOR . The method was later modified with time and adapted to suit the context of developing countries (Ngnikam 2000). The adaptation done by Dr. Ngnikam was mainly at the level of the sorting platform which consisting of only 20mm and so the particles less than 20mm were classified as fines. However this case was further adapted to sieves of 8mm

The MODECOM methodology takes the following into consideration;

- The Preliminary Inquiry: It consists of gathering background information on the area of study and stratifying or sub-dividing it into different sectors either based on geographical zoning, population density or economic activity.
  The case of the Yaoundé city is subdivided into 7 main districts numbered Yaoundé 1 to Yaoundé 7 (in a rather not unique way) which have sectors or circuits serving public skips or ground depots located at strategic sites. This was the zoning chosen for this study. However, other studies have been done based on quarter's stratification that was done according to living standards, socio-economic activities, characteristics of roads, streets and the housing conditions (Vermande et al, 1994; Ngnikam, 2004; tanawa et al, 2002).

  - Collection mode: This method is based on characterization of MSW from collection vehicles which suits our context as compared to the EPA manual or the SWA methodology of characterization which place more emphasis on characterization from site of production. For each zone, the vehicles used were either the "Benne Ville de Paris" (VDP) which have access to descent in the quarters or another vehicle type, the "Porte Coffre" (PC). The specifications of the MODECOM require that each of these vehicles should not contain less than 2tonnes of which 500 kg would be used as sample but the realities of the field made use both the VDP which carries more than 2tonnes and the PC which carries lesser.

- The method offered several possibilities based on the characterization procedures of which screening through a sieve of 8 mm, 20 mm and 100 m but just 8 mm was chosen and used to define to category of fines following the table below which specifies the categories and subcategories. The alternative of drying was not done as well as the laboratory analysis.
- Nature of waste: This was taken into account as per the various sectors they are collected from. The waste generated close to markets and households will contain greater percentages of biodegradables as compared to waste around schools and offices. The frequency of collection as well was taken into account as the sampling was done for 6 zones with varying sectors covered. Seasonality was also taken into consideration as work was done during the rains. More waste (especially putrescible) be produced in the rainy season which is considered the harvesting than in the dry season due to a greater availability of food crops, fruits and vegetables.

b) Materials to be sorted

Table 3: List of various waste categories for characterization according to MODECOM

Categories	Sub-categories
Putrescible waste	➢ Food waste ➢ Garden waste ➢ Other putrescible such as wood
Papers& Cardboards	➢ Packaging ➢ Newspapers, magazines, brochures ➢ Office papers, other papers etc. ➢ All packaging cardboard
Textiles	➢ Textiles

Plastics	➢ Polyethylene, polyvinylchloride, polypropylene, polyurethane etc.
Metals	➢ Ferrous metal packaging ➢ Aluminum packaging ➢ Other ferrous metal waste
Glass	➢ Colorless glass ➢ Color glass as well as any other glass material, ceramic material
Others	➢ Batteries, bulbs, lamps, chemical products, tires, hospital stuffs, stones
Fine elements	➢ Elements < 8mm

c) Materials Used

a) EPI

- pairs of gloves for each personnel
- facial masks
- Chasuble for security/security attire
- Security Boots

b) For the weighing;

- A 100 kg hand scale was purchased to weigh the various waste fractions
- The weighing bridge was used to get the net weight of the waste from trucks
- A large plastic paper and mosquito nets of negligible weight (<0.5 kg)to tie up the waste fractions to be weighed

c) Other items needed

- A phone, calculator, notebook and pen to put down data
- An excavator or bulldozer was used to spread out the waste.
- A rake to further spread and carry up the waste
- A sieve of 8mm diameter
- 2 Personnel to help

2.4.2. Work Plan/Pattern

- Trucks which were used to carry out this exercise are the **VDP** and the **PC**

Fig 15: Waste vehicles used for work; VDP to the left and PC to the right.

(Source: Nkolfoulou Landfill Site, February 2021)

Table 4: Work pattern for characterization

- Lot 1

Zone 1	Day 1 11/03/2021	PC
Zone 2	Day 5 22/03/2021	VDP
Zone 4	Day 2 12/03/2021	VDP
Zone 5	Day 3 16/03/2021	PC

- Lot 2

Zone 3	Day 4 18/03/2021	PC
Zone 6	Day6 24/03/2021	VDP

2.4.3. Calculation of net weight of waste

Upon arrival of the chosen trucks, their incoming weight i.e. combination of truck weight and waste weight is gotten as they mount on the weighing bridge which has sensors attached to connected to an electronic balance and information stored with the help of the software PRECIA. It then moves to the site allocated for the characterizing to be done, offloads the waste and then returns to the weighing bridge so that the empty weight is gotten before leaving the landfill.

The net weight which stands for the actual weight of the waste is obtained from subtracting the empty weight from the total incoming weight.

$$\text{Net weight} = \text{Incoming weight} - \text{Empty weight}$$

- Individual waste percentages per category would be gotten from

$$\mathbf{(W_C / W_T) * 100}$$

- W_C= waste per category
- W_T = Total weight

2.4.4. Calculation of gain in Air Space

From the air space balance equation:

$$Air_I - Air_F + S = Air_R$$

Where:

Air_I =Initial Airspace

Air_F =Airspace filled

S= Settlement

Air_R =Remaining Airspace

- For Calculating area gain from landfill mining, the equation used was

Area gain = Current mass rate/New mass rate *Tot Area of land used

2.4.5. Density

❖ Fresh waste

The fresh waste mass was determined as the weights were gotten from the weighing bridge based on the truck types. The occupancy rate was estimated by visual observation and the density was therefore obtained based on the equation below;

$$\boldsymbol{Density(tonne/m3) = r * \frac{m}{V}}$$

Where;

- r represents the occupancy rate(%),
- m is the mass of waste (t)
- V= Capacity of trucks(m^3)

❖ Old waste

The mass was excavated from a trench using an excavator and placed in a truck and weighed on the weighing bridge where mass was gotten. The occupancy rate was estimated by vision, the volume was calculated from the bucket capacity of the excavator and the density was obtained as shown using the same equation above.

2.4.6. Data Collection

I. Characterization of Fresh Waste (Assessing resource potential of incoming waste)

- The chosen waste trucks coming from six districts in the Mfoundi department were directed to a part of the dumpsite where the sorting procedure was done
- The chosen waste offloaded and approximately 500 kg was withdrawn following MODECOM protocol, meanwhile the remaining waste was later discarded.
- This portion of waste used as sample was worked upon by putting it progressively on an 8mm sieve where sorting was done manually into various categories (papers, plastics, textiles etc.) there after placed on various mosquito nets (carefully collected on site) using the rake and then tied and weighed in a series of turns using a scale (100 kg) attached to the support which was put together on the site.
- The particles that went through the sieve were considered as fine particles (<8 mm)
- The weights were then read one after the other and noted down in a note book.
- The time of sorting per day varied from five to six hours depending on the time of arrival of the various trucks.
- The total amount of waste sorted for all six zones for the six days amounted to approximtely 3 tons

a)

b)

Fig 16: a)100g Weighing scale hung on locally made wooden suppport

b) 8mm sieve used for manual sorting

(Source: Nkolfoulou Landfill Site, March 2021)

a) b) c) d)

Fig 17: Some categories of the sorted waste: a) plastics; b) Paper and carton; c)Putrescibles; d) Textile

(Source : Nkolfoulou Landfill Site March 2021)

II. Characterization of Older waste (Assessing Landfill mining as a Post treatment remedial Action)

- A potential zone already exploited of age, two years or greater was excavated with the help of an excavator.
- The waste was loaded in a truck and measured on the weighing bridge to get the weight
- The waste was then spread on the working suface and 500kg of waste was characterised using the same procedure as stated above and the various categories weighed and recorded.

