ASSESSMENT OF THE EFFECTIVENESS OF USING BLACK SOLDIER FLY LARVAE IN TREATMENT OF MUNICIPAL SOLID WASTE

RICHARD MUGAMBWA MUKASA

RS16M45/019

A DISSERTATION SUBMITTED TO THE FACULTY OF ENGINEERING, DESIGN AND TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN WATER AND SANITATION OF UGANDA CHRISTIAN UNIVERSITY

October,2025

UGANDA CHRISTIAN
UNIVERSITY
A Centre of Excellence in the Heart of Africa

ABSTRACT

The study intended to find the potential of Black Soldier Fly (BSF) larvae as a sustainable solution for managing municipal solid waste (MSW) in Uganda, a country grappling with significant waste management challenges. Kampala generates an alarming 2,000 to 2,500 tons of waste daily, yet only a fraction is effectively collected and processed, rendering traditional disposal methods inadequate. The research primarily focused on analyzing the composition of MSW, assessing the weight reduction over a nine-day composting period, and examining the influence of moisture and temperature on waste processing efficiency. The study's methodology combined both quantitative and qualitative approaches. Waste was collected from Nakawa Market, sorted into organic, inorganic, and recyclable components, and processed into uniform 1-2 cm particles. Simultaneously, BSF larvae were reared and monitored, with experiments conducted using five-day-old larvae. The findings revealed that the waste largely consisted of jackfruit and onion residues, which exhibited a moisture content of 79% and a pH of 6.7. A preliminary fermentation process resulted in 275 kg of material at a measured temperature of 24.95°C. Over the nine-day trial, weight reduction was consistently monitored across 22 samples (12.5 kg each), following the addition of 0.003 kg of BSF larvae. The experiment resulted in an average weight decline from 12.5 kg to 9.7 kg, demonstrating statistically significant differences through ANOVA analysis ($p < 0.05$). Notably, temperature variations were significant throughout the study, with an initial decrease followed by a peak of 37.5°C for one sample, highlighting the dynamic nature of microbial activity. A notable strong negative correlation ($r = -0.967$) was identified, suggesting that as waste weight diminished, temperature elevated. The relationship between moisture content and waste reduction index (WRI) was also significant: moisture levels at or below 55% maintained a WRI below 1.5, while levels between 60% and 80% peaked at a WRI of 2.5. Conversely, moisture content above 80% led to a decrease in WRI. Waste reduction efficiency was found to be optimal between 60-80% moisture, with temperature playing a pivotal role in the composting process optimal at 30°C for enhanced decomposition rates. Recommendations for effective MSW reduction include routine monitoring of environmental conditions, implementing preliminary fermentation, and promoting aerobic conditions to enhance microbial activity and waste management strategies in Uganda.

DECLARATION

I Richard Mugambwa Mukasa hereby declare that there is no conflict of interests regarding this work and material presented. This MSc. thesis is my original production and it has never been produced or submitted by any one for academic award.

Signed... Date..

Richard Mugambwa Mukasa

This thesis has been submitted to the directorate of research and graduate training with the approval as my university academic supervisors;

1. First supervisor

Signed... Date.......................................

Dr. Joel Kinobe

2. Second supervisor

Signed...Date.......................................

Rogers Tayebwa

DEDICATION

I dedicate this thesis to my Wife, Daughter and Mother Mrs. Anita Murungi Mugambwa, Ms. Gabriella Kirabo Mugambwa and Mrs. Margaret Mukasa Mugambwa to whom I owe my academic journey. Your confidence in me has never wavered and you have time and again provided invaluable advice and support throughout this journey. You are my inspiration and you’ve followed me through this academic pursuit and have modelled me for greater possibilities and opportunities.

ACKNOWLEDGEMENTS

First, I thank the Almighty God for the opportunity and I consider the successful completion of this work a gift from God to whom I am sincerely indebted. My sincere thanks go to my supervisors Dr. Joel Kinobe and Rogers Tayebwa for their encouragement and acceptance to supervise this research. I am grateful for your guidance, technical advice and suggestions, significantly contributed to the success of this research. I am also thankful to Mr. Philip and Joseph of Marula Proteen Limited that gave me access to their facilities to conduct this wonderful research.

I further recognize with appreciation, the inspiring environment provided by Uganda Christian University through this entire research period.

Last but not least, I acknowledge all efforts of my wife Anita Murungi Mugambwa, my parents Mr. and Mrs. Mukasa Mugambwa, my children, brothers and sisters whose support and encouragement was invaluable in enabling me accomplish this master’s program. I will forever be indebted to the unquantifiable support and encouragement extended.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

5DOL	Five Day Old Larvae
ANOVA	Analysis of Variance
BCE	Before Christ Existence
BSF	Black Soldier Fly
BSFL	Black Soldier Fly Larvae
C&D	Construction and demolition
C:N.	Carbon to Nitrogen ratio
$C0_2$	Carbon dioxide
$C0_{2eq}$	Carbon dioxide equivalence
CH_4	Methane
EDF	Environmental Defense Fund
GHGs	Green House Gases
GKMA	Greater Kampala Metropolitan Area
GR	Growth Rate
KCCA	Kampala City Council Authority
MCCM	Moisture Content Control Medium
MS	Moisture Content
MSW	Municipal Solid Waste
N_20	Nitrous Oxide gas
NEMA	National Environment Management Authority
NO_3	Nitrate(s)
SWMS	Solid Waste Management Strategy
UBOS	Uganda Bureau of Statistics
UN	United Nations
WRI	Waste Reduction Index
WWF	World Wildlife Fund

CHAPTER ONE: INTRODUCTION

1.1 Background

Municipal solid waste (MSW) management is a critical global challenge, exacerbated by increasing urbanization, population growth, and unsustainable waste disposal practices. According to Kaza et al. (2018), approximately 2.01 billion tonnes of MSW are generated annually, a figure projected to rise to 3.40 billion tonnes by 2050. Among this waste, organic materials constitute a significant portion, accounting for 40-60% of MSW, particularly in low and middle income countries. Inadequate disposal of organic waste leads to environmental pollution and public health risks (Hoornweg & Bhada-Tata, 2012). Conventional waste treatment methods, such as landfilling and incineration, contribute to environmental degradation through greenhouse gas emissions, soil contamination, and resource inefficiency (Hoornweg & Bhada-Tata, 2012). These challenges underscore the urgent need for sustainable and cost-effective alternatives that align with the principles of a circular economy. One promising approach involves the utilization of black soldier fly larvae (BSFL, *Hermetia illucens*) for organic waste bioconversion. This method not only provides a viable solution for waste reduction but also yields valuable biomass applicable in animal feed and other industries (Diener et al., 2011).

The benefits of BSFL-mediated waste treatment are numerous. Unlike traditional composting methods, BSFL operates at a significantly faster rate, requires less physical space, and generates fewer greenhouse gas emissions, making it a compelling option for urban waste management (Klenovšek et al., 2017). Several studies have demonstrated the larvae's ability to efficiently degrade diverse organic waste streams, including restaurant leftovers (Manurung et al., 2016), fruit and vegetable waste (Nguyen et al., 2015), and sewage sludge (Lalander et al., 2015). For instance, research by Dortmans et al. (2017) reported that BSFL could reduce mixed organic MSW by up to 58% within 15 days while simultaneously producing protein-rich larvae suitable for animal feed. Further investigations by Mertenat et al. (2019) tested BSFL on source-separated household food waste, revealing a 50-70% reduction in waste mass along with high larval protein content (40-45% dry matter). Likewise, a study conducted by Rehman et al. (2017) found that a mixer of BSFL and processed market waste, which primarily consisted of fruit and vegetable scraps, achieving a notable 62% reduction in waste volume. Conversely, a study by Shumo et al. (2019) indicated that while BSFL efficiently consumes starchy and sugary waste, fibrous materials such as peels and husks require microbial or mechanical pretreatment to enhance digestibility.

A critical aspect of the BSFL-mediated waste treatment process is the quality of the by-products. The larvae produced are rich in protein (40-45%) and lipids (15-35%), making them suitable for application in poultry, aquaculture, and livestock feed (Barragan-Fonseca et al., 2017). Additionally, the residual frass generated from the treatment process demonstrates potential as an organic fertilizer due to its high nitrogen, phosphorus, and potassium content (Beesigamukama et al., 2020). However, the economic viability of BSFL-based MSW treatment is influenced by factors such as larval yield, processing time, and market demand for by-products (Surendra et al., 2020). However, the practice is highly utilized in developed countries; Austria, Netherland, Ireland, and European Union (Kaza et al., 2018). In contrast, nations such as India and China exhibit lower composting rates at 10% and 3%, respectively, primarily due to concerns over contamination and inadequate waste management practices (Pujara et al., 2019; Ding et al., 2021). Furthermore, vermicomposting in Africa remains behind global trends, processing only 5-10% of organic waste through this method (Asase et al., 2019). In East Africa, Uganda faces both potential opportunities and significant challenges, as low public awareness results in merely 2% of urban organic waste being composted (Kibuga et al., 2020). Given the variability in organic MSW composition and the pressing need for effective waste management solutions, this study aims to comprehensively evaluate the effectiveness of BSFL in processing market municipal organic waste.

1.2 Problem statement

In Uganda, the management of MSW presents significant challenges due to rapid urbanization, population growth, and inadequate waste management infrastructure (Kinobe et al., 2015). The Kampala Capital City Authority (KCCA) reports that the city generates between 2,000 and 2,500 tons of waste daily, yet only manages to collect and dispose of 1,300 to 1,500 tons. This results in approximately 50% of waste remaining uncollected or improperly disposed. Traditional disposal methods, such as landfilling at Kiteezi, have become increasingly ineffective, as the landfill has surpassed its carrying capacity. Initially occupying 29 acres upon its establishment in 1996, Kiteezi was expanded by 6 acres in 2007 as a temporary measure to prolong its lifespan (Mboowa et al., 2017); however, it is now an open dump (Aryampa, 2021). The improper waste management contributes to nutrient pollution in water bodies, primarily from nitrates and phosphates originating from various sources, including sewage and industrial waste (Wamalwa, 2016). This leads to adverse environmental effects, such as eutrophication, oxygen depletion, and potential health risks like methemoglobinemia in infants (Chhabra et al., 2021). Consequently, there is an urgent need to explore sustainable and environmentally friendly waste treatment methods, such as Black Soldier Fly Larvae (BSFL), to improve waste management practices in Uganda.

1.3 Main objective of the study

To assess the effectiveness of the use of Black Soldier Fly Larvae (BSFL) to manage solid municipal waste

1.3.1 Specific Objectives

- To analyze and characterize the composition and properties of municipal solid waste used for the study
- To find out the effect of BSFL on the reduction of MSW and analyze the differences in weight over time.
- To assess moisture content and temperature effects on mixture of BSFL and waste over time.

1.3.2 Research questions

- What are the components and properties of MSW used for this research?
- How effective are BSFL in reducing the volume and mass of MSW over a nine-day period?
- Is their statistically significant differences in waste reduction performance of BSFL under varying optimal conditions (moisture and temperature)?

1.4 Research hypotheses

- Black soldier fly larvae significantly reduced the weight of municipal solid waste over time.
- There is no difference in Municipal Solid Waste reduction among the different levels of moisture content over time.
- There is no difference in Municipal Solid Waste reduction among the different levels of temperature over time.

1.5 Justification of the study

The integration of Black Soldier Fly (BSF) larvae into municipal solid waste management presents a compelling solution that addresses multiple sustainability challenges, resonating with the United Nations Sustainable Development Goal (SDGs) 12 and Uganda's Vision 2040 emphasizing environment protection. As waste generation rises due to population growth and changing consumption patterns, using BSF larvae can effectively convert organic waste into valuable resources, thereby improving waste management practices (Shittu et al., 2021). The frass produced by BSF larvae serves as a high-quality organic fertilizer, enhancing soil fertility and promoting sustainable agriculture, which aligns with SDG 2: Zero Hunger (Chandrappa et al., 2012). Furthermore, the larvae offer a nutritious protein source for livestock, containing over 40% crude protein, thus reducing reliance on traditional feed sources and promoting sustainable food systems (Bandari and Sheppard, 1987). This innovation not only supports economic opportunities for farmers and entrepreneurs but also contributes to environmental protection and resource management, advancing Uganda's commitment to fostering an inclusive economy and sustainable practices as outlined in Vision 2040.

1.6 Significance of the study

The significance of this study lies in its potential to revolutionize MSW management in Uganda, particularly within the rapidly urbanizing parts of the country. By closely examining the effectiveness of BSFL in treating MSWs as an alternative to traditional waste disposal methods, the research aims to provide innovative solutions that could enhance waste management practices. The study findings will catalyze economic growth by creating new job opportunities within the waste management sector and fostering a market for organic fertilizers derived from BSFL processing, benefiting local farmers and promoting sustainable agricultural practices. The insights gained could inform policymakers and stakeholders, guiding the development of effective, evidence-based waste management strategies that not only address current challenges but also usher in a paradigm shift towards sustainable urban planning. By highlighting the economic, environmental, and public health advantages of BSFL usage, this research has the potential to drive forward a more sustainable and efficient waste management system in Uganda, inspiring further research and innovation in the field.

CHAPTER TWO: LITERATURE REVIEW

2.1 General approaches to waste management

2.1.1 Landfill

Open dumping and landfills continue to be common methods of waste disposal around the world. Engineered landfills, in particular, provide a more economical solution for keeping waste away from the natural environment and human populations compared to open spaces. By covering the waste with soil on a daily basis, these landfills help to deter scavenging by wildlife and reduce the risk of air and groundwater contamination (Swati et al., 2019). Furthermore, advancements in technology, such as bioreactors (Siddiqua et al., 2022) and enzymes that biodegrade plastics (Lin et al., 2023), offer innovative strategies for waste management. Additionally, projects focused on generating power from landfill gas present interesting economic opportunities (Cudjoe et al., 2021). In Dhakashi, Bangladesh, Hossain et al. (2022) conducted a thorough examination of the potential for biogas generation from a combination of a mixed sewage treatment facility and landfill, taking into account factors like population growth, energy needs, and financial limitations.