Fig 18: Excavated waste of age > 2years

(Source: Nkolfoulou Landfill Site, March 2021)

2.4.7. Difficulties encountered

Field work

i. Lateness and unavailability of trucks at respective time of work which led to work prolonging into evening hours.
ii. The period of the year which was the conducted was characterized with a lot of rains and so a) A lot of the fines which are one of the waste categories were lost since we worked with wet waste b) many work days were cancelled and postponed due to inaccessibility on the side of the trucks to the dumpsite.
iii. The work hours for the workers at the landfill happen to be in shifts and so prolonging work to later hours became difficult as those with whom we were assigned to work were mostly morning shift workers
iv. The 20mm sieves to render the data up to MODECOM standard were not available and so the sieving was done using only one sieve.
v. Samples for the dry season couldn't be obtained due to the short period of work
vi. Waste from last district which was Yaoundé 7 couldn't be obtained due to the long distance from the landfill and so waste mostly ended up in transit zones and was brought to the landfill already mixed with waste from other unknown sectors
vii. Some of the waste appeared to be mixed, implying that some fraction were composed of several material categories (Heterogenous). This made the characterization process especially for the old waste, very difficult.
viii. The Nets which were used for gathering and weighing were fragile and could easily tear up when dealing with very heavy waste. To deal with this, weighing was partitioned and done severally making the weighing process tedious and took a longer period.

Interviews: Getting information or pictures related to scavengers was difficult because of the previous experienced they had with giving out information

Conclusion

This chapter presented the methodology that was used to carry out the work. The initial standards for this context was intended to be respected as much as it could but the limitations and realities faced on the field caused a lot of modifications and adaptations so that objectives could be attained. The next chapter presents the results and analysis.

CHAPTER 3

RESULTS AND DISCUSSION

In this chapter, the results obtained from the different investigations will be presented, analysis will be made and various field observations included. The state of art of the landfill is summarized, the limitations of the various resource recoveries are put forward, and then results of the other subjects studied are portrayed and analyzed using tools of MS Excel.

3.1. The state of art of the landfill and waste treatment

The figure below gives a summary of the waste cycle in the landfill as illustrated in the previous chapter

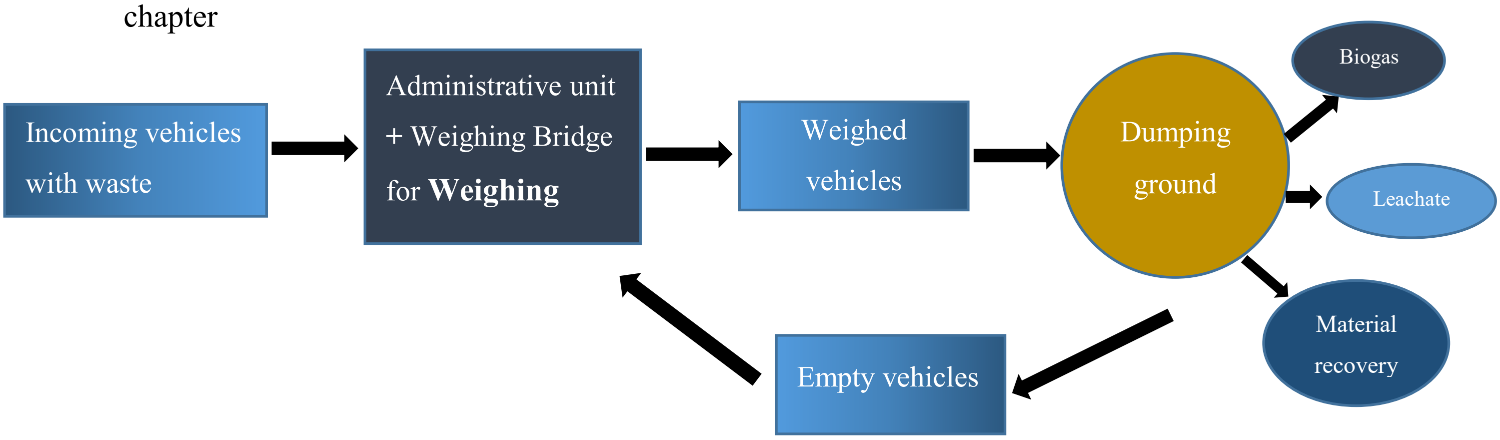


Fig 19: Summary of waste cycle in Landfill

(Source: N Ateh, March 2021)

Four zones were reserved for exploitation in the landfill. The first two had already have been exploited and the third and fourth are in process. Information about their status and surface area are stipulated in the table below;

Table 5: The state of the various exploitation as described in the 2019 contract

Zones	Surface Area (Hectare)	Status
Zone 1 + Complementary trench	6	Exploited from 1999-December 2011
Zone 2	7.5	Partially exploited in an intermittent way between 1990-2003; 2008-2010; then 2016 till 2019
Zone 3	14	Has been exploited since 2011 and is still on
Zone 4	4	Shall most likely be exploited between 2024-2027

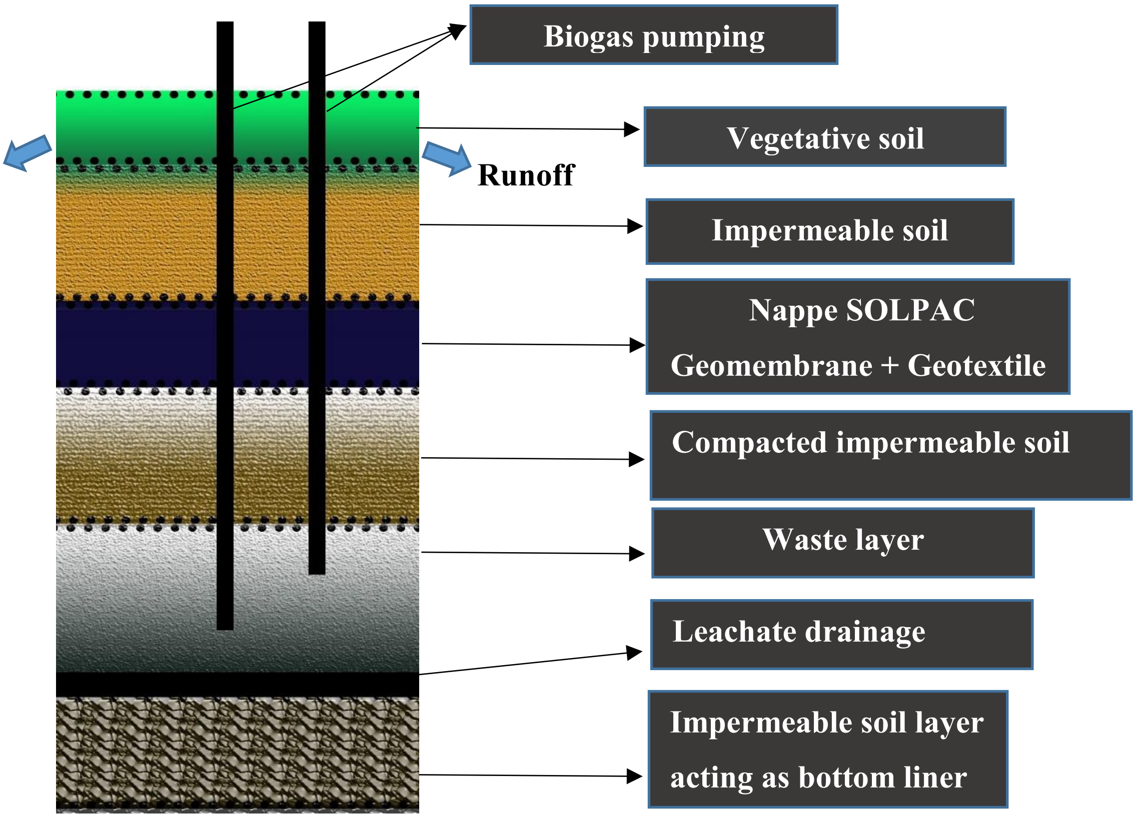


Figure 20: Cross sectional view of landfill after final surface capping

(Source: N Ateh, March 2021)