Unfortunately, the effectiveness of these methods is often diminished in developing nations that lack the necessary infrastructure and trained personnel. For example, in India, unsorted waste from various sources, including hospitals and households, is often mixed together, resulting in toxic waste combinations (Swati et al., 2019). Additionally, landfill leachate poses significant concerns (Khan et al., 2016), particularly regarding indicators of soil health; both physical and chemical, as well as biological. A study by Kooch et al. (2023) in the Kirkania forest region of northern Iran found that soil carbon and nitrogen mineralization, along with populations of animals and microbes, were negatively impacted. While initiatives like green landfills and integrated waste management aim to enhance waste processing, their success has primarily been seen in developed regions, highlighting a significant opportunity for improvement in low- and middle-income countries (Nanda and Berruti, 2021; Siddiqua et al., 2022). Managing landfills effectively has emerged as a critical challenge for many countries in Asia and Africa.

2.1.2 Heat treatments

Heat treatments like incineration, gasification, and pyrolysis play a crucial role in managing waste effectively while generating energy. I find incineration particularly impressive due to its capacity to greatly reduce waste volume while also producing electricity. Innovations such as fluidized and flow-bed gasifiers really enhance the overall efficiency and quality of this process. According to recent studies, incineration can reduce waste volume by up to 90% and mass by nearly 80% (Tian et al., 2023). On the other hand, pyrolysis offers a cleaner approach by converting waste materials like tires into valuable products like crude oil, charcoal, and syngas, without releasing harmful gases (Zerin et al., 2023). Additionally, both fluidized-bed and flow-bed gasifiers excel in producing high-quality syngas and maximizing capacity efficiency, respectively (Amin et al., 2023). That said, we also need to be aware of the challenges these processes present, especially the generation of inorganic residues such as fly ash, which raises serious environmental and disposal concerns (Pastapure et al., 2023). For instance, higher heating rates during pyrolysis can lead to lower carbon porosity, which may inhibit the release of volatiles and consequently diminish reactivity (Copik et al., 2023). Despite ongoing research into improving residue stability and reducing heavy metals (Liu et al., 2023), practical implementations are often limited, especially in open-air incineration practices found in various developing regions (Chen et al., 2022; Pastapure et al., 2023; Xiang et al., 2022). It's important to highlight that the benefits mentioned are primarily applicable to properly managed heat treatment processes. In contrast, informal open-air treatments do not leverage the advantages of incineration, highlighting a significant limitation in waste management practices today.

2.1.3 New means of waste utilization

The idea has been highlighted, especially in the context of low-income urban areas, that waste can be transformed into valuable resources through processes of enrichment, commercialization, and appropriate treatment (Kalkanis et al., 2022). This transformation can facilitate the conversion of waste into energy and the production of fertilizers. A significant portion of waste-to-energy generation relies on municipal solid waste (MSW), which, due to its organic content, can also be processed to create fertilizers (Peng et al., 2023).

2.1.3.1 Waste to energy

While some developed nations express concerns regarding waste-to-energy projects, many developing countries in Asia and Africa are increasingly adopting these systems to address their energy needs (Hoang and Fogarassy, 2020). An analysis by Sondh et al. (2022) highlights the importance of national policies and income levels, pointing out that legislation plays a crucial role in shaping waste management practices, while also stressing the concept of turning waste into valuable resources. The rise of waste-to-energy initiatives in developing regions is closely tied to their specific energy requirements. Fluctuations in oil prices (Vu et al., 2019) and a mismatch between energy supply and demand serve as significant motivators for these initiatives (Amin et al., 2023). Furthermore, waste-to-energy generation aligns with sustainable development goals, despite some inefficiencies in the treatment processes. This transition can reduce reliance on fossil fuels and chemical products while contributing positively to the development of a global bio-economy (Varjani et al., 2022). Nevertheless, the effectiveness of these technologies is largely influenced by the types and composition of solid waste present (Varjani et al., 2022), which poses considerable challenges.

2.1.3.2 Waste to fertilizer

Regions with high levels of organic matter often consider transforming the main constituent into fertilizers or biogas through anaerobic digestion, especially in research areas. For instance, the organic composition of municipal solid waste (MSW) in cities across South Asia is significantly greater than the one-quarter level typical in developed nations (Kabir and Kabir, 2022). The application of inorganic fertilizers has been associated with greenhouse gas emissions and water body eutrophication, which can be mitigated by using organic fertilizers, including lignocellulosic biomass (Chen et al., 2023). From a bioeconomic viewpoint, the process of generating biofertilizers and bringing them to market is a suitable method for recovering nutrients from waste, while also recycling 30% of non-renewable energy (Mishra et al., 2023). However, mixed solid waste, particularly municipal waste from varied sources, poses challenges for direct processing, primarily due to high pretreatment costs and energy consumption. Recent developments have been made, such as Alam et al. (2022), which examined energy generation, processing, and cost evaluation, based on a system dynamics (SD) model. In this scenario, the collected waste can undergo effective recycling and reuse, and uncollected waste does not need to be incinerated or relocated. Nevertheless, finding a practical solution to this issue remains unresolved. Due to differences in economic progress, political contexts, and social conditions across countries, the applicability of various processing methods may vary. In conclusion, each treatment method presents its own advantages and drawbacks, represented by the green and red rectangles, respectively. It is evident that landfilling and thermal treatments are well-established with the benefit of simplicity, but they also obstruct the implementation of innovative approaches to some degree. Regardless, where conditions allow, the long-term advantages of exploring new models, such as pollution reduction and resource conservation, should be emphasized. At the same time, the principles of good practice must be highlighted to prevent counterproductive outcomes, beginning with the sorting of MSW.

2.2 Composting

Composting is an effective method for managing municipal solid waste, where the organic fraction of the waste undergoes a controlled decomposition process (Argun et al., 2017). During this biological breakdown, microorganisms break down organic matter, potentially reducing the original volume by up to 50%. The end product of this process is known as compost or humus, which has a texture and smell similar to potting soil and can serve as a soil enhancer or mulch (Zuberer et al., 2021). This method allows for the simultaneous treatment and recycling of both household waste and sewage sludge, providing an alternative as regulations become more stringent regarding waste incineration and landfill usage (Wei et al., 2017). The composting process generally involves several key steps: sorting and separating materials, reducing their size, and digesting the organic waste (Sarc et al., 2013).

Sorting and shredding

The decomposable materials in waste are separated from glass, metal, and other inorganic items through sorting operations. These processes rely on mechanical methods that utilize differences in physical characteristics such as size, density, and magnetic properties. To create a uniform mass of material, the waste is shredded or pulverized using equipment like hammer mills and rotary shredders.

Digesting and processing

Pulverized waste can be composted using either the open windrow technique or in a mechanical facility. Windrows consist of long, low piles of organic material that are mixed or turned every few days to ensure proper air circulation for the microbes responsible for decomposing the matter. Depending on moisture levels, the complete breakdown of the waste typically takes between five to eight weeks. The activity of aerobic bacteria generates heat, which can raise the temperature in a compost pile to around 65 °C (150 °F), effectively eliminating harmful pathogens present in the waste. Open windrow composting requires a significant amount of land, whereas enclosed mechanical composting systems can decrease land usage by about 85%. These mechanical systems utilize closed tanks or digesters with rotating elements that mix and aerate the shredded material. In such systems, the waste can be fully digested in about a week. Once the compost has been fully digested, it undergoes several processing steps before being suitable for use as mulch or a soil conditioner. This processing includes drying, screening, and either granulating or pelletizing. These steps are essential for enhancing the compost's marketability, which is a major challenge for composting as an effective waste management strategy. The demand for digested compost in agriculture is generally low, largely due to the high costs associated with transportation and competition from synthetic fertilizers.

2.2.1 Feedstocks

The growth of industry and urban expansion has led to a more complex makeup of Municipal Solid Waste (MSW), as larger and more varied feedstock supply chains emerge. This complexity further diversifies the properties of compost produced from these materials. MSW is typically categorized into two main types: green waste and food waste. Green waste, which includes garden debris, leaves, tree trimmings, and grass cuttings, generally features low moisture content, a high level of organic matter (OM), and limited nutrients (Reyes-Torres et al., 2018). The composition and characteristics of green waste can significantly differ depending on geographical regions and seasonal changes, influenced by factors such as climate, geography, and the types of vegetation present (Boldrin and Christensen, 2010; Reyes-Torres et al., 2018). Taking Europe as a case study, we can identify four key biomes: temperate forests, Mediterranean scrub forests, boreal forests, and tundra, each with distinct plant life and geological traits. Specifically in Belgium, green waste is predominantly composed of pruning materials in spring, shifting to grass clippings in summer, and mostly consisting of leaves during winter (Vandecasteele et al., 2016). Likewise, in Denmark, winter months (December to April) see an increased presence of woody materials in garden waste (Boldrin and Christensen, 2010). In addition, the compost produced from green waste collected in spring tends to have higher dry matter (DM) and organic matter contents, accompanied by lower pH levels and electrical conductivity (EC) (Vandecasteele et al., 2016). These seasonal variations also impact nitrogen (N) and potassium (K) concentrations, with higher levels typically observed in late summer (Boldrin and Christensen, 2010). Most research on seasonal variability in compost characteristics has been conducted in Europe, with limited data available regarding seasonal trends in (sub)tropical regions, where temperatures and day lengths remain relatively stable, but rainfall patterns can vary significantly throughout the year (Boldrin and Christensen, 2010).

Food waste, when compared to green waste, has a higher moisture content and a more favorable nutrient profile, particularly with a lower carbon-to-nitrogen (C/N) ratio (Farrell and Jones, 2010). It is notably abundant in calcium (Ca) and magnesium (Mg), primarily sourced from fruits and vegetables (Hanc et al., 2017). Like green waste, food waste exhibits variations in nitrogen (N), phosphorus (P), and potassium (K) due to both spatial and temporal factors (Cestonaro et al., 2019). The proximity of food production and its seasonal availability significantly impact consumption patterns and the resulting waste generated. Additionally, temporal variations in toxic elements (TE) can be observed, with significant fluctuations in contaminant levels found in urban and family organic waste compared to other quality indicators (Hanc et al., 2011). Cultural eating habits, local agriculture availability, lifestyle choices, economic factors, waste management systems, and industrial activities contribute to the unique properties of food waste in different locations (Abdel-Shafy and Mansour, 2018; Al-Dailami et al., 2022). It is also important to recognize spikes in food waste production during major festivals like Christmas, Eid al-Fitr, and the Lunar New Year. For instance, during the Christmas season alone, the UK generates approximately 270,000 tons of food waste (Respect Food, 2022). These variations in the types of waste impact the quality of the final compost. Generally, in Europe and North America, spring is considered an ideal season for composting due to the high nutrient content and favorable conditions for rapid decomposition (Hanc et al., 2017).

2.2.2 Composting technologies

Compost maturity is significantly influenced by technology, particularly the type of composting system in use, whether it is open or semi-enclosed. A notable challenge in the composting process is the loss of nutrients, which can occur through leaching or volatilization, and this issue tends to worsen over time. Additionally, the application of immature compost can be harmful, negatively affecting its market value and competitiveness, as it may exhibit phytotoxic properties (Wang et al., 2021). Therefore, measuring and monitoring the development of compost is essential to ensure that a high-quality end product is achieved. Several factors influence the composting process, including temperature, the initial carbon-to-nitrogen (C/N) ratio, aeration, porosity, moisture content, and pH levels (Shafawati and Siddiquee, 2013). The objective of managing these conditions is to create an environment conducive to the microbial breakdown of organic waste. Fungi are particularly important in the process of humification; adequate water content is vital since dissolved organic matter serves as an essential energy source. However, excessive moisture can lead to anaerobic conditions, which can hinder fungal growth (Zhao et al., 2016). To prevent the development of anaerobic conditions, it is recommended that compost moisture levels be maintained between 40% and 65% (Fourti, 2013). The aeration rate also plays a crucial role, with a rate of 3.25 L/kg DM initial/min being ideal for promoting timely maturation and nitrogen retention within the compost (Wang et al., 2021). In evaluating compost maturity, key indicators include a C/N ratio of less than 15, cation exchange capacity (CEC) greater than 60 mEq/100 g, and an electrical conductivity (EC) level at 50% EC0 (Lopez et al., 2021). Additional metrics such as the carbon-to-sulfur (C/S) ratio, water-soluble carbon (WSC) to organic nitrogen ratio, and

Germination Index (GI) are also utilized to assess compost maturity and quality (Meena et al., 2021).

Composting systems can be categorized based on their aeration methods and closure periods. These include windrow systems, which may be turned or passively aerated; in-vessel systems, such as silo-type and agitated bed designs; and aerated static piles (Chia et al., 2020). Research comparing various approaches, such as turned piles and static forced-aerated piles, indicates that turning the pile can lead to reduced variability and improved stability and maturity of compost (Ruggieri et al., 2008). From an operational and sanitary standpoint, closed systems like in-vessel composting outperform windrow systems due to their ability to maintain high consistency, especially in mass composting (Cestonaro et al., 2022). Each method carries its own benefits and drawbacks, particularly regarding costs, time commitments, and land requirements. Therefore, combining different methods known as two-stage composting systems, such as integrating windrow with in-vessel techniques is gaining popularity for enhancing overall efficiency (Chia et al., 2020). The composting industry is evolving towards more industrial practices, producing larger quantities of higher-quality compost. Key to this advancement has been enhanced feedstock management and improved separation technologies. For instance, air separation systems effectively eliminate plastics from compost by utilizing aspirators that differentiate materials based on density and air flow patterns. A deeper understanding of compost biogeochemistry, along with rigorous monitoring, is contributing to the production of safer and more consistent compost products. In the UK, compliance standards necessitate periodic sampling for pathogens, toxic substances, stability, physical contaminants, and plant responses from every 2,500 tonnes of compost produced (PAS-100). This focus on quality is fostering collaborations between compost producers and various industries, leading to innovative blended compost materials designed for specific agricultural applications, such as vegetable farming, general-purpose use, and mulching. Despite the significant attention on industrial-scale composting, small-scale household composting remains crucial and effective, capable of generating high-quality outcomes and contributing significantly to nutrient sustainability (Barrena et al., 2014).

2.2.3 Strengths and opportunities

Municipal solid waste (MSW) compost enhances the nutrient profile of soil and increases soil organic carbon (SOC), positively impacting soil microbial biomass and functionality. Moreover, MSW compost is crucial in regulating carbon (C), nitrogen (N), and phosphorus (P) cycling by influencing the activity of specific enzymes. These include dehydrogenases, cellulases, and β-glucosidases for carbon cycling; ureases and proteases for nitrogen mineralization; and phosphatases for the removal of phosphate groups (Rastogi et al., 2019).

2.2.4 Modulating C, N, and P cycling

2.2.4.1.1 Carbon

Around 1.6 billion metric tons of greenhouse gas emissions, specifically carbon dioxide (CO2) equivalents, are produced from municipal solid waste (MSW), primarily due to practices such as open dumping and landfill disposal (Kaza et al., 2018). Composting serves as a practical and cost-effective method for carbon sequestration, transforming unstable carbon into a stable organic structure without the energy demands associated with other methods like biochar production (Ye et al., 2023). During the decomposition phase, larger molecular compounds in the composting materials break down into smaller units thanks to extracellular hydrolytic enzymes. These smaller fragments can then be utilized by microorganisms for growth, leading to the production of CO2, water, and various secondary metabolites through their metabolic processes (Qiao et al., 2019). In the humification phase, these metabolic intermediates and smaller molecules further react to create stable humus (Wei et al., 2022).

Introducing mature compost into the soil can facilitate carbon (C) sequestration through both direct incorporation and indirect processes that lower carbon mineralization rates. For instance, studies have shown that applying 10% municipal solid waste (MSW) compost can lead to a 2.8% increase in soil carbon content (Lopez et al., 2021). Furthermore, applying 15 t/ha of compost can help maintain soil organic carbon (SOC) levels, enhance biological activity, and boost vegetable crop yields (Morra et al., 2010). Long-term compost amendments also promote the transformation of iron (Fe) oxides from crystalline forms to more short-range-ordered structures, which improves mineral availability. This, in turn, fosters carbon binding, enhances soil aggregation, and ultimately increases carbon sequestration (Huang et al., 2022). Incorporating MSW compost into the soil has been linked to increased activity of dehydrogenases and β-glucosidases, which leads to the formation of humic substances and enhances organic matter stability (Garau et al., 2019). This stability benefits microbial communities that are crucial for nutrient cycling (Pedra et al., 2007). Additionally, the presence of low molecular weight acids in mature compost boosts mineral availability and reduces carbon mineralization, promoting SOC sequestration (Yu et al., 2018). Evidence supporting this includes comparisons showing lower mineralization rates in soils enriched with MSW compost compared to those with sewage sludge (Pedra et al., 2007). Moreover, MSW compost has demonstrated a favorable carbon balance in intensive horticulture, based on data from a seven-year trial in the Mediterranean region (Morra et al., 2021). Nevertheless, further research is essential to understand the long-term stability of SOC sequestration. Accurately estimating the storage potential of SOC over very long periods remains challenging, as no reliable methods currently exist for assessing the amounts of persistent SOC over multiple decades or centuries (Chenu et al., 2019).

2.2.4.1.2 Nitrogen

Throughout the composting process, nitrogen-containing compounds transform into soluble organic molecules, including nitrogen-rich proteins, eventually leading to the creation of more stable forms. This results in a decreased likelihood of mineralization (Oladeji et al., 2020). Consequently, most forms of nitrogen in compost are found as stable organic compounds (Oladeji et al., 2020). The release rate of inorganic nitrogen is primarily influenced by the availability of carbon and nitrogen, particularly the carbon-to-nitrogen (C/N) ratio (Weber et al., 2014). Compost with a high C/N ratio tends to undergo quick nitrogen mineralization and ammonia (NH3) release, resulting in significant nitrogen loss (Jiang et al., 2011). When municipal solid waste (MSW) compost is added to soil, nitrogen undergoes various transformations, starting with ammonification (conversion of organic nitrogen to NH3), followed by ammonification (conversion of NH3 to NH4+), nitrification (conversion of NH4+ to nitrite (NO2−), and then to nitrate (NO3−)), then denitrification (conversion of NO3− to nitrogen gas (N2)), and anammox (conversion of NH4+ and NO2− into N2) (Manu et al., 2021). Additionally, MSW compost can enhance urease activity, facilitating the breakdown of urea into NH3 (Srivastava et al., 2016).

Upon the addition of compost to soil, the amines it contains are quickly mineralized and oxidized by ammonia-oxidizing bacteria (Paranychianakis et al., 2013). A six-year study found that applying MSW compost significantly boosted nitrate reductase activity (Srivastava et al., 2016). Following the amendment with MSW compost, nitrate was initially immobilized, but after 16 weeks, there was an increase in nitrate leaching concentrations, primarily attributed to compost decomposition (Page et al., 2014; Oladeji et al., 2020). MSW compost also enhances microbial respiration and nitrification, partly due to its calcium carbonate content (Castán et al., 2016). Overall, MSW compost offers numerous benefits as a nitrogen fertilizer. However, it's essential to manage it carefully to mitigate denitrification and prevent nitrogen losses in the form of nitrous oxide (N2O) and nitrogen gas (N2) (Weber et al., 2014), a topic that will be explored further in Section 5.4.

2.2.4.1.3 Phosphorus

To enhance the circularity of phosphorus (P) cycling, it is essential for crop production to make the most of nutrient-rich waste materials. In municipal solid waste (MSW) compost, approximately 70% of phosphorus is found in inorganic forms, while the remaining 30% is organic (Turrión et al., 2018). Inorganic phosphorus primarily exists as calcium phosphates, which may be in the form of soluble orthophosphates like Ca(H2PO4)2 or as slower-release compounds such as apatites or Ca8H2(PO4)6. The soluble forms are more readily available to plants at neutral pH, whereas the slower-release forms tend to be more mobile in acidic soils (Lemming et al., 2019). Finer particle sizes typically result in higher extractable organic phosphorus and overall phosphorus concentrations compared to coarser aggregates (Turrión et al., 2018). Therefore, the size of the particles plays a crucial role in nutrient release.

The role of MSW compost in P cycling consists mainly of two processes: decomposition and mobilization, facilitated by organophosphorus-degrading and inorganic phosphate-solubilizing bacteria (Wei et al., 2018). When compost is applied to soil, the conversion of organic phosphorus to inorganic phosphorus largely depends on biochemical processes. Soil phosphatase activity is vital for this transformation and tends to increase with the addition of MSW compost (Hargreaves et al., 2008). Additionally, the application of compost enhances microbial and biological activity in the soil, including that of earthworms, which further contributes to phosphorus release during the breakdown of organic matter (Mkhabela and Warman, 2005).

The inclusion of organic matter (OM) in municipal solid waste (MSW) compost has the potential to enhance phosphorus (P) mobilization. Throughout the composting process, the acids generated from the decomposition of OM contribute to the increased solubility of inorganic P (Wei et al., 2015). The mobilization of P in soil can occur through the formation of complexes between OM and its breakdown products with active aluminum (Al) and iron (Fe) (Mkhabela and Warman, 2005). Moreover, the interaction of OM in MSW compost with calcium ions can produce complexes that elevate the levels of calcium phosphates in the soil solution (Hosseinpur et al., 2012). The retention of P, driven by high soil organic carbon (SOC) and calcium carbonate concentrations, results in an increased fraction of carbonate phosphate in soils that receive MSW compost (Turrión et al., 2018).

When MSW compost is applied, the introduced humic acid (HA) ions can displace phosphate anions in the soil, while humus can form a protective coating over sesquioxide particles, thereby enhancing P solubility (Mkhabela and Warman, 2005). The elevated pH resulting from the application of MSW compost promotes the precipitation of exchangeable Al and Fe, which can reduce P precipitation (Toundou et al., 2021). Conversely, the combination of high pH and calcium in the soil can lead to the transformation of soluble P into calcium phosphates, potentially limiting the mobility of compost-derived P (Lemming et al., 2019). Initially, when compost is introduced to the soil, the breakdown of low-molecular-weight compounds stimulates the growth of microorganisms that utilize dissociative P, gradually making it available for plant uptake (Wei et al., 2015). Over time, however, the application of MSW compost may enhance the soil's capacity to absorb P. Its low density and porous microstructure also facilitate access to inorganic binding sites, promoting P absorption (Schefe et al., 2008). To date, there has been a limited exploration of how P fraction characteristics change during the composting of MSW and after its incorporation into soil. There is a pressing need for further investigation into the interactions between soil and P from MSW compost across a wider array of soil types and physicochemical conditions.

2.2.4.2. Remediation

One often overlooked benefit of municipal solid waste (MSW) compost is its ability to enhance environmental health by reducing toxic and potentially harmful substances in both soil and water. Thanks to its organic makeup, MSW compost serves as a valuable tool for remediation, functioning both as an adsorbent and a source of electrons for redox-mediated breakdown of organic pollutants. The effectiveness of MSW compost in absorbing trace elements (TE) largely hinges on complexation and cation exchange processes. Its capacity to absorb these contaminants also relies on the existing levels of TE, as there is a limited number of binding sites along with varying affinities for different metals. For instance, lead (Pb) binds strongly, while nickel (Ni) does not. This means that MSW compost with a high concentration of exchangeable or organically bound Pb may be less effective in immobilizing other metals. While examples of MSW compost in soil remediation are not extensive, studies have demonstrated its efficacy in immobilizing Pb, copper (Cu), and zinc (Zn). Furthermore, experiments have shown that applying 2% to 4% MSW compost to soil can reduce the mobility of cadmium (Cd), lead (Pb), zinc (Zn), and antimony, while boosting microbial activity and overall catabolic performance, which is linked to an increase in soil pH.

Research has shown that composting the organic component of municipal solid waste (MSW) can aid in creating sorbents that immobilize cadmium (Cd), lead (Pb), and zinc (Zn) in contaminated waters and soils (Lima et al., 2022). The organic substances found in compost, such as humic acid (HA) and fulvic acid (FA), are particularly effective at capturing trace elements (TEs), playing a crucial role in the retention of metals (Saha et al., 2013). Additionally, cation exchange capacity (CEC) and physical entrapment contribute to these metal retention processes. For example, MSW compost demonstrated the ability to adsorb 94% of Pb and 55% of Cd, indicating its effectiveness in metal immobilization (Lima et al., 2018). Similarly, a study from Argentina revealed that applying MSW compost reduced the concentrations of chromium (Cr), nickel (Ni), Pb, and Zn in lettuce (do Carmo et al., 2021). Beyond metals, MSW compost also plays a role in breaking down organic pollutants, enhancing the biodegradation of total petroleum hydrocarbons (TPH) by 68.5% when paired with cultivated ryegrass (Yousaf et al., 2021). This improvement is linked to better microbial nutrient availability, improved soil structure, and the release of catabolic enzymes. In terms of microbial activity, the decomposition of MSW compost in soil promotes the growth of microorganisms, particularly ligninolytic fungi, which help degrade polynuclear aromatic hydrocarbons (PAHs) through co-metabolism (Brimo et al., 2018). Research from Greece also demonstrated that MSW compost could retain up to 90% of harmful compounds like benzene, toluene, ethylbenzene, and xylenes from groundwater through physical absorption (Simantiraki et al., 2013). Interestingly, the aerobic composting process can also aid in the degradation of plastics in situ. Free radicals generated during composting through reduction-oxidation reactions can partially oxidize and cleave plastic polymers (Xing et al., 2022). Numerous studies have suggested that humus containing more alkanes can significantly improve soil quality and agricultural productivity, while compost with a higher degree of humification is particularly beneficial for remediating contaminated soils (Ye et al., 2023a).

2.2.5 Weaknesses and threats

2.2.5.1 Toxic elements

Municipal solid waste (MSW) compost can transform from a nutrient reservoir into a source of pollutants when it contains high levels of metals and is applied to soils that are either uncontaminated or minimally contaminated (Paradelo and Barral, 2012). During the aerobic composting process, trace elements (TEs) present in organic waste tend to bind strongly to organic matter (OM) and the compost matrix (Smith, 2009). Research indicates that fine particle sizes (less than 0.8 mm) exhibit a higher concentration of TEs (Zhao et al., 2012). The main source of TEs in MSW compost originates from the raw materials used, with only a small portion coming from atmospheric deposition (Smith, 2009). In a study conducted in Shanghai, China, waste from three MSW treatment facilities revealed that zinc (Zn), chromium (Cr), copper (Cu), and lead (Pb) posed significant TE concerns (Zhang et al., 2008). Similarly, research conducted in Brazil found that compost samples had troubling concentrations of cadmium (Cd) and lead (Pb) that surpassed intervention thresholds. Notably, experimental trials with lettuce demonstrated significant transfer of TEs to the crops (Asensio et al., 2018). In Srinagar, India, levels of Zn, Cd, Pb, and nickel (Ni) in MSW compost also exceeded the limits set by the Fertiliser Control Order (Hameed et al., 2021). Boron (B) is often overlooked when assessing compost quality, and there are no established benchmarks for its concentration. Nevertheless, a Canadian field trial indicated a dramatic increase of 96% in B levels in MSW compost over a five-year timeframe (Abbey et al., 2021). B can become phytotoxic if its soil concentration exceeds acceptable limits (2 mg/kg), as evidenced in the same study (Abbey et al., 2021). Advanced analytical techniques like inductively coupled plasma mass spectrometry enable the simultaneous measurement of around 50 elements (Hong et al., 2023). Given the variable nature of feedstocks, implementing untargeted broad element screening of samples is technically feasible and should be considered.