3.2. Limitations associated to Treatment

3.2.1. Limitations of Biogas and Leachate treatment

i. *Lack of maintenance and insufficiency of equipment:*

- It was observed that most of the equipment which were installed for leachate and biogas treatment several years ago are either absent, in bad shape or completely worn out. For example the manometers meant to read the gas pressure for biogas are not in good shape, the pneumatic pumps meant for leachate extraction are out of service together with the compressor needed to provide the necessary pressure for suction and treatment of the leachate. This probably happened due to the clogging of the pipes and general blockages by waste material, thereby reducing efficiency. As a result, treatment by aeration in the basin is now just a theory and removal of leachate is done now sparsely using specially equipped trucks with pumps.
- Also due to fire accidents, many pipes have been destroyed coupled with the insufficiency, thereby reducing general efficiency of the biogas flaring plant which needs a minimum amount of biogas coming in for it to effectively work.

ii. *Effect of season changes on Leachate Treatment*

During the dry season, the quantity of leachate generated is small as compared to that during the rainy season and so leachate is more controlled during the dry season. The period of rains come with a lot of water infiltrating through the waste resulting to a great increase in the amount of leachate which finds itself in the basins and this becomes difficult to contain together with the runoffs and the un-channeled leachate. As a result of this, enormous amount of leachate eventually find itself running over the basins and down the slopes into the Foulou River which shares boundary with the landfill, thus leading to serious water pollution. In addition to this, the bottom liners are absent in the landfill, so percolation and consequently contamination of groundwater is inevitable.

iii. *The Life span of the these Treatment systems*

As reviewed earlier in literature, all these equipment put in place for either leachate or gaseous emissions and the cover as well all have a lifespan. This implies putting all predicaments aside, they will eventually deteriorate. As explained in the first chapter and perceived in the Nkolfoulou landfill, pieces of the Geomembrane could be seen which could either have been damaged by machines, soil action or corrosive chemicals.

3.2.2. Dangers and Limitations associated with recovery done by waste pickers

i. They do a lot of bending, pulling and carrying on their back. These results to health issues like lower back pain, headaches amongst others.

ii. A good number of them do not have complete Personal Protective Equipment (PPE) and so they are very exposed to emissions of all kinds. In addition to these, they face problems of poor sanitation, noise, vibrations from machines and overheating. . Information gotten from the scavengers via face-to-face interviews (based on their socioeconomic conditions, work shifts, health status, academic backgrounds and knowledge towards self-protective measures, challenges, motivations amongst many others), revealed that they were all young men within the ages of 25-40, some well-educated but sadly, most had a common believe that as you spend a longer time working in those conditions, you adapt, get stronger and immunized against sickness but the reality is that although there is insufficient data on the long-term effect of exposure to airborne bacteria as well as infectious or toxic materials present in solid waste, respiratory and dermatological problems, eye infections and low life expectancy are very common (Owusu-Sekyere et al., 2013). Without which the short term effects are still very pertinent and visible ranging from injuries to gastro-intestinal problems, eye and skin irritations.

iii. Given the fact that competition amongst the waste pickers for materials bring them to running behind trucks upon spotting of valuables in them, this is a risky venture as scavengers could be accidentally knocked down by these trucks.

iv. Waste dumps are not very stable as solid ground. Therefore walking on this very unstable mounts could be very dangerous as landslides could occur or one might just sink in areas with huge amount of leachate in the waste. The activity of excavators and bulldozers could equally bury someone in waste dumps unknowingly. These are all incidents which have taken place in the landfill and this information was gotten from both interviews and observations.

v. A limitation with this this way of material recovery is that the full potential of landfills cannot be well exploited by this disorganized way of recovery. Since waste is dumped directly in trenches allocated for exploitation at a given time and the machinery is working at the same time, recovery it is difficult and ineffective. There is no clear and stable platform for recovery and so each gathers what he can see whereas there is still so much underneath which still ends up being buried in the landfills.

vi. Also, given that the responsibility of recovered materials is on the scavengers, no formal stores have been made for these materials to be kept in and since they are just kept opened in various places in the landfill, un-perceived and uncontrolled events like fires could spark up and destroy so much material recovered, thereby ravaging several months of work. This waste could be psychologically and emotionally torturing to the waste pickers.

a)

b)

Fig 21: Picture depicting Dangers associated with scavenging: a) loss of resource due to accidents (fires); b) back and neck pain which could as a result of carrying heavy load.

(Source: Nkolfoulou Landfill Site, March 2021)

3.3. Results of Characterization of waste

The exercise of characterizing waste had as aim to quantify categories of material in the landfill before and after capping into various categories largely based on MODECOM. This would then give an idea of the landfill space which could be gain by removing this material as well as other economic and environmental benefits which could come as a result of recovering material and reintroducing them into another life cycle.

3.3.1. Results of fresh waste Characterization

Below are figures,illustrating the weighing of the waste after characterization to the left and reading of results on the scale, to the right.

Fig 22: Readings from weighed waste (by category) on suspended scale

(Source: Nkolfoulou Landfill Site, March 2021)

Characterization of solid waste coming into the Nkolfoulou landfill was done onsite. It was done manually and the results are presented on the table below. These results are a consequence of sorting over 3000 kg of waste spread out over six days of work from six districts in the Mfoundi division (Yaoundé I to Yaoundé VI).

Table 6: Waste percentage composition from characterizing fresh waste

Zone	Paper & Carton (kg)	Plastics (kg)	Textile (kg)	Metal (kg)	Glass & Ceramic (kg)	Putrescible (kg)	Fines (<8mm) (kg)	Others (kg)	Total (kg)
Zone 1	22.1	61.4	84.5	5	4	295.8	20.1	7	499.9
Zone 2	50	48.4	44.4	4.7	7.1	326.2	16.7	2.4	500
Zone 3	53	149	41.3	5.4	6.3	225.3	16.2	3.6	500.1
Zone 4	42	59	85	4.5	10	279	15.5	5	500
Zone 5	62.6	51.5	69.1	5.2	5.2	271.2	30	5.2	500
Zone 6	31.4	56.1	55	7.8	7.8	306.1	25.8	10.1	500.1
Total mass (Kg)	261.1	425.4	379.3	32.6	40.4	1703.6	124.3	33.3	2999.9
Percentage by category	9%	14%	13%	1%	1%	57%	4%	1%	100%