In various quality and safety standards, the measurement of arsenic (As) is not a requirement (e.g., UK PAS-100). However, research has detected As in compost materials. An example is a study conducted in India, which found that compost derived from kitchen waste contained As at a concentration of 15 mg/kg (Mahongnao et al., 2023). The common reasoning for the exclusion of As from testing is that its concentrations in compost are typically lower than those found in soil and therefore do not pose a significant threat. Yet, it is important to note that baseline soil concentrations of As in Southeast Asia can vary widely, ranging from 0.8 to 21 mg/kg (Lu et al., 2009). In the United States, As is ranked as the top substance on the Agency for Toxic Substances and Disease Registry's (ATSDR) priority list, followed closely by lead (Pb). This raises concerns about the lack of monitoring for As in composts, particularly when feedstock contamination risks are significant and testing technologies are readily available. Additionally, the rich organic content in municipal solid waste (MSW) compost can increase the risk of As becoming bioavailable. The application of MSW compost may lead to elevated levels of dissolved organic carbon (DOC) in the soil, which can bind to iron oxides (FeOOH) via ligand exchange. This interaction could hinder the adsorption of inorganic As species like As(III) and As(V) to active sites within the soil, leading to greater mobility of these arsenic forms as DOC levels increase (Williams et al., 2011).

2.2.5.2 Microplastics

Microplastics present in organic solid waste can pose significant ecological threats, potentially impacting both wildlife and humans due to bioaccumulation (Xing et al., 2022). Plastic polymers that originate from the compost feedstock persist in the compost even after processing. While larger plastic items (macroplastics; >25 mm) can be manually sorted out from the feedstock, this technique is ineffective for extracting smaller plastic fragments in high-throughput operations (Gui et al., 2021). The issue of plastic contamination in compost worsens due to the generation of microplastics during the processing and separation of mixed waste materials. Research on municipal solid waste (MSW) has indicated an average concentration of microplastics at 24 particles per kg, which escalates to 17,407 particles per kg after the mechanical treatment of the resulting compost (Sholokhova et al., 2022). This underscores a significant increase in plastic particles resulting from the reduction in size of polymers during both biotic and abiotic waste treatment processes. This surge primarily stems from the mechanical forces applied during the shredding and separation of mixed waste (Sholokhova et al., 2022; Tong et al., 2022), along with chemical degradation and partial microbial breakdown of plastics or their byproducts (Gui et al., 2021). Though using pre-sorted waste as feedstock can substantially diminish plastic contamination in compost (Rodrigues et al., 2020), effective strategies to manage microplastic contamination in compost after its production remain insufficient, resulting in the risk of environmental dissemination of microplastics (<5 mm) via contaminated compost.

2.2.5.3 Organic pollutants

In addition to focusing on transformation elements (TEs) and plastics, it is equally crucial to address organic pollutants, which present significant risks to both the environment and public health. These organic contaminants require careful evaluation in waste composting practices. For example, a study found that composted municipal solid waste (MSW) had a median concentration of polycyclic aromatic hydrocarbons (PAHs) at 1.9 mg/kg (Farrell and Jones, 2009). While some PAHs can be broken down during composting, certain persistent organic pollutants, such as polychlorinated biphenyls (PCBs) and dioxins, resist degradation (Lakhdar et al., 2009). Compost created from MSW typically has higher levels of PAHs and PCBs compared to compost made from the biodegradable components of municipal waste or green materials, with concentrations sometimes being as much as tenfold higher (Houot et al., 2012). Research into the organic compounds produced during the composting of MSW identified that toluene, ethylbenzene, 1,4-dichlorobenzene, p-isopropyltoluene, and naphthalene were among the most prevalent (Srivastava et al., 2016). Although the decomposition process involving microorganisms can mitigate the toxicity of these organic pollutants, their adsorption to organic matter limits degradation effectiveness (Lashermes et al., 2010). The stabilization of organic pollutants occurs when initial physical and chemical interactions lead to irreversible adsorption (Barriuso et al., 2008). Consequently, these retained organic pollutants remain in the compost and can later leach into the soil when the compost is applied, resulting in environmental contamination (Houot et al., 2012).

2.2.5.4 Other threats

Composting municipal solid waste (MSW) comes with various risks, including potential air pollution, inhibition of plant growth, and disruptions to microbial communities. One major concern is the release of greenhouse gases (GHGs) during the composting process, which arises from the energy used by the machinery in composting facilities as well as the natural biodegradation processes that emit CO2, CH4, and N2O. Ammonia (NH3) emissions are another significant issue associated with MSW composting. In some composting plants, the levels of NH3 in exhaust gases can reach high concentrations, with measurements showing up to 1000 ppmv. Although there is limited data regarding nitrogen oxides (NO/N2) emissions from composting processes, the loss of NH3 is well-documented. Furthermore, volatile organic compounds (VOCs) are also released during composting, with emissions levels recorded at around 400 ppm. The production of VOCs tends to be higher when the compost consists of a greater amount of food waste. While these gaseous emissions can be mitigated using scrubber systems, further research and validation in operational industrial composting settings is necessary to optimize these solutions.

From a chemical standpoint, municipal solid waste (MSW) compost can be prone to elevated salt levels, which can hinder plant growth (Hargreaves et al., 2008). Nonetheless, frequent monitoring of electrical conductivity (EC) can help address this issue. A more complex concern lies in biological control. Compost has the potential to spread invasive and problematic weed species (Vaverkova et al., 2020). While composting typically involves heat treatment to eliminate pathogens, there are still significant risks. A recent investigation indicated that the composting process may actually enhance the presence of antibiotic resistance genes, such as aadA and intI1, largely due to environmental stresses linked to the improper disposal of pharmaceuticals and horizontal gene transfer (Tang et al., 2020). Our understanding of antibiotics within MSW remains fragmented and necessitates further research. Food scraps refer to unwanted remnants from cooking preparation and dining, which can include items like banana peels, apple cores, vegetable trimmings, bones, eggshells, meat, and pizza crust. Compostable paper, often referred to as food-soiled paper, typically originates from the kitchen and is unsuitable for recycling due to contamination. Examples of compostable paper include stained pizza boxes, uncoated paper cups and plates, used coffee filters, paper food cartons, napkins, and paper towels, all of which are suitable for recycling in yard waste containers.

The rapid urbanization, industrial growth, technological advancements, and rising population globally have created significant challenges related to the increasing generation of solid waste. The burden of managing these vast amounts of waste continues to grow (Ferronato et al., 2019). Over a billion tonnes of solid waste are produced each year, much of which is improperly disposed of, resulting in various social, economic, and environmental issues (Vaish et al., 2016). Effectively handling this massive waste volume presents a substantial challenge for humanity (Sharma et al., 2019). Researchers worldwide are actively exploring innovative and environmentally friendly technologies for waste management (Almalki et al., 2023). Among these, biological methods, particularly vermicomposting, stand out as effective waste treatment strategies. This process involves the collaboration between earthworms and microorganisms in breaking down waste (Sharma et al., 2019). Vermicomposting is a natural bio-oxidative decomposition method that operates optimally under mesophilic conditions and relies on the biochemical activity of various microorganisms (Sharma et al., 2023). Different types of waste can be composted using various earthworm species (Bhat et al., 2018). Through the combined action of earthworms and microbes, waste is transformed into a nutrient-rich, odor-free, and homogeneous product known as vermicompost (Azab et al., 2022). As earthworms digest waste material, they enhance its physicochemical properties by promoting the breakdown of organic matter (Ali et al., 2015). The microorganisms residing in the digestive tracts of earthworms contribute significantly to the biochemical degradation of waste. Vermicompost serves as an effective growth enhancer for plants, containing nutrients readily available to plants, a rich microbial population, humic substances, growth hormones, and enzymes (Ceritoğlu et al., 2018). Numerous studies demonstrate that applying vermicompost as an organic fertilizer can significantly boost crop growth and yields (Joshi et al., 2015). Additionally, vermicomposting promotes a circular bioeconomy by converting waste into beneficial products, ultimately supporting the sustainable development of nations (Ashokkumar et al., 2022).

Vermicomposting has been shown to effectively reduce the levels of tetracycline resistance genes, as well as those linked to quinolones and fluoroquinolones, in sewage sludge (Cui et al., 2018; Huang et al., 2018). Additionally, the activity of earthworms influences both bacterial and fungal diversity during the processing of complex materials through vermicomposting (Cui et al., 2019; Domínguez et al., 2021; Gómez-Brandón and Domínguez, 2014), potentially altering the main carriers of antimicrobial resistance genes (ARGs) throughout the process. There is also evidence that the presence of earthworms can lead to a reduction in the abundance of the integrase gene intl1, which may impact the horizontal gene transfer (HGT) of ARGs during vermicomposting (Li et al., 2021c; Yang et al., 2021). While vermicomposting does influence ARG-carrying plasmids and integrons, some new ARG subtypes have been detected within the final vermicompost, suggesting that HGT could still take place (Huang et al., 2020). The effectiveness of this process appears to vary by species; for example, the endogeic earthworm Metaphire guillelmi has been found to reduce ARGs more significantly than the epigeic E. fetida in field fluvo-aquic soil used for corn cultivation (Yang et al., 2021). Based on these findings, several mechanisms have been proposed as key factors driving the removal of ARGs during vermicomposting due to earthworm activities: (i) shifts in microbial community dynamics; (ii) alterations in the physical and chemical properties of the initial feedstock, such as pH and organic matter quality; and (iii) a reduction in pathogenic bacteria (Cui et al., 2019, 2020). All these elements could affect the bacterial hosts harboring ARGs and/or the abundance of mobile genetic elements (MGEs) during vermicomposting, potentially influencing ARG transfer (Huang et al., 2018). Research has indicated that maintaining a temperature of 20°C is optimal for achieving reductions in ARG abundance in sludge processed with E. fetida during vermicomposting (Cui et al., 2022a). Furthermore, the presence of antibiotics such as tetracycline in sewage sludge has been associated with an increased presence of related resistance genes in the final vermicompost (Xia et al., 2019). Despite the observed decreases in ARG abundance during vermicomposting, it has been suggested that the final product can still be enriched with these genes, making it unsuitable for certain agricultural applications (Huang et al., 2020).

The elimination of antibiotic resistance genes (ARGs) by earthworms has been noted in soil systems enriched with organic manure. This can be seen in the gut microbiomes of various soil organisms, such as collembolans and enchytraeids, where there is a notable reduction in the number and prevalence of ARGs (Zhu et al., 2021a). Additionally, specific bacterial genera, including Microvirga, Sphingomonas, Methylobacterium, and Bacillus, found in the earthworm gut, were shown to enhance the breakdown of sulfamethoxazole (SMX) by 35.7% over 30 days during a vermicomposting process (Zhang et al., 2022c). The study also highlighted that the bacterial community—aside from the genus Bacillus—entered soil through earthworm casts, leading to further SMX degradation. Moreover, the levels of sul1, sul2, and intI genes increased in SMX-contaminated soil throughout the vermicomposting process with E. fetida, which raises concerns about the horizontal gene transfer of antibiotic resistance within the soil microbiome (Zhang et al., 2022c). However, the presence of antibiotic-resistant bacterial hosts within the earthworm gut (Yang et al., 2023) poses a risk for the spread of ARGs in soil (Li et al., 2021e). Consequently, it has been recommended that additional treatment steps for vermicomposted sewage sludge be considered before it is applied to soil (Kui et al., 2020). Vermicomposting is an ecologically innovative process that involves the collaboration between earthworms and microorganisms to transform organic waste into nutrient-rich vermicompost. Various species of earthworms, including red worms, tiger worms, and red wigglers, are tasked with consuming organic materials such as flower waste, agricultural waste, and sewage sludge. In ideal conditions—where temperatures are below 28°C, moisture levels are between 60% and 80%, and aerobic conditions are met—earthworms process organic waste, such as vegetable scraps and industrial sludge, resulting in the production of a humus-like excrement. This excretion, which is uniform in consistency, is generated through the earthworm's physical and biochemical activities. The physical processes include aeration, fragmentation, and turnover, while the biochemical processes involve the enhancement of nitrogen content and the transport of various organic and inorganic substances along with enzymatic digestion.

This process is vital for transforming organic waste into essential nutrients for plants, including nitrogen, calcium, phosphorus, and potassium. This transformation occurs through the combined efforts of earthworms and microbes, resulting in nutrients that are more soluble and beneficial to plants compared to those found in the original organic material. The conversion process is facilitated by various enzymes in earthworms, including proteases, lipases, amylases, cellulases, and chitinases. Earthworms contribute in two significant ways: they convert organic or industrial sludge into vermicompost and help manage the pollution caused by the rapid increase in population, urbanization, intensive agriculture, and industrial activities. Vermicomposting can be performed on a household, community, or city scale using food waste or other organic materials. Several factors impact the vermicomposting process, which can be categorized into abiotic and biotic components. Abiotic factors include temperature, pH, moisture, aeration, feed quality, light, and the carbon to nitrogen (C/N) ratio. Biotic factors involve earthworm stocking density, microorganisms, and enzymes. Earthworms thrive in temperatures ranging from 10°C to 28°C, prefer moisture levels between 12% to 34%, and grow best in a pH range of 5 to 7. Their survival rate improves in darkness, making it preferable to keep them in low-light conditions. The ideal C/N ratio for earthworms is between 20 and 30, and they require oxygen for survival, necessitating good aeration in their environment. Manual turning of waste mixtures can help maintain aeration. The quality of food is crucial for an earthworm's growth and reproductive success. Factors influencing the food they consume include the particle size of the waste mixture, the degree of organic waste degradation, salt concentrations, and the C/N ratio. Smaller particles improve aeration, and earthworms typically consume between 100 to 300 mg of food per gram of body weight daily. Stocking density of earthworms significantly influences the vermicomposting process, affecting their respiration, reproduction rates, feeding behavior, and burrowing activities. Additionally, microorganisms are crucial for processing organic matter, working in collaboration with earthworms. Earthworms are classified into three morphological categories: (1) Epigeic, (2) Endogeic, and (3) Anecic.

2.3 Black soldier flies

The black soldier fly, scientifically known as Hermetia illucens, is a species commonly found in tropical and warm temperate regions. Adults of this fly, resembling wasps, typically measure 15-20 mm in length. They are predominantly black, with females exhibiting a reddish coloration at the tip of their abdomen and two translucent spots on the second segment, while males have a bronzed abdomen. Native to tropical, sub-tropical, and warmer temperate areas, the larvae of H. illucens are known for their insatiable appetite and ability to consume various types of organic waste, including food and municipal waste. Unlike many other fly species, black soldier flies do not tend to invade human habitats, which significantly reduces their risk of spreading diseases. Additionally, they contribute to controlling housefly populations by preventing them from laying eggs in the environments where black soldier fly larvae thrive. These flies are generally associated with outdoor environments and livestock and are often found in decaying organic materials like animal waste and plants. Adults can be identified by their long antennae. This species is notably resilient, capable of surviving in challenging environmental conditions such as drought, food shortages, and low oxygen levels. The black soldier fly has a wide distribution in areas ranging from approximately 45°N to 40°S latitude. Its larvae thrive on decaying organic substances, including spoiled fruits and vegetables, animal manure, and even human waste. Adult flies are relatively inactive and do not fly well. Females typically mate two days after emerging and lay their eggs in dry crevices near food sources, ensuring that the eggs are not placed directly on moist decaying material. Throughout their adult life, black soldier flies do not feed, relying on stored body fat. Due to their behavior, they pose no risk as disease vectors, as they avoid contact with decomposing organic matter. Upon hatching, the larvae begin consuming waste, resulting in a significant reduction of around 55% in the volume of dry waste. Thanks to their high densities and appetite, the larvae process fresh materials rapidly while simultaneously suppressing bacterial growth, which helps minimize unpleasant odors. In optimal conditions with abundant waste sources, these larvae can mature efficiently. One of the key benefits of utilizing black soldier fly larvae in waste management is their ability to convert significant amounts of carbon into insect protein and oils, as opposed to merely breaking it down into carbon dioxide and methane.

Figure 2. 1: Life stage of Black Soldier Fly

2.6 Greenhouse gas emission

The growth in population and increasing levels of prosperity are major factors contributing to the generation of waste. Annually, around 2.01 billion metric tons of municipal solid waste (MSW) are produced worldwide, and this figure is anticipated to double by 2059, raising significant concerns for the future. A life cycle assessment of MSW management in relation to greenhouse gas (GHG) emissions reveals that over 50% of the waste collected is not adequately handled; instead, it is often openly burned or disposed of in landfills, particularly in many developing countries. Additionally, only about 10-40% of waste is subjected to recycling and composting processes. The total GHG emissions, including methane (CH4), carbon dioxide (CO2), and nitrous oxide (NO2), resulting from waste management make up approximately 5% of the total GHG emissions released into the atmosphere. Methane alone contributes to 1-2% of these emissions during waste management activities. The release of these GHGs exacerbates global warming and climate change, negatively impacting living organisms on Earth. Thus, implementing sustainable management practices from waste collection through to treatment and disposal with a strong focus on minimizing GHG emissions is essential for preserving resources and protecting the environment. This review serves as a foundation for policymakers at local, national, and regional levels to develop and implement strategies aimed at reducing GHG emissions linked to MSW management.

A study examining the composting process and gas emissions related to food waste identified the release of greenhouse gases (GHGs) such as carbon dioxide (CO2), methane (CH_4), and nitrous oxide (N_2O) at various intervals: 2, 9, 16, 23, 30, 37, 44, 51, 61, 71, and 84 days into the composting process. The total Global Warming Potential (GWP) was measured between 2.7 and 6.9 kg CO2 equivalent per kilogram of dry material. Another investigation compared compost generated under controlled conditions to that produced under typical conditions, revealing that the compost from community sources emitted 4.6 times more CH4 and 5.8 times more N_2O. The increased CH_4 emissions were linked to insufficient aeration, while elevated N2O levels were attributed to high moisture content in the compost (Quirós R, 2014). In a study conducted in Depok City, Indonesia, greenhouse gas emissions from municipal solid waste management were estimated, showing emissions for four different scenarios as 6,800; 25,700; 34,300; and 42,900 kg CO2 equivalent per day, respectively. Another research project focused on the potential greenhouse gas emission reductions achievable through the use of Black Soldier Fly Larvae (BSFL) as a carbon sink that could mitigate emissions from microbial decomposition. In experiments, equal amounts of moist feed material were either consumed by BSFL or allowed to decompose via microbes. The BSFL consumed the feed within 7 days, whereas microbial decomposition took 45 days. The carbon mass balance indicated that with BSFL, 28.54% of the initial carbon was lost as CO_2, with minimal methane emissions. In the absence of BSFL, the loss of original carbon rose to 48.62%. The larvae converted approximately 41% of the feed carbon into body mass, resulting in protein, edible oil, and chitin (Perednia A., 2017).

2.7 Empirical review

2.7.1 Moisture content effects on BSFL and waste processing

The BSFL have emerged as a promising agent for organic waste decomposition, with environmental benefits underscored by their efficient nutrient recycling capabilities. The optimal moisture content is critical for their growth and efficiency, with studies indicating that BSFL thrive in moisture levels ranging from 60% to 80%. Deviations from this optimal range hinder growth and reduce waste reduction efficacy. A study by Diener et al. (2009) highlighted that moisture levels below 50% lead to sluggish larval development due to insufficient hydration, which is essential for metabolic processes. Conversely, excess moisture, typically above 85%, create anaerobic conditions detrimental to both BSFL and the waste degradation process. Specifically, the anaerobic environment led to the proliferation of harmful microbes, thus degrading the quality of the end products. The interaction between moisture and microbial activity plays a pivotal role; high moisture levels enhance microbial action, aiding BSFL digestion, but beyond a certain threshold, it restricts oxygen diffusion, impeding the waste processing capability.

Furthermore, Lalander et al. (2019) reinforced the significance of maintaining a fine balance in moisture content by identifying an optimal moisture level of around 70% for both larval biomass production and effective waste reduction. At this moisture level, BSFL not only thrive but also accelerate the decomposition of organic matter, leading to the rapid transformation of waste into valuable organic fertilizer. This finding emphasizes the necessity for precise moisture management in BSFL systems to ensure maximum efficiency. The intricate interplay between moisture and decomposition rates underscores the paramount importance of maintaining optimal environmental conditions to harness the full potential of BSFL in waste management. Continuous monitoring and adjustments in moisture content are vital in long-term applications to avoid negative impacts resulting from desiccation or waterlogging, highlighting the complexity of employing BSFL as a waste processing mechanism.

2.7.2 Temperature Effects on BSFL and Waste Processing

Temperature is another critical factor influencing the metabolism and efficiency of BSFL during waste processing. Studies indicate that BSFL thrive at temperatures ranging from 25°C to 35°C, with a peak development rate occurring at approximately 30°C. At this temperature, larval activity accelerates, leading to improved rates of microbial activity and, consequently, more efficient waste decomposition. Tomberlin et al. (2002) observed that temperatures below 20°C slow larval growth, while excessive heat above 35°C led to high mortality rates among BSFL. The delicate balance of temperature is therefore crucial; maintaining it within the optimal range can enhance the waste management process by reducing processing times and increasing the efficiency of mass reduction. The interaction between temperature and waste degradation is explicitly evident in the findings of Rehman et al. (2017), where the researchers noted that at the optimal temperature of 30°C, BSFL could reduce the mass of waste by 50% more rapidly compared to operations at 25°C. However, temperatures exceeding this threshold not only posed risks of increased evaporation, a phenomenon leading to larval desiccation, but also increased the metabolic stress on the larvae, ultimately hindering the waste conversion process. This stresses the need for precise environmental control in BSFL systems to sustain optimal temperature conditions while executing waste decomposition. When these factors are managed effectively, BSFL not only contribute to waste management solutions but also stand as a sustainable model for creating organic fertilizers, enriching the soil without the side effects often associated with chemical fertilizers.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

This chapter details the methodology employed to investigate the effectiveness of BSFL in the treatment of MSW. The methodology section is structured to illustrate the sequential steps undertaken, from the collection and preprocessing of waste to the specific experimental designs used to assess the impact of various environmental variables on waste decomposition. The materials utilized in the study, including equipment and personal safety measures, are also outlined to ensure clarity in the procedures followed.

3.2 Study design

An experimental research design was employed to evaluate the efficacy of Black Soldier Fly Larvae in the treatment of municipal solid waste. The study was structured to investigate the impact of key environmental variables; temperature and moisture content on the decomposition process. Quantitative methods were utilized to quantify waste reduction rates, generating measurable data to support the analysis. Concurrently, qualitative observations enriched the numerical findings, providing a holistic understanding of the treatment process. The research was conducted within controlled experimental settings, where waste samples were systematically prepared and inoculated with BSFL, followed by exposure to varying experimental conditions. Baseline measurements were established by recording the initial weight, moisture content, pH, and temperature of each sample. Over a nine-day observation period, samples were monitored with daily assessments documenting variations in substrate weight, fluctuations in temperature, and changes in moisture levels. This approach ensured comprehensive data collection and analysis, elucidating the effectiveness of BSFL in MSW treatment.

3.2.1 Control of Temperature and Moisture in the Study Design

To ensure the reliability and validity of the experimental results, control of temperature and moisture levels was implemented through a systematic approach. Temperature regulation was achieved using environmental chambers, where samples were exposed to specific temperature conditions of 15°C, 30°C, and 40°C. These temperature-controlled incubators maintained stable thermal environments throughout the duration of the experiment, while a calibrated digital thermometer was employed to accurately record the temperatures at the center of each container. This method allowed for the detection of any deviations from the set parameters. Furthermore, insulation measures were integrated by situating the experimental setup within a climate-controlled laboratory to mitigate external temperature fluctuations. A control group maintained at ambient temperature facilitated the assessment of natural decomposition rates without the intervention of Black Soldier Fly larvae, thereby providing a comparative baseline. Moisture control was equally prioritized, with the substrate's moisture content adjusted to predefined levels ranging from 50% to 90% using a precision moisture analyzer. The consistent application of distilled water ensured that targeted moisture levels were upheld, while excess moisture was managed through air-drying techniques or the incorporation of dry substrate. To guarantee uniformity, organic waste samples were shredded to a consistent size of 1–2 cm and homogenized prior to moisture adjustment, allowing for even distribution throughout the experimental conditions. Daily verification of moisture levels, conducted with a moisture meter, was critical, with necessary adjustments made whenever readings deviated by more than ±2%.

3.3 Materials

The equipment used for experimenting were proposed by Zurbrugg;

- Waste samples
- Weighing scale
- Thermometer
- pH meter
- Moisture analyzer
- Sample containers
- Laboratory balance
- Data recording sheet
- Personal protective equipment (gloves, lab coat, goggles)

3.4 Methods

3.4.1 Waste collection and processing

A garbage truck from Nakawa Market was selected for a detailed waste management study. The truck's contents were systematically emptied, and a thorough sorting of the waste constituents was conducted, categorizing the materials into organic, inorganic, and recyclable fractions. Following this initial segregation, the sorted waste was transported to the Bugolobi KCCA recycling facility for a comprehensive secondary classification, aimed at validating and quantifying the waste composition with enhanced accuracy. The recycling plant operates across six specialized departments: sorting, waste reception, inoculation, harvesting, pupation, and breeding. Within the sorting department, the waste underwent an additional level of scrutiny to identify and remove any inorganic or recyclable materials that may have been unintentionally left behind during the preliminary sorting process at the truck level. To facilitate effective treatment, the waste was subjected to examination to confirm the absence of hazardous materials and inorganic substances. Subsequently, the waste was processed to reduce its particle size to a diameter ranging from 1 to 2 cm, a dimension deemed critical as BSFL exhibit limited capacity to process larger substrate particles. A shredding machine was utilized to process 250 kg of organic waste, from which samples for subsequent experimentation were extracted. Water was infused into the waste to expedite the shredding process, ensuring a uniform consistency. After shredding, the quality of the resulting mixture was carefully evaluated to ascertain its appropriate thickness for optimal processing. In instances where the mixture demonstrated excessive liquidity, additional organic waste was added to achieve a thicker consistency, thereby enhancing the quality of the compost produced.