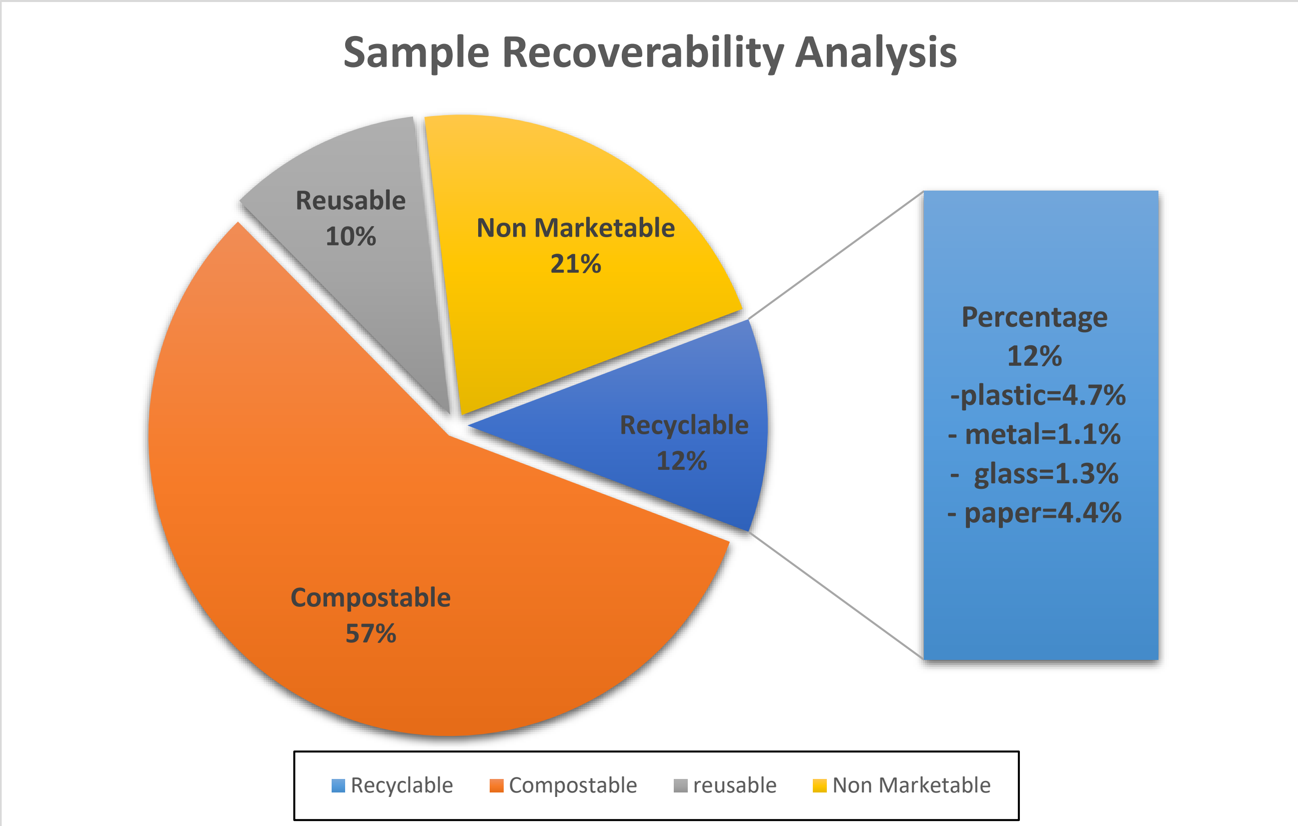


Fig 23: Sample Recoverability Analysis

These results portrayed the fact that the greatest weights came from putrescible with a general average of 57% as presented on the chart above. These results were not different from what was obtained in antecedent years and could be justified given the fact that not much has changed with respect to the huge amount of food waste produced by the population. The fine particles represented 4% of the weight which was different from what was gotten from past years, (5.8% obtained in 2015 and 6.1% in 2011). This could be accounted due to the fact that the screen/sieve used for the exercise was only that of diameter 8mm unlike the standard which included 20mm Sieve. However these fine particles were mainly composed of smaller organic particles as well as sand, small stones and smaller food particles (Groundnut, beans, egusi peelings etc.)

Following it were plastics with 14% which is 2.3 times higher than the percentage obtained in 2015 (6%), reason being that the various measures put in place earlier to reduce plastic usage and disposal have had a lower efficiency as time went on. For example, the embargo/ban on non-plastic biodegradable bags that came into effect in 2014 was overthrown by a bigger influx of plastics from the black market and in response to that, the government gave incentives for collection of plastics which wasn't sustainable and so much collection has been done by some individuals and later still found dumped and brought back to landfills; this was observed from waste sorted from zone 3 where plastics occupied approximately 29% of waste that day. Paper and carton represented a percentage of 9% which like plastic used to be highly valorized but with time, has given way to other items recovered (metals & glass) and so its presence in landfills has increased by two times what was obtained in antecedent years

Textiles composed mainly of sanitary napkins and diapers represented a percentage of 13% which is higher than what was gotten in previous years given that the average rate of births increased over the past years and there has been more dependence on disposable pads and napkins.

At the bottom Glass and ceramics was composed of broken plates, jars, mugs, glasses, wine and beer bottles as well as metals, whom all had a percentage on 1% which was lower as compared to the last years due to the fact that a lot of private companies now valorize these and so much of it is recovered by individuals before it gets to the landfills.

Others was equally at the bottom and as specified by the standard were batteries, bulbs, tires etc. (see table 2 above) were identified. This could be accounted for; based on the introduction of the new recycling center for electronic gadgets in Yaoundé which reduces the presence of electronic gadgets on the landfill, the recent tire recycling facilities help reduce the amount of tires which previously found its way in landfills.

Hospital waste which considered hazardous still happened to find itself in these waste surely due to the creation of so many quarter clinics which unlike hospitals, dispose of their waste in the regular waste skips/bins.

So generally, the results portrayed the following potential;

- **Compostable material** had the highest percentage of **57%** from food waste.
- **Reusable material** had a potential of **10%**
  This was a sum of the fine particles which could be reused as cover material and half the percentage of textile which was considered to be reusable.

- **Recyclable material** had a percentage of **12%**
  These percentage was from metals, glass, 1/3 of plastics and paper which was assumed a recyclable fraction
- **Non-marketable material** had a potential of **21%** which was obtained from the remaining fraction of textile, paper and plastic together with others,

3.3.2. Results from characterization of older waste (waste of age >2years)

When an older sample of waste was excavated and hand sorted from an already exploited zone, the following results were obtained.

Table 7: Percentage composition of waste categories from landfill mining

Zone	Paper & Carton (kg)	Plastics (kg)	Textiles (kg)	Metals (kg)	Glass & Ceramic (kg)	Putrescible (kg)	Fines (<8 mm) (kg)	Others	Total (kg)
Zone 3M (>2years)	5.7	110.3	89.1	5.7	7.4	212.4	0	69.4	/500
Percentage by category	1.14%	22.06%	17.82%	1.14%	1.48%	42.48%	0	13.88%	

Generally, we observed loss in volume thus increase in density as the size appeared to be smaller as compared to fresh waste. The waste mass had a dark appearance and muddy texture. The results above showed that putrescible which had the highest percentage weight on entry to the landfill, though still highest percentage underwent a loss of 15% from the general weight, which was presumed to the fast degradation process. A dramatic drop was equally observed with paper and carton as about 8% of it was lost, certainly due to degradation since they too are easily decomposed. This reflects a direct relationship with results gotten from work carried out 3years ago in Yaoundé (Nkolfoulou landfill) on consolidation of waste samples.

The results portrayed were accounted for by the huge presence of biodegradable organic matter in municipal waste (Ngnikam et al, 2018).

The other components including plastics, textiles did not change a lot as their degradation process would take a longer time, so their percentages rather increased as the decomposed waste gave way for these rearrange themselves and fill the air spaces due to consolidation. Others, was mainly composed of rubber and tires and a very small percentage of electric waste.

The fine particles were totally absent as much of the waste was dark in appearance and a moist texture. This could be accounted for by the fact that the area from which the excavation was made hadn't yet been treated completely and thus the final cover was not yet placed. Hence giving way to infiltration from rain.

- Generally, there was **no reusable component**.
- The potential of **recyclables** already buried is about **19%** obtained from 1/3 of plastics, 2/3 of others, glass and metals.
- **43**% was **compostable**
- The remaining **32%** was **non marketable** and could be re-landfilled.

However the sorting procedure was very difficult given the quality of the mass and since experiments such as the fermentation potential of the sample (putrescible fraction) or comparism with several samples wasn't possible, the precision of these samples is very little.

3.4 Report of material recovery pattern by the Scavengers

As described at the level of the methodology, the material recovery done at the landfill is by the waste pickers. It brings financial benefit to them and on the part of the landfill, it is a way of helping the landfill get rid of certain material thereby reducing the bulk of what is finally landfilled. The role of scavengers is equally of vital importance as they contribute to reducing a considerable amount of heavy metals like lead (from batteries, some toys, paint cans etc.) in leachate which has proven from a lot of past studies and seen to have serious impacts to the Foulou river, hence the population and environment.

Table 8: Report for waste material recovered by scavengers from October 2020-February 2021

Month	Waste Type	Weight(kg)	Weight(Ton)	Destination
October 2020	• Plastics	18,220	18.22	Douala
November 2020	• Metals	7,220	36.92	Douala
	• Plastics	29,700		
	Total	36,920		
December 2020	• Metals	7400	37.76	Douala
	• Plastics	10,660		
	• Glass	19,700		
	Total	37,760		
January 2021	• Metals	14.300	26.44	Douala
	• Plastics	12,140		
	Total	26,440		
February 2021	• Metals	20,180	110.020	
	• Plastics	33,360		
	• Glass	8440		
	• Worn-out tires	48,040		
	Total	110,020		

From the following report, the items recovered by the scavengers are plastics, metals, glass and worn-out tires. It is obvious that there is no particular or distinct relationship observed between the various weights of materials leaving the landfill both per month and category wise. This is due to the fact that recovery depends largely on the individual's expertise, availability and convenience. Trucks come in only at the satisfaction and arrangement of the scavengers and their agreement with their partners/market.

Plastics are the most permanent materials recovered throughout the periods recorded and it was composed of the following in the family of thermoplastics; high density polyethylene, polypropylene and polyvinyl chloride. The system of plastic recovery is still very narrow and so much of it is done at the landfill. This is not same case with metals, glass and worn out tires which have a lot of informal collection done in the skips and bins before they get to the landfill.

3.5 Results for density of waste

The density of the waste was measured and the results were obtained with respect to the trucks used and displayed as follows

Table 9: Density of Fresh waste

Truck type	Mass (kg)	Volume (m3)	Occupancy rate	Density
VDP	5435	16.00	1	0.34
PC	1500	6. 00	1.3	0.33
Average				**0.335**

The densities for the two trucks just varied very slightly from the other given that they carry waste with similar characteristics.

Density of Old waste

$$"Density\ (t/m3) = 1 * (2t \div 1.4\ m3)"$$

$$\mathbf{= 1.4\ t/m^3}$$

The density for old waste far out passes that of the fresh waste. This is accounted for due to a significant reduction in volume due to consolidation and an increase in water content of the waste. The results reflect what was gotten in antecedent works.

3.6 Assessing benefits of mining out waste

3.6.1. Gain in airspace

A comparism is made between the airspace obtained from the formal scavenging and airspace gain based on the open dump mining procedure we carried out which is considered more accurate and then the reclaimed area and airspace from landfill mining is also calculated for the already exploited zones 1 and 2.

I. <u>From scavenging</u>

Assuming;

- Surface area of 1Hectare =10,000 m^2
- average depth of 20 m giving a volume/capacity of 200,000 m^3
- Average exploitation rate on waste trench, mass rate (t/ha)=76,086 t/ha (Most recent exploitation)

i. This implies, Initial airspace=200,000 m^3

ii. Airspace filled for 1ha =

$$(\text{mass rate (t/ha)} \div \text{density (t/m3)}) * 1\text{ha}$$

=227,122.4 m^3

iii. Settlement based on earlier experiments in landfill revealed to be a 0.13 (Ngnikam et al) which is proportional to a 13% drop in height=29,526 m^3

According to equation;

$$\boldsymbol{Air_I - Air_F + S = Air_R}$$

Remaining Airspace Air_R = (200,000-227,122.4+29,526) m^3

=2403.6 m^3

II. <u>Using an improved strategy</u>

Assuming;

- Surface area of 1Hectare =10,000 m^2

- average depth of 20 m giving a volume/capacity of 200,000 m^3
- Recovery of only 22% (a sum of reusable + recyclable waste percentage), gives an average exploitation rate on alveoli, mass rate (t/ha)=59,347 t/ha
    i. This implies, Initial airspace=200,000 m^3
    ii. Airspace filled for 1h a =

$$(\text{mass rate (t/ha)} \div \text{density (t/m3)}) * 1\text{ha}$$

=171,185.07 m^3

    iii. Primary settlement based on earlier experiments in landfill revealed to be a 0.13 which is a 13% drop in height=29,526 m^3

According to equation 3;

$$\boldsymbol{Air_I - Air_F + S = Air_R}$$

Air_R = (200,000-171,185.07+29,526) m^3

=**58,341 m^3**

This capacity of withdrawing just recyclables would account for a volume gain of 29.2% per hectare which would prove more beneficial to the landfill on the long run by prolonging the lifespan of the landfill by approximately 2years.

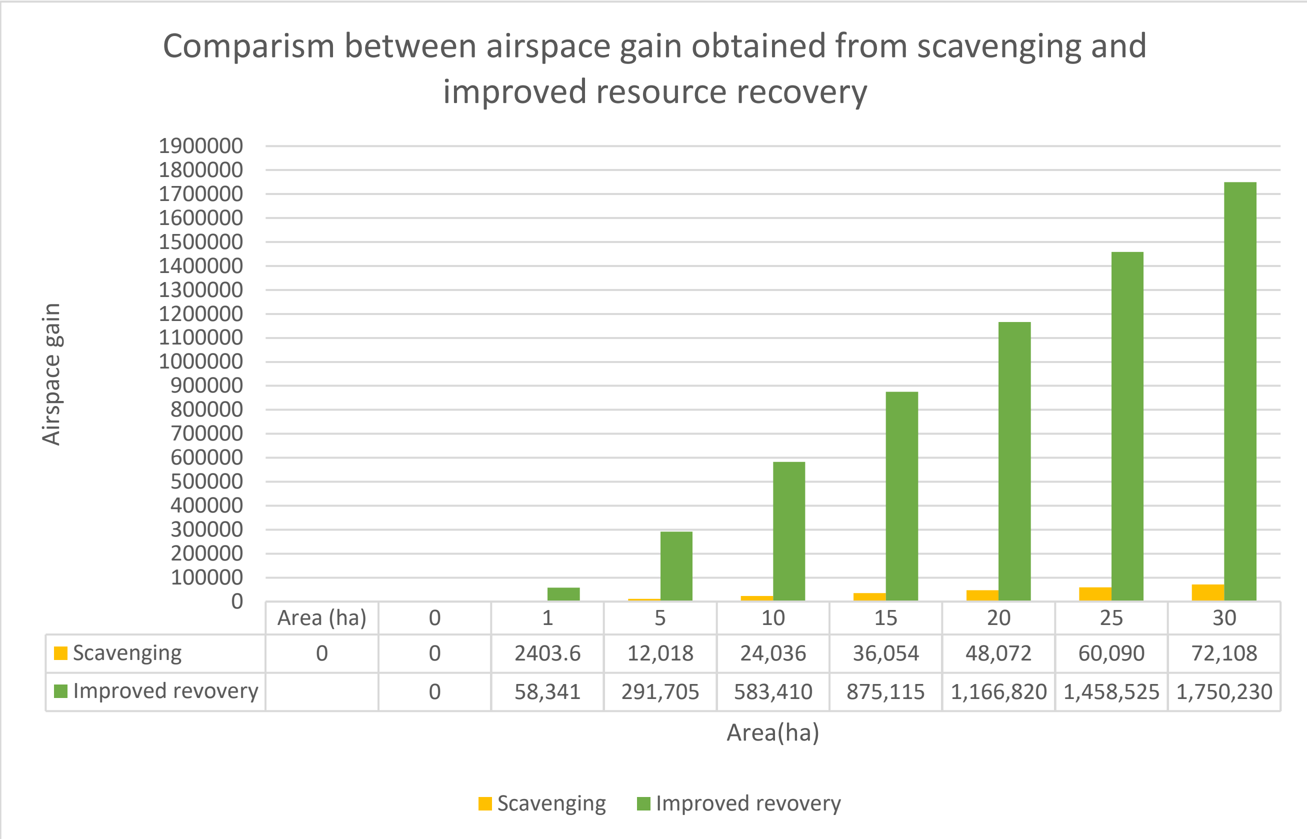


Fig 24: Comparism between the airspace gain from scavenging and improved recovery

III. Landfill mining

This activity gave a 19% of recyclables which could be recovered and sent back to the market. This implies if in every 1t on waste excavated, 19% is withdrawn, excavating the first two zones of the landfill which have already been exploited would reveal the following results:

- **Zone 1**: Total mass of waste buried in 6ha is 1,747,197 tons of waste.