3.4.2 Black Soldier Fly Larvae

The rearing of flies was performed in a designated nursery, distinctly segregated from the waste treatment operations to maintain clear operational boundaries. This process consisted of four phases: initially, adult flies were housed in cages for mating and egg laying, followed by observation of the hatching process where the eggs developed into larvae. The larvae were monitored until reaching five days of age (indicated as 5-DOL), at which point a significant portion was transferred to the waste treatment section to assist in organic waste degradation. The remaining larvae continued to receive nourishment until they reached the pre-pupae stage, after which they were placed in dark cages to undergo pupation. This carefully controlled environment facilitated their metamorphosis into adult flies, effectively completing the rearing cycle and enabling the repetition of the process for sustainable waste management.

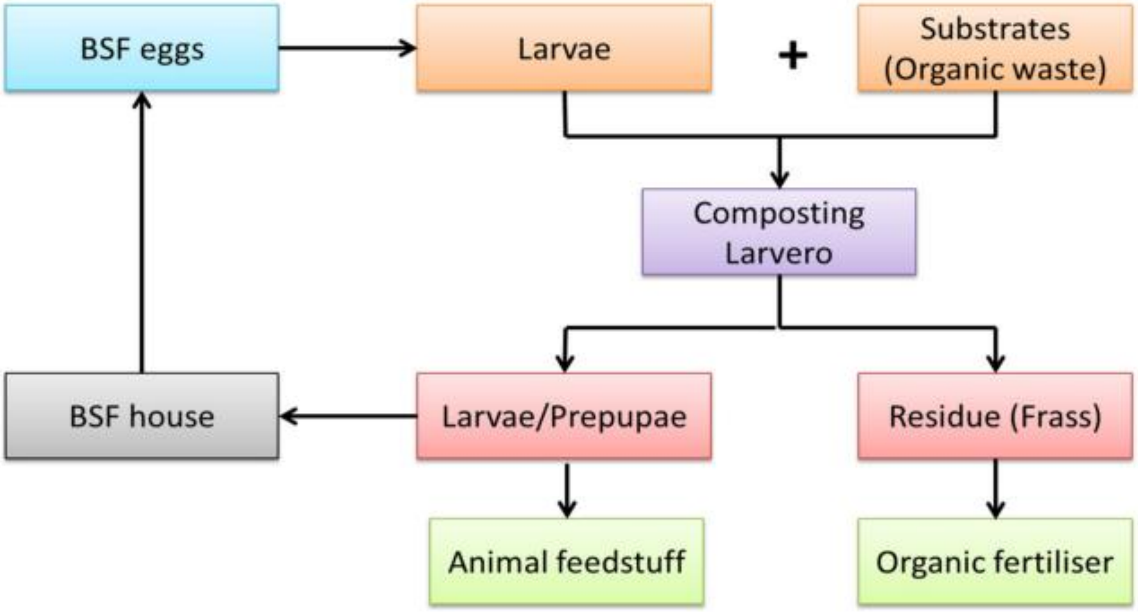

Figure 3. 2: BSF treatment process

3.4.3 Procedures

A total of 22 samples were prepared including 5-day-old BSFL weighing 30 grams for each sample, mixed with shredded organic substrates, and their initial weights recorded. Over a nine-day period, ten samples were designated to evaluate the efficacy of BSFL in degrading MSW under consistent temperature and moisture conditions, with daily observations conducted to measure degradation rates through weight loss and visual inspections of the substrate volume. Concurrently, three samples were assigned to study the impact of temperature variations on the composting process, with environments maintained at 15°C, 30°C, and 40°C. Additionally, the remaining nine samples were used to assess the effects of varying moisture content on decomposition efficiency, with moisture levels set at 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, and 90%. Throughout the nine days, daily measurements were meticulously recorded to evaluate changes in substrate weight, enabling a comprehensive understanding of how these critical factors influence the efficiency of BSFL in organic waste management.

3.4.4 Calculations

3.4.4.1 Determination of moisture content

A small proportion of the MSW weighing 150g (Initial Weight recorded as $\mathbf{W_0}$) initially was placed on a balance pan of the moisture analyzer machine, and then heated. After some time, the analyzer automatically turned off, that is when moisture content in MSW has been thoroughly removed. After the machined cooled, it as well measured the final weight of the sample (**W₁**). Then the amount of moisture content in the MSW was calculated from the formula below;

$$MC = \left(\frac{W_0 - W_1}{W_0}\right) * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. eqn1$$

Where MC stands for moisture content.

3.4.4.2 Determination of potential hydrogen

The pH of the substrate was determined using a litmus test strip, which is designed to visually indicate the acidity or alkalinity of a solution through a color change reaction. The test strip consists of pH-sensitive dyes that react with hydrogen ions in the substrate, resulting in a color transformation that corresponds to specific pH levels. To conduct the test, a small sample of the substrate was placed in a clean container, and the litmus strip was immersed for a brief period. The strip was then compared to a standardized pH color chart that correlates color variations to pH values, allowing for accurate assessment of the substrate's pH level.

3.4.4.3 Determination of temperature

The initial substrate temperature was accurately determined using a calibrated digital thermometer, which was strategically positioned at the center of the sample to ensure uniform measurement. Subsequently, we established specific experimental conditions by setting the temperature of each sample to 15°C, 30°C, and 40°C. This temperature variation was carefully chosen to examine their respective effects on the decomposition process, allowing for a thorough analysis of thermal influences on substrate behavior.

3.4.4.3 Waste reduction rate

The amount of waste decomposed in specific time by use of BSFL was computed using the Waste Reduction Index (WRI) method, for the different samples. The formulae below was used to compute the WRI.

$$WRI = \left(\frac{W - R}{\frac{W}{t}}\right) * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where,

W= total quantity of feeding substrate used during the time t,

R= the residue left at harvesting time t

Note: A higher WRI value indicates a better waste reduction efficiency (Irfarma Kabir Ahmed *et al.*, 2023).

3.5 Data analysis

The data collected during the study was organized and entered into a spreadsheet for efficient analysis using SPSS (Statistical Package for the Social Sciences) for statistical analysis. To clearly illustrate the discrete data, a line graph was created, complemented by descriptive statistics that summarized key metrics such as means and standard deviations. To identify optimal conditions for effective waste decomposition using BSFL, statistical methods, including T-tests and ANOVA (Analysis of Variance) was used to compare means and evaluate the influence of various independent variables on MSW reduction.

CHAPTER FOUR: RESULTS

4.0 Introduction

This chapter evaluates the effectiveness of black soldier flies in treating municipal solid waste.

4.1 Characterization of municipal solid waste

The municipal solid waste designated for vermicomposting comprised predominantly of jackfruit and onion residues sourced from local markets, with a moisture content of 72% and pH of 6.7. Before composting process, the waste underwent fermentation, resulting in the formation of a pastry weighing a total of 275 kg. Notably, this mass exhibited a temperature of 24.95°C.

Table 4. 1: MSW characteristics

<table>
<tr><th></th><th colspan="2">MSW Composition</th></tr>
<tr><th>Properties</th><th>Jack fruit</th><th>Onion leftovers</th></tr>
<tr><td>Moisture Content (%)</td><td colspan="2">72</td></tr>
<tr><td>Condition</td><td colspan="2">Fermented</td></tr>
<tr><td>Weight (kg per sample)</td><td colspan="2">275</td></tr>
<tr><td>Temperature (°C)</td><td colspan="2">24.95</td></tr>
<tr><td>Form</td><td colspan="2">Pastry</td></tr>
<tr><td>Potential Hydrogen</td><td colspan="2">6.7</td></tr>
</table>

4.2 The effects of BSF larvae on the rate of weight reduction in MSW

In a study examining the decomposition of municipal solid waste (MSW), comprised ten samples, each initially containing 12.5 kg of MSW mixed with 0.003 kg of larvae, were analyzed over a nine-day period. During the first five days, all samples exhibited a partial reduction in weight. By the ninth day, the weight changes recorded were as follows: Sample 1 decreased by 3.13 kg, Sample 2 by 2.93 kg, Sample 3 by 3.03 kg, Sample 4 by 2.43 kg, Sample 5 by 4.43 kg, Sample 6 by 2.03 kg, Sample 7 by 2.83 kg, Sample 8 by 3.03 kg, Sample 9 by 2.43 kg, and Sample 10 by 2.52 kg.

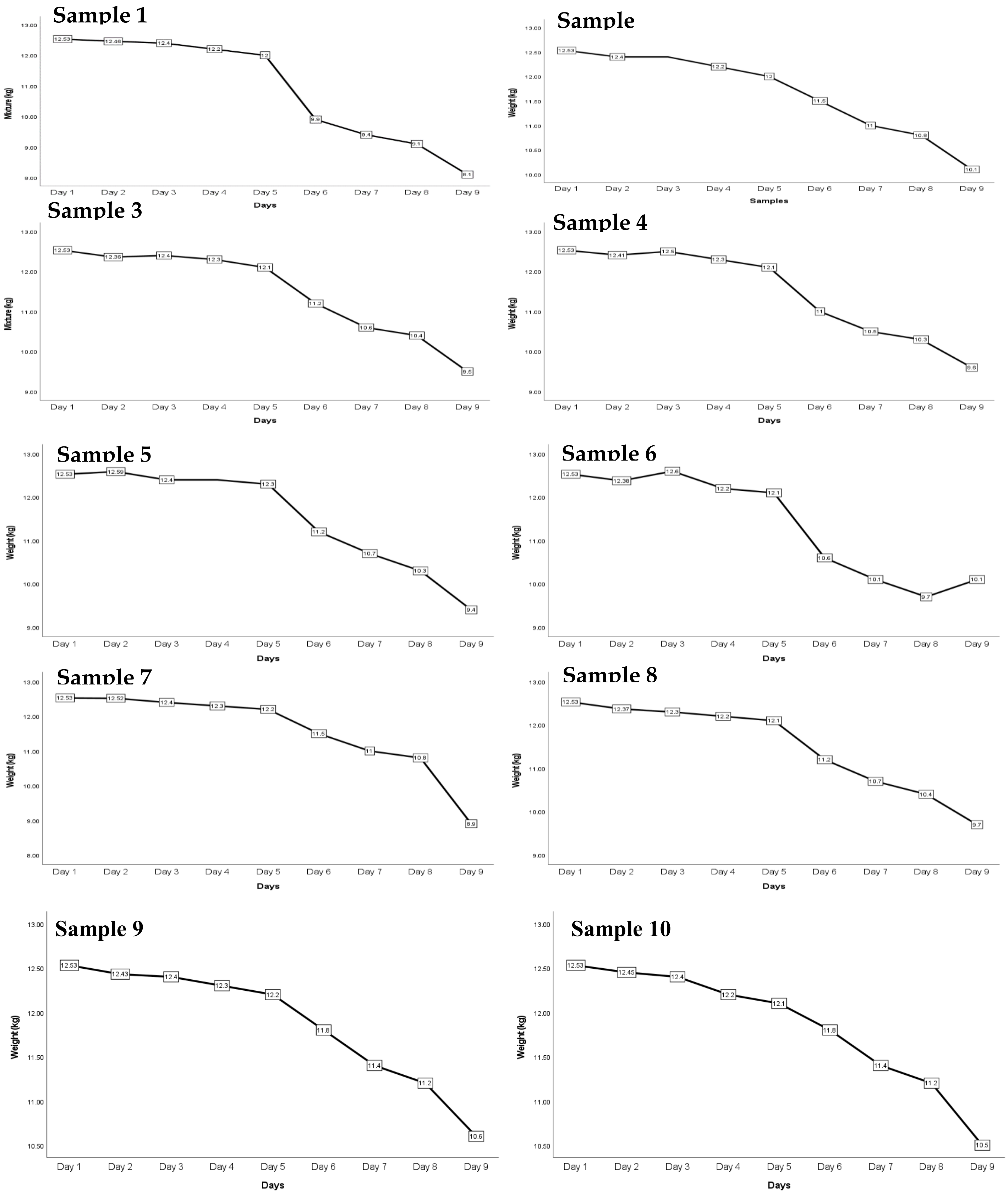

Figure 4. 1: The effects of BSF larvae on the rate of weight reduction in MSW

4.2.1 Descriptive Statistics of Composited Samples Over a Nine-Day Period

Table 2 Present a detailed analysis of the average weights of various samples after a nine-day compositing process. Sample 1 exhibited the lowest average weight, recorded at 10.899 kgs, accompanied by the highest variance of 3.071 kgs. In contrast, the other samples demonstrated average weights that fell within a narrower range, specifically between 11.368 kgs and 11.842 kgs. This trend shows that sample 2 to sample 10 maintained relatively consistent weights compared to sample 1. Furthermore, when examining the overall average weight of all samples, a noteworthy decline was observed from an initial average of 12.503 kgs to a diminished 9.7 kgs by the end of the nine days. The variance analysis also sheds light on how the weight distribution evolved over time. As the duration of the compositing process increased, the standard deviation from the mean weight climbed steadily from 0.00 kg to 0.0565 kgs.

Table 4. 2: Descriptive Statistics of Composited Samples Over a Nine-Day Period

Summary	**Count**	**Sum**	**Average**	**Variance**
Sample 1	9	98.09	10.899	3.071
Sample 2	9	104.93	11.659	0.737
Sample 3	9	103.39	11.488	1.215
Sample 4	9	103.24	11.471	1.273
Sample 5	9	103.82	11.536	1.385
Sample 6	9	102.31	11.368	1.463
Sample 7	9	104.15	11.572	1.437
Sample 8	9	103.5	11.500	1.061
Sample 9	9	106.86	11.873	0.451
Sample 10	9	106.58	11.842	0.470
Summary	**Count**	**Sum**	**Average**	**Variance**
Day 1	10	125.3	12.503	0.000
Day 2	10	124.4	12.4	0.005
Day 3	10	124.2	12.4	0.006
Day 4	10	122.6	12.3	0.005
Day 5	10	121.2	12.1	0.008
Day 6	10	111.7	11.2	0.331
Day 7	10	106.8	10.7	0.362
Day 8	10	104.2	10.4	0.422
Day 9	10	96.5	9.7	0.565

4.2.2 Statistical Analysis of Weight Differences Among Samples Using ANOVA

Interestingly, the differences among the samples were examined using ANOVA analysis. The results presented in Table 3 indicated a significant difference between the samples, as the p-value was found to be less than 0.05. This suggests that the variations in weights across the samples are statistically significant.