Implying mass rate (t/ha) = 291,199.5 t/ha, density=1.4 t/ m^3

Mass rate considering 19% withdrawal = (291,199 -55,328) t/ha =235,871 t/ha

Area gain = Current mass rate/New mass rate *Tot Area of land used

This would occupy an area of **4.9 ha** therefore reclaiming **1.1 ha** of land.

$$\text{Airspace gain} = \text{mass rate}\left(\frac{\text{t}}{\text{ha}}\right) \div \text{density}\left(\frac{\text{t}}{\text{m3}}\right) * 6\text{ ha}$$

$= (55{,}328 \text{ t/ha} \div 1.4 \text{ t/m}^3) * 6\text{ha}$

$= \mathbf{237{,}120\ m^3}$

- **Zone 2**: total mass of waste buried in 7.5 ha is 2,339,203 tons of waste,

Implying a mass rate (t/ha) = 311,894 t/ha

Mass rate considering a 19% withdrawal = (311,894 - 59,259) t/ha =252,635t/ha

Area gain = Current mass rate/New mass rate *Tot Area of land used

This would occupy an area of **6.1ha** therefore reclaiming **1.42ha** of land

$$(\text{Airspace gain for 6ha} = \text{mass rate (t/ha)} \div \text{density (t/m3)}) * 6\text{ha}$$

$= (59{,}259\text{t/ha} \div 1.4\text{t/m}^3) * 7.5\text{ha}$

$= \mathbf{317{,}459\ m^3}$

3.6.2. Environmental impact

a. <u>Leachate</u>

Results of physico-chemical studies of the Mfoulou River (Ako et al, 2008) portrayed serious bacteriological contamination from the Nkolfoulou landfill. Studies were also carried out in 2012 by Ngnikam et al on the characteristics of leachate produced in the landfill which revealed a high organic pollution which was predicted high enough to cause eutrophication in the Mfoulou River as well as the presence of metals which needed attention such as Chromium, Lead, Copper and Cadmium.

Pollution caused by these metals could be curbed through effective material recovery, given that their origin could be drawn from the same metallic materials deposited. Likewise, organic pollution could be curbed by recovering and treating the putrescible waste to be used as compost. Therefore setting up effective material recovery system for fresh waste will serve as a first barrier and pretreatment and would assist the measures already put in place to mitigating further pollution tendencies. Mining out previously deposited waste in this case would serve as a suitable remediation and after-care control measure.

b. Landfill gas (LFG)

Landfill gas (LFG) is a natural byproduct of the decomposition of biodegradable waste under anaerobic conditions in a landfill site. It is itself legally considered to be a waste and composed mainly of Methane and Carbon dioxide whose emissions could last for decades but have been proven to reduce through mechanical-biological pretreatment. Every model used for predicting LFG generation are based on the waste composition i.e. its carbon content, degradability and kinetics of degradation. The most widespread model used in Europe is the Tabasaran's expression (Tabasaran 1976), which is a relationship designed for anaerobic digestion of sewage which simulate carbon degradation following a first order approach.

$$G_a=G_e\,(1-e^{-ka})$$

Where:

Ga: accumulated gas generation until year a [Nm3 t-1]

Ge: gas formation potential [Nm3 t-1]

k: degradation constant = ln2/t½ [time unit-1]

a: time [number of time units]

Ge = 1.868 CO (0.014T + 0.28)

CO: content of degradable carbon in the waste [kg t-1]

T: temperature [°C]

From the gas formation potential, that LFG generation clearly has a strong linear dependence on nutrient availability and temperature. Based on studies carried out in antecedent years in the Nkolfoulou landfill using a similar model, largely based on Rettenberger's equation and some estimations from the Tabasaran equation and Intergovernmental Panel on Climate Change (IPCC) by Ngnikam et al, 2012,

$$QLFG=\sum_{x} A*K*MSW(x)*Lo*e^{-k(t-x)}$$

Where:

t: year of inventory (1994 for Cameroun)

x: number of years for which data is

A = (1e-k)/K Normalization factor to correct the sum

k: emission rate of methane (1/year)

MSWt (x) = Total amount of waste treated in year x (Gg/year)

Lo: Methane Emission potential = [FCM (x)*COD (x)* COD* F *(16/12) (Gg CH4/Gg of waste)]; **FCM (x)**: Correction factor for methane (fraction) ;

COD (x): Dissolved Organic Carbon (DOC) or Chemical Oxygen Demand (COD) for year x (fraction) (Gg C/Gg of waste);

CODL: Liberated fraction of COD

F: Fraction per volume of CH4 in landfill gas

Based on this model, the gas formation potential was **79 kg de CH4/ton of wet waste.** Given that these quantity was attributed to the nature of waste and conditions for treatment, decreasing the amount of organic material through material recovery will automatically result to an overall decrease of the nutrient availability (degradable Carbon in waste) and heat generated during the degradation process thus hindering the gas formation process and mitigating pollution.

3.7. Estimation of Economic gain from Enhanced Selection and Recovery

Below, the economic benefits gotten from the characterization and projecting benefits that could be gotten on monthly basis with an improved recovery system.

3.7.1. Plastics

- Before final cover is placed;

Given that the percentage recovered during studies was 14%, this will imply that in every 1400tons of waste recovered a day,

Approximated amount of plastics which could be recovered if the activity is done in a more structured manner would be

$$\frac{14}{100} * 1400 = 196\frac{tons}{day}$$

From which, if it is assumed just about a third in this fraction are highly recyclable and would have potential buyers in the market, we are working with about 65tons per day of marketable plastics

Given that the average amount recovered by scavengers per month is just 21 tons, using a more structured recovery system, we would be much more efficient and the benefits will equally be greater.

The range (depending on the market) for selling price for plastic gotten from the waste pickers is between 100 FRS and 150 FRS per kilo, thus average per kilo would be 125 FRS. This implies per month, we would obtain

(65 * 1000) kg * 125 *30 = **243,750,000 FRS**

- After the cover is placed and mining takes place;

Percentage recovered during studies was 22% of 500kg.

This is equivalent to 220kg in 1 ton

Considering the fact that age and the decomposition process further reduces the quality of the material and so assuming that just 1/3 is recyclable, it implies every 1ton, we get 73 kg which represents an economic gain of 9125 FRS per ton of waste.
Therefore mining 1000 tons would have an economic gain of 9,125,000 FRS.

3.7.2. Metals

- Before final cover is placed;

Percentage recovered during work was 1%, which would give us

$$\frac{1}{100} * 1400 = 14\frac{tons}{day}$$

Given the average recovered per month by waste pickers is 12.275 tons, recovering metals gives 420 tons per month which is far greater. The average and most constant amount for which 1 kg of metal is sold by waste pickers is 75 FRS, therefore we could get a monthly benefit of **31,500,000 FRS**

- After the cover is placed;

1% was recovered and so in 1tonne we can sort out 10 kg of metal which is 750 frs/ton. This means mining out 1000tons would give **750,000 FRS**

3.7.3. Glass

Given that the same percentage was gotten from the metals, we have a daily recovery of 14 tons of glass and ceramic. The range (depending on the market) for selling price is between 75 FRS and 150 FRS per kilo, thus averagely, a kilogram goes at a hundred francs. Therefore in a month we have 420 tons implying **42,000,000 FRS** per month
After the cover has been placed and glass is mined out, 15 kg is withdrawn which represents benefits of 1500 FRS per ton and so 1000tons will represent a benefit of 1.5millionfrs.

3.7.4. Reclaimed Airspace

Given that the company is payed about 2500 FRS for each ton of treated waste,

- ❖ The gain in airspace per hectare from the recoverable fraction of fresh waste gives way for waste occupying approximately $58{,}341 m^3$

Therefore for 8ha of land we'll have a profit of:

Gain = 2,500 FCFA* M_{Sup}

= 2500 * V_{Sup}*Density

= (2500* ((58,341 m^3/ha * Area) * 0.34 t/m^3)) FCFA

=**396,718,800 FCFA**

- The gain from mining zone 1 & 2 (oldwaste)

Gain = (776410 t * 2500 FCFA/t)

= 1, 941, 026,250 FCFA

CHAPTER 4

PROPOSALS AND RECOMMENDATION

Following the studies which were carried out, the results and analysis in the previous chapter, it was clear that the constraints at the level of material recovery are still very large at the detriment of both the institution and the waste pickers. Relying on a manual form of recovery has been proven to bring a far low return to the waste pickers as well as the institution. On another end completely tilting towards a mechanized technology would be too expensive and render so many youths jobless.