Table 4. 3: Statistical Analysis of Weight Differences Among Samples Using ANOVA

Variation	SS	df	MS	F	P-value	F crit
Rows	5.973	9	0.664	5.101	2.47E-05	2.013
Columns	91.136	8	11.392	87.561	5.46E-34	2.070
Error	9.367	72	0.130			
Total	**106.4766**	**89**				

4.3 Effect of compositing process on temperature

Over the course of the nine-day compositing period, the temperature variations among the ten samples were notable. As illustrated in Figure 2, a decrease in temperature was observed from day 1 to day 2 for all samples. Despite this initial decline, a partial increase in temperature was subsequently recorded across all samples. The highest temperature increase was recorded for sample 5, which exhibited a rise of 37.5°C, while sample 4 demonstrated the smallest increase at 31.65°C.

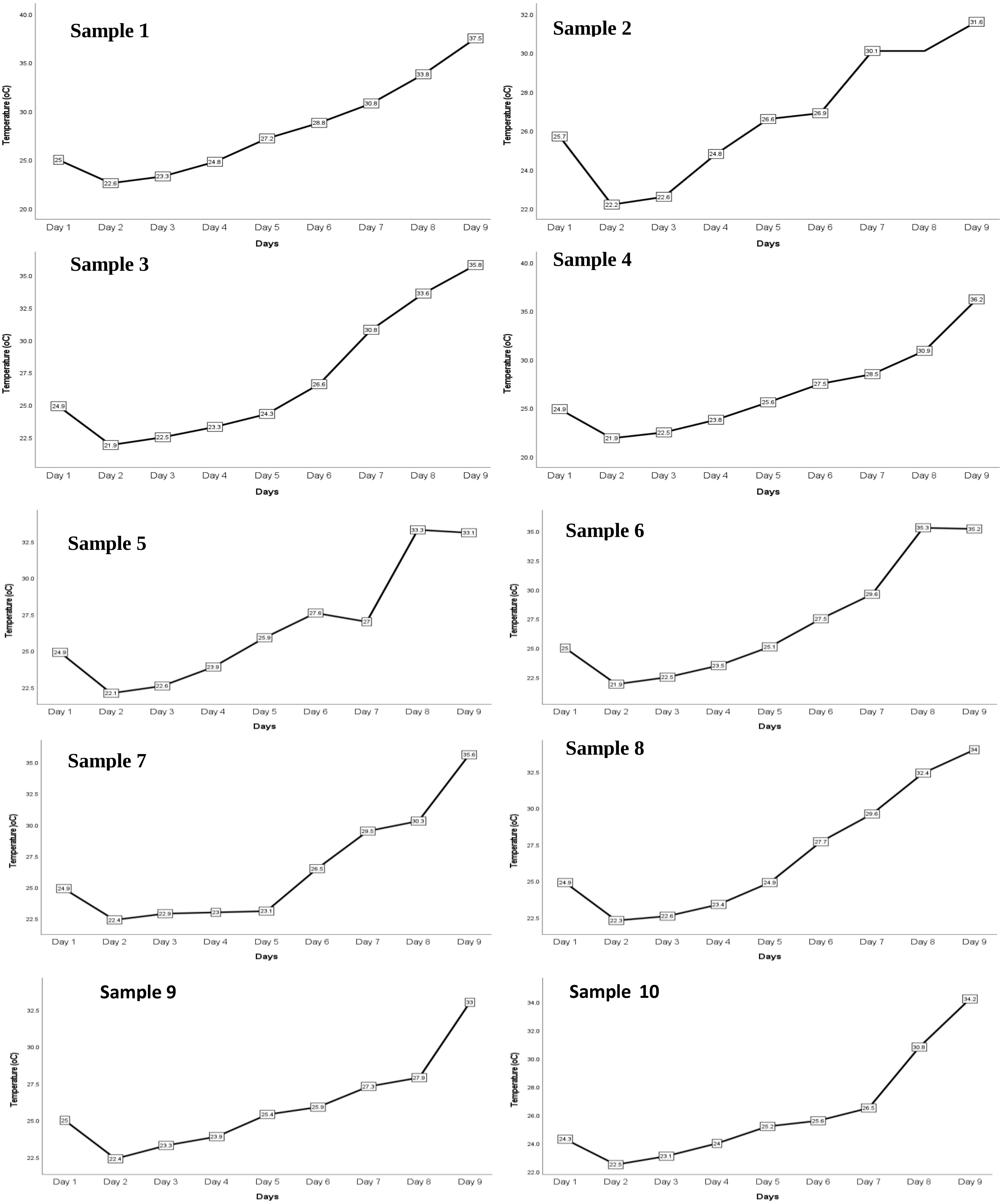

Figure 4. 2: Temperature variation for nine days

4.3.1 Analysis of temperature Variability in Composited Samples

Result in Table 4 show that the average temperature for the sample ranged between 26.011^{0}C to 28.2^{0}C, with a varying variance ranging between 10.041^{0}C to 26.064^{0}C. The temperature of the sample increased with the number of days from 24.95^{0}C on day 1 to 34.62^{0}C on the 9th day of the process. However, it was noticed that the temperature between day 1 and day 2 slightly decreased by 2.73^{0}C. The variation from the average temperature was as well observed to have increased from 0.112^{0}C on day 1 to 3.122^{0}C on the 9th day.

Table 4. 4: Analysis of temperature Variability in Composited Samples

Summary	Count	Sum	Average	Variance
Sample 1	9	253.8	28.200	25.392
Sample 2	9	240.6	26.733	11.105
Sample 3	9	243.7	27.078	25.899
Sample 4	9	241.8	26.867	20.632
Sample 5	9	240.4	26.711	16.889
Sample 6	9	245.6	27.289	26.064
Sample 7	9	238.2	26.467	20.298
Sample 8	9	241.8	26.867	18.560
Sample 9	9	234.1	26.011	10.041
Sample 10	9	236.2	26.244	14.793
Day 1	10	249.5	24.95	0.112
Day 2	10	222.2	22.22	0.068
Day 3	10	227.9	22.79	0.110
Day 4	10	238.4	23.84	0.354
Day 5	10	253.3	25.33	1.311
Day 6	10	270.6	27.06	0.905
Day 7	10	289.7	28.97	2.449
Day 8	10	318.4	31.84	4.916
Day 9	10	346.2	34.62	3.122

4.3.2 Statistical Analysis of temperature Differences Among Samples

The results presented in Table 5 indicated a significant difference between the samples, as the p-value was found to be less than 0.05. This suggests that the variations in temperature across the samples is statistically significant.

Table 4. 5: Statistical Analysis of temperature Differences Among Samples

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Rows	29.860	9	3.318	2.647	0.010	2.0127
Columns	1427.124	8	178.391	142.301	5.78E-41	2.0698
Error	90.260	72	1.254			
Total	**1547.244**	**89**				

4.3.3 Effect of compositing process on temperature

Figure 3 illustrates a substantial negative correlation between the compositing process and temperature, with a Pearson correlation coefficient of -0.967. This strong inverse relationship indicates that as the weight of the MSW combined with BSLs decreases between nine (9) days, the temperature within the mixer tends to increase. The data reveals a statistically significant variation in temperature relative to changes in the composition of the waste mixture, as evidenced by a p-value of 0.000.

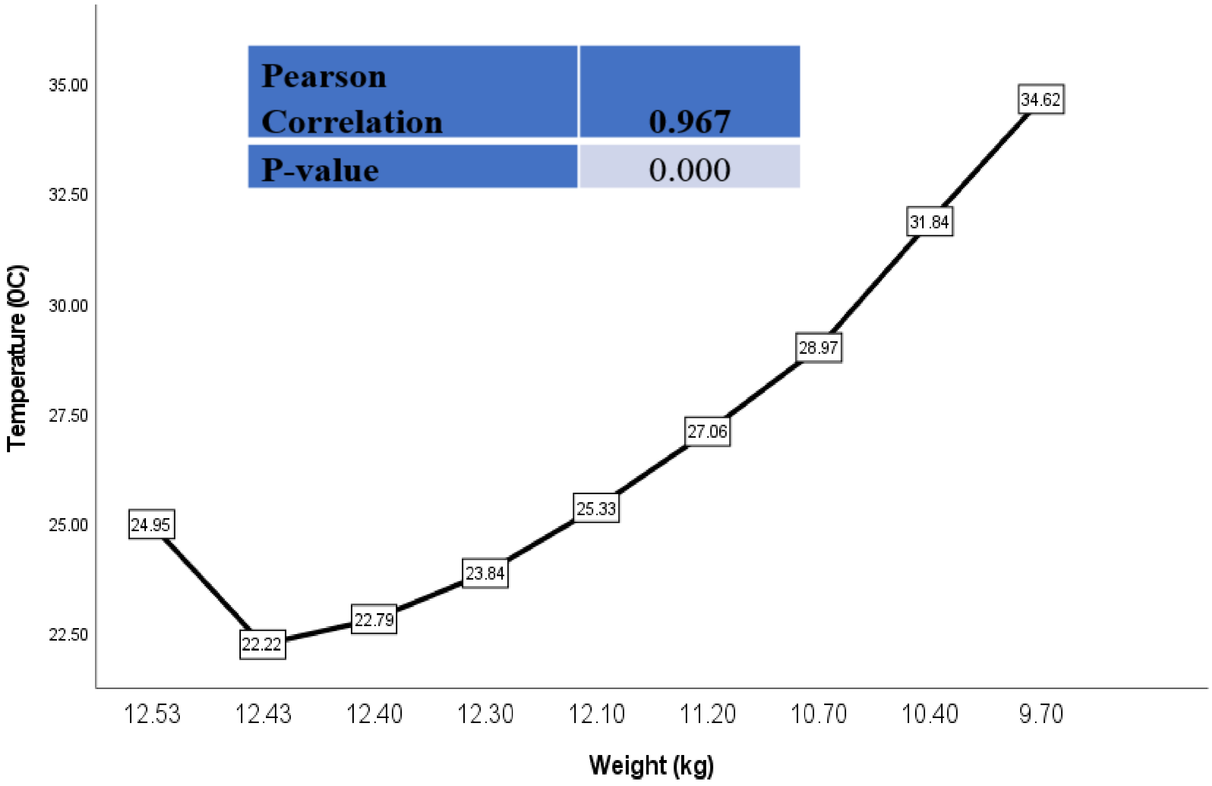

Figure 4. 3: Effect of compositing process on temperature

4.3 Effect of moisture content on composting process

The findings presented in Figure 4 indicate a clear relationship between substrate moisture content and WRI. Specifically, when the moisture content is 55% or lower, the WRI remains below 1.5. As the moisture content increases to the range of 60-80%, the WRI rises significantly, reaching a peak of 2.5. However, when the moisture content exceeds 80%, the WRI tends to decrease, at around 1 or slightly higher.

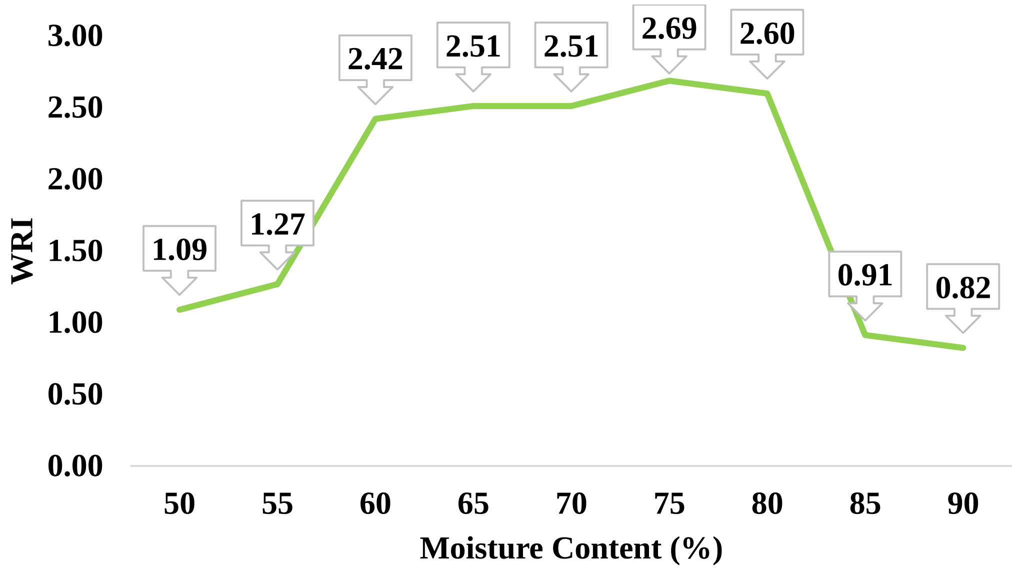

Figure 4. 4: Moisture content vs WRI

Figure 4.4 illustrates the waste reduction rate in the presence of Black Soldier Fly Larvae (BSFL) over a period of nine days while varying the moisture content. At a moisture content of 50-55%, the reduction in waste was minimal. The highest reduction was recorded when the moisture content ranged from 60-80%. However, when the moisture content increased to 85-90%, the rate of waste reduction slowed significantly.