Therefore in envisioning a sustainable society, the best approach would be installing a Material recovery plant with an integrated system whereby the scavengers who master their craft, are accommodated in under healthier working conditions as this would tremendously improve output and would be maximized by a machinery to facilitate the work. Considering the present context of a landfill as such in a developing country, this would be far cheaper than a completely mechanized system and would equally reduce poverty level through employment of youths to work and manage this system. From an economic perspective, it would bring revenue in cash and kind to landfill owners and contribute greatly to reducing the environmental impacts generated by waste in landfills. Below is a summary of an integrated waste cycle/process in landfill

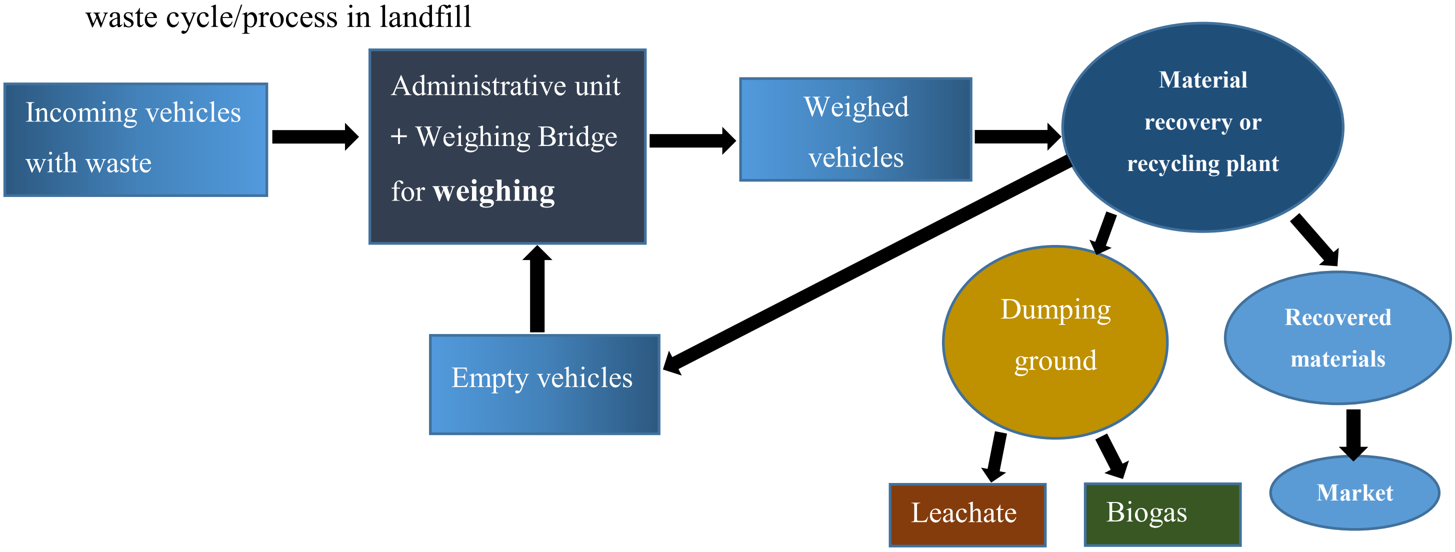
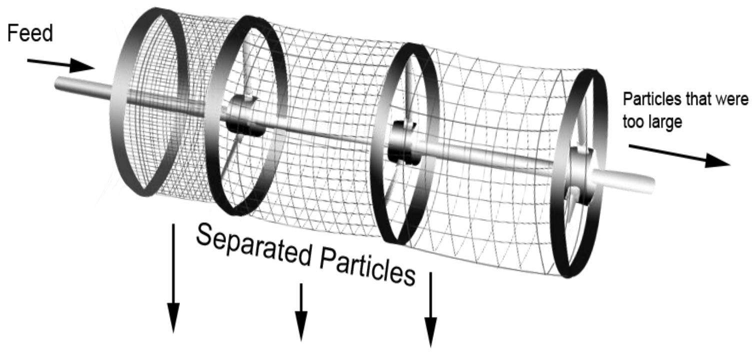


Fig 25: Proposed new waste cycle

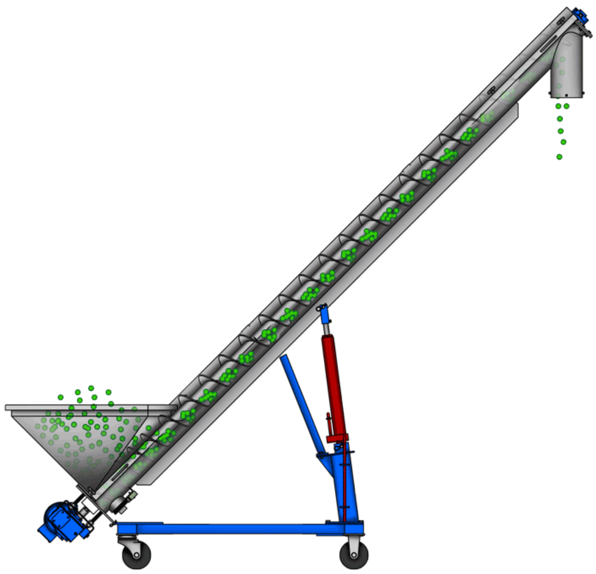
Considering that the landfill already possesses 2 weighing bridge, trucks and front-head loader, below are some other important components used in Material recovery plants

a) Trommel:



This is an important part of waste pretreatment facilities and is composes usually of screens based on the need of the treatment plant. In our case two sieves of 20 mm and 8 mm would be recommended for recovery pf fines which could be used as soil cover.
An average model has an average power of 15 KW and a performance of 150 m3/h.

b) Hopper and Conveyor belt:



The hopper and conveyor belt are primary components of waste treatment plant. The entire process begins with them, from reception of waste from loader and movement of waste for segregation in to select recyclables. Specifications for a conveyor belt with hopper used in a waste treatment plant as follows;

Table 10: specifications for conveyor belt with hopper

Power	3.7 kWh	Belt speed	0.2 m/s-1.2 m/s
Conveyor Material	Heavy Rubber of preference (Tenacity and resistance to corrosion)	Performance	100 tons/h
Loading method	By hand Excavator or front head loader	Hopper	785*850 mm 0r 940*940 mm
Length	Up to 40 m	Max angle	350
weight	70 kg/m		
Belt width	600 mm		

c) Electromagnet or magnetic separator

This device utilizes the mechanical properties of iron and steel which allows them to be removed from the refuse stream with a magnet. Two major separators for MSW recovery facilities exist, which are the drum magnet and the over-head belt magnet. This device has a capacity of 10-100 tons per hour. It has a low operation cost and consumes just an average of 2.1 kw for a working distance of 300-350 mm.

d) Manual Separation cabin

The conveyor belt finds its way through a secured cabin where manual sorting takes place and the sorted materials are placed in the appropriate bins allocated for various categories of waste. The bins could vary from 660l to 1100l,

e) Shredder

In order to break and reduce particle sizes for so as to get a bigger proportions of fines, a shredder would be used. Thereafter the fines could undergo necessary treatment and used as landfill cover material and the left overs landfilled. Another advantage of the shredder is that

the general particle size landfilled is smaller hence reducing stress on the bulldozer during re-profilation of waste in trenches and increases the efficiency of the magnetic separator.
An average shredder has a capacity of about 40 t/h and power of 18,8 kWh.

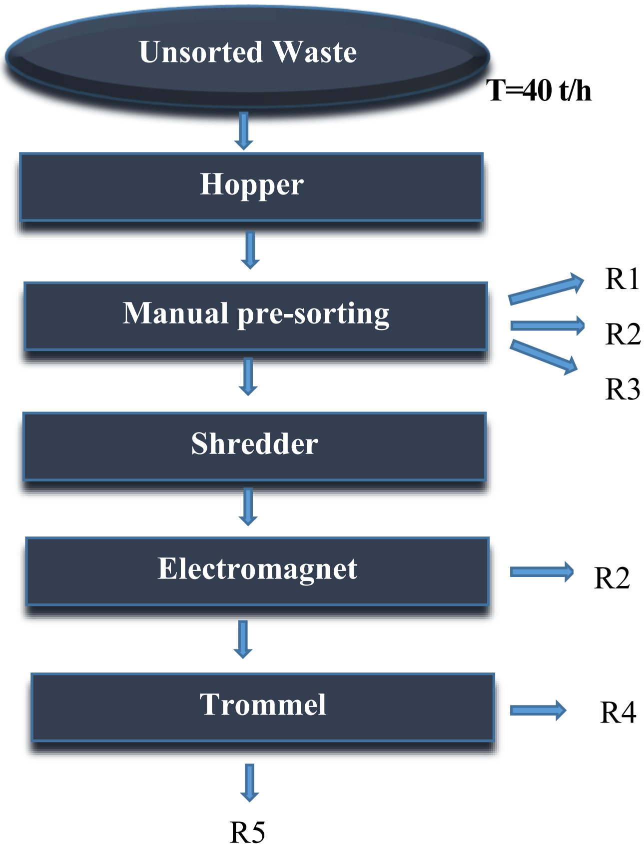
f) Baler

Based on the specifications and needs of the market or the need to ease transportation on the recovered materials such as plastics, metals or even tires, a baler would be used. It has an average capacity of 40 tons per hour and a power of 7.6 kWh

Fig 26: Main components of proposed semi-automated material recovery system;

a) Trommel; b) Hopper and Conveyor belt c) Electromagnet/magnetic separator d) Cabin for manual selection containing bins for waste segregation e) Shredder f) Baler

Pre-treatment scenario



R1=plastic
R2=metal
R3=glass
R4=Fine particles
R5=Residue to landfill

Cost – Benefit Analysis for mining waste by Semi -Automated mechanism

In order to evaluate this, 2 scenarios are envisaged and evaluated; Scenario 1 with the proposed system and Scenario 2 without, from which the investments and benefits would be evaluated for the extra 2years of lifespan.

Scenario 1

- Income from sales is defined from the publicly available waste selling prices of recyclables and calculated;
- Given that the council pays about 2500 frs for treatment of a tonne of waste, the extra gain per tonne of waste is calculated,

  Gain = 2,500 FCFA* M_{Sup}

  = 2500 * V_{Sup}*Density

  =2500* ((58,341 m^3/ha * Area) * 0.34 t/m^3)
- Purchase and installation of proposed system in a following a paralllel circuit connection is considered. Following the protocol for public contracts, the installation cost is 20% the purchase of the equipments;
- The energy price charged per kWh by ENEO to enterprises as such is 80frs, consumption using proposed system is evaluated ;
- Considering three work shifts ;12 scavengers are employed, 4 per shift with a salary of 100,000frs per month for the 2years;

Scenario 2

- Site doesn't implement system, closes up earlier and moves to a new location of distance X. The landfill is 16km away from the central town and so we would be working on a new distance, **(16 + X) km**,
- The additional fuel which would be required for this extra distance X for extra 2 years is calculated and would avail as gain in the case system is adopted.

E.g. Average monthly fuel refill at landfill currently stands at 130,000l of fuel, if site is changed to new anticipated site at Mfou (40km further), for those 2 years, average fuel consumed would be (130,000 + 325000) l = 455,000 l/month

This implies that in 2 years, an extra **7,800,000l** of fuel which is equivalent to an extra expenditure of **4,914,000,000 FCFA.**

Table 11: Investment-Benefit Estimation assuming scenario of Semi-Automated System

Input/Investment (millions)		***Output/Benefits(millions)***	
Equipment cost	**744.2**	Income from sales of recyclables	**3,353.4**
Construction and Installation works	**148.8**	Gain in airspace (assuming 8 unexploited hectares in zone 3 & 4)	**396.7**
Wages	**29**	Gain in fuel	**X**
Electrical energy and fuel (2years)	**70**		
Indirect cost and maintenance	**123.6**		
Total	**1115.6**	Total	**3750.1 + X**

Balance= Benefits - Investment = (2,911.5 +X) millions

This reveals that though the installation cost could be expensive, acquiring a Semi-automated recovery system offers far more benefits and opportunities to the stakeholders and the environment at large on the long run.

In an attempt to achieving sustainable cities and communities (SDG 11), managing landfills sustainably should not be taken for granted. These study has shown feasibility of recovery of materials from the municipal landfill of Yaoundé as a beneficial remediation technique but a lot still needs to be put in place to ensure sustainability. Stated below are some recommendations which would prove beneficial if given due attention.

❖ Policies:

Formulation and enforcement of comprehensive and consistent frameworks for waste management in Cameroon beginning right from the top of the solid waste pyramid as emphasized by EPA would be an efficient way of managing waste. Presently there is no official policy to regulate recovery and recycling practices and as such funding is unavailable thereby making it very informal, slag and rudimentary. Also, policies emphasizing on waste segregation at various sources of production will facilitate recovery at the landfill and thus enable better management.

❖ **Incentives :**

Incentives should be given to encourage private companies and boost the morale of individuals who venture into recovery and recycling of waste materials as this activity has proven beyond reasonable doubts to be a vital tool in building sustainable cities. The formulation of policies to sustain such initiatives would be important to ensure longevity.

❖ Studies of Economic Instruments to promote waste reduction and recovery

This would involve major participative consultations through facilitated workshops involving all the stake holders (the councils, government, waste contractors, community groups and representatives). At the level of the landfill, their standards should be upgraded to integrated schemes and proposals to render it sustainable and lengthen its lifespan while giving healthier jobs openings to scavengers should be considered.

Analysis in the work revealed that the only form of recovery done is by scavengers and they master their craft as well as demands in the market and so involving them in an integrated scheme would take little training time and yield very positive returns.

For further research

- Up to date studies should be done to determine the exact biological and chemical composition of the putrescible waste fraction at the Nkolfoulou landfill so as to know the requirements for treatment and reusability as compost.
- Studies should be done to assess the state of the market outlets and requirements needed for recovered materials as well as the Institutional and technical challenges faced in the implementation of policies for a waste recovery scheme in the Nkolfoulou landfill.

GENERAL CONCLUSION

This research work was centered on finding a way of reducing the impact of landfills (using Nkolfoulou landfill as case study) on the environment by remediation while looking at benefits that could be gained in the process particularly by bringing out the importance of resource recovery and gain of airspace. For this reason the ideal technique adopted was that landfill mining. The idea of mining out waste was viewed from two different perspectives and all assessed. In order to achieve that, we had as specific objectives assessing; i) the limitations of the current emission management ii) the recovery potential of materials by both open-dump mining and landfill mining iii) the possible gain in airspace, the economic and environmental impact of mining out waste from the landfill.

The research methodology used to achieve these objectives were split into a thorough desk study and field study. The desk study was mainly documentary research from past works, articles etc. while the field study interviews, survey and field work.

The field work enabled waste sampling and characterization which was largely based on an adapted version of the MODECOM which is the French standard for Characterization was carried out for six districts (Yaounde1- Yaoundé 6) and the results obtained revealed the following;

- Open dump mining yielded a potential of roughly 22% of recoverable material (12% recyclable and 10% reusable) and a 29.2% gain in airspace per hectare which is more significant than the 1% average recovery potential and gain in airspace from the present recovery system. The results of the density permitted calculation of this gain in volume which yielded 58,341 m^3 per hectare of land. This would consequently prolong the lifespan of the landfill by at least two additional years.
- Also, assessing the landfill mining brought forward a recovery potential of 19% of which no reusable fraction was obtained.
- From an Environmental perspective the recovery of material is beneficial as it withdraws potential reserves of heavy metal contamination in leachate and recovery of

organics. Thus, will contribute to significantly reducing the total amount of greenhouse gases generated by landfills

- From the both, the fraction of putrescible was the greatest fraction and would prove very beneficial if recovered and so it was proposed for further research, the required analysis is done.
- The proposal of adopting and integrated waste management involving scavengers upgrading the system of recovery to a Semi-automated system proved very feasible and beneficial of the long run for remediation purposes and economic purposes.

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