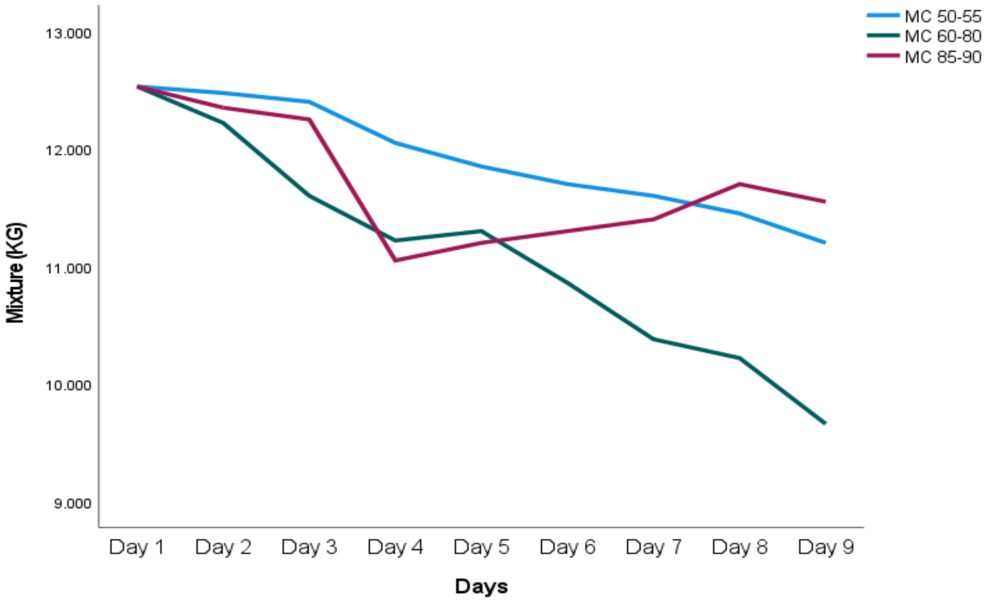

Figure 4. 5: Effect of moisture content on MSW over nine days

The ANOVA results presented in Table 4.6 indicate a significant statistical difference among the groups categorized by moisture content, with a p-value of 0.050. This suggests that moisture content notably affects waste reduction. Specifically, the group with moisture content ranging from 60-80% exhibits a variation of 0.878 from an average value of 11.110, while the 50-55% moisture content group shows a smaller variation of 0.228 from an average of 11.917. Additionally, the 85-90% moisture content group has a variation of 0.295 from an average of 11.700.

Table 4. 6: Statistical difference between groups of moisture content

Groups	**Count**	**Sum**	**Average**	**Variance**		
MC 50-55	9	107.255	11.917	0.228		
MC 60-80	9	99.990	11.110	0.878		
MC 85-90	9	105.330	11.703	0.295		
ANOVA						
Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	3.148	2	1.574	3.371	0.050	3.403
Within Groups	11.208	24	0.467			
Total	14.356	26				

4.4 Effect of temperature on composting process

The results from =Figure 4.6 illustrate the impact of temperature variations on the Waste Reduction Index (WRI). Specifically, at a low temperature of 15°C, the WRI was measured at 0.135, indicating a low level of waste reduction effectiveness. As the temperature increased to a moderate level of 30°C, the WRI rose significantly to 2.867, suggesting a much higher efficiency in waste reduction at this temperature. However, when the temperature reached a high level of 40°C, the WRI decreased again to 0.291, showing a drop in waste reduction effectiveness.

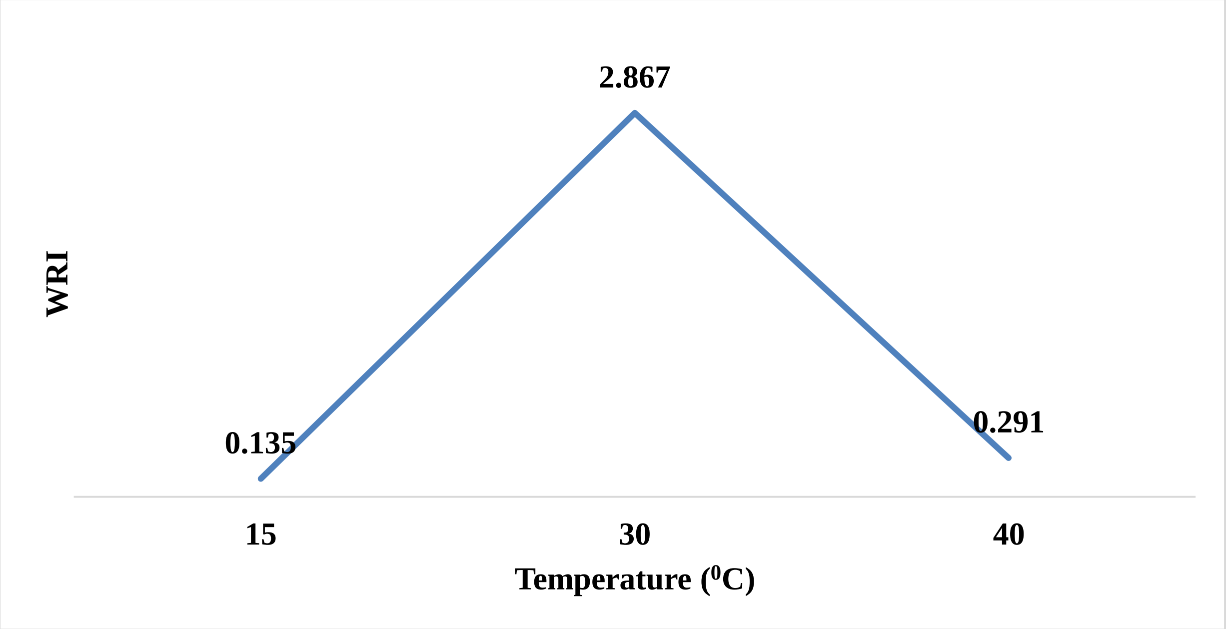

Figure 4. 6: Temperature against WRI

The results in Figure 4.7 indicate that temperature affects the decomposition process over the 9-day period. At 15°C, the compositing process was notably slow throughout, demonstrating that lower temperatures hinder decomposition. In contrast, at 30°C, the decomposition was highly effective and consistent for the entire duration, suggesting that this moderate temperature promotes optimal microbial activity. Meanwhile, at 40°C, there was a marked increase in decomposition rates from day 1 to 3, but this trend reversed, resulting in a slowdown from day 3 to day 9.

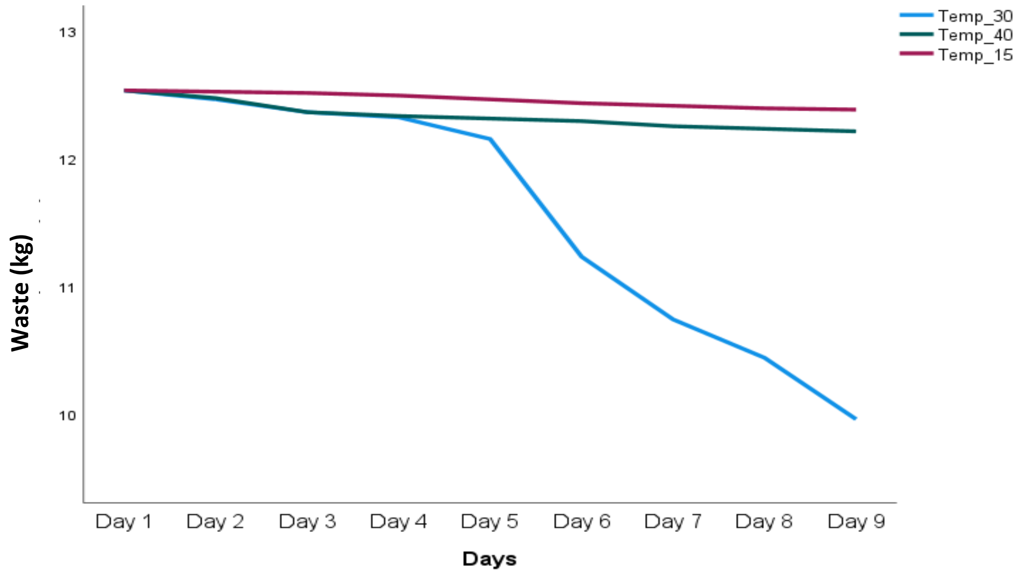

Figure 4. 7: Effect of temperature on MSW over nine days

The ANOVA results presented in Table 7 reveal a significant statistical relationship between temperature variations and the decomposition process of MSW, highlighted by a p-value of 0.007. This effect is evidenced by measurements taken at three distinct temperatures; at 15°C, the average weight of MSW was recorded at 12.458 kg, with a notably low variance of 0.003 kg. In contrast, at 30°C, the average weight dropped to 11.577 kg, accompanied by a higher variance of 0.989 kg, which suggests increased variability in the decomposition process. Finally, at 40°C, the average weight rebounded to 12.331 kg, while the variance decreased significantly to 0.012 kg.

Table 4. 7: Statistical difference between groups of temperature

Groups	Count	Sum	Average	Variance
15^0C	9	112.120	12.458	0.003
30^0C	9	104.190	11.577	0.989
40^0C	9	110.980	12.331	0.012

ANOVA

Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.085	2	2.042	6.105	0.007	3.403
Within Groups	8.030	24	0.335			
Total	12.114	26				

CHAPTER FIVE: DISCUSSION OF RESULTS

5.1 Discussion of characteristics of MSW

The results indicate that the municipal solid waste designated for decomposition was primarily composed of organic residues from jackfruit and onions, which are high in moisture content (79%) and slightly acidic (pH of 6.7). This specific combination of materials is crucial, as moisture content is a key factor influencing the decomposition process. High moisture levels enhance microbial activity, facilitating the breakdown of organic matter (Zhang et al., 2019). The slightly acidic pH is also favorable for earthworms, as they thrive in environments with a pH range of 6.0 to 7.5 (Edwards & Bohlen, 1996). The fermentation process that the waste underwent prior to experiment is noteworthy. Fermentation initiates the decomposing process, lowering the Carbon: Nitrogen ratio, which is important for promoting microbial growth and optimizing nutrient availability for the composting worms (Lazcano et al., 2008). Temperature plays a crucial role in the composting process. The observed temperature of 24.95°C is relatively low, because the fermentation process was still in its initial stages. In traditional composting, higher temperatures are beneficial as they help in pathogen inactivation and further breakdown of organic matter. However, in vermicomposting, earthworms thrive in lower temperatures, and it is essential to strike a balance where aerobic conditions are maintained without overheating (Domínguez & Edwards, 2010).

5.2 Effects of BSF larvae on the rate of weight reduction in MSW

The findings on decomposition of MSW using BSFL provide valuable insights into the weight reduction trends and variations among different samples over a nine-day compositing period. Initially, each sample contained 12.5 kg of MSW mixed with 0.003 kg of larvae, and by the end of the study, a notable decrease in weight was observed. The weight changes recorded for each sample varied individually, with Sample 5 showing the most significant reduction of 4.43 kg, while Sample 6 exhibited the least decrease at 2.03 kg. This variability suggests differing rates of decomposition among the samples which maybe due to the biological agents involved (Zheng et al., 2020). The average weight of all samples declined from an initial 12.53 kg to a final average of 9.7 kg. This reduction highlights the effectiveness of BSFL in composting MSW, thereby illustrating its potential in waste reduction. Examining the variance further revealed that the standard deviation from the mean weight increased from 0.00 kg at the study’s commencement to 0.0565 kg by its end. This increase in variability indicates that while some samples decomposed more rapidly, others were less effective in their weight reduction, confirming that biological decomposition processes do not progress uniformly across all samples (Yamato et al., 2019).

5.3 Effect of compositing process on temperature

The nine-day compositing period revealed significant temperature variations among the ten samples, particularly illustrating an initial decline in temperature from day 1 to day 2 across all samples, which indicate a temporary dip in microbial activity as organic materials begin their decomposition (Belt et al., 2019). Following this decrease, a notable increase in temperature was observed, especially in sample 5, which experienced a substantial rise of 37.5°C, likely reflecting peak microbial metabolism, while sample 4 recorded a smaller increase of 31.65°C, suggesting that variations in waste composition influence microbial efficiency (Scheu et al., 2012; Etbah et al., 2021). The average temperature rose from 24.95°C on day 1 to 34.62°C by the ninth day, with a variance indicating diverse responses among the samples, thus highlighting the need to consider initial material properties in composting dynamics (Adhikari et al., 2019). Additionally, the observed decrease of 2.73°C between the first two days, alongside a rise in temperature variation from 0.11°C to 3.12°C by day 9, highlights the complex interplay of physical and chemical changes within the compost pile that influence microbial communities (Zhang et al., 2020). The statistical analysis revealing a p-value of less than 0.05 further corroborates the significant differences in temperature among samples, affirming that compost composition directly affects heat generation (de Bertoldi et al., 2011). Lastly, the substantial negative correlation (Pearson coefficient of -0.967) between the weight of municipal solid waste combined with BSFL and temperature reinforces the idea that as the mass decreases over time, temperature increases, highlighting the critical role of material balance in optimizing the composting process for effective waste management (Kumar et al., 2020).

5.4 Effect of moisture content on composting process

The findings regarding the relationship between substrate moisture content and Waste Reduction Index (WRI) provide significant insights into the optimal conditions for waste processing using Black Soldier Fly Larvae (BSFL). As illustrated in Figure 4, the data suggest that moisture content is a critical factor influencing the efficiency of waste reduction. The statistical analysis provided in Table 6 confirms the variations in waste reduction due to different moisture content levels, with a p-value of 0.051 indicating a significant difference among the groups. The results show that the group with moisture content between 60-80%

displays a variation of 0.878 from an average value of 11.110. In contrast, the 50-55% moisture group shows a smaller variation (0.228 from an average of 11.917), and the 85-90% group presents a variation of 0.295 from an average of 11.700. At moisture levels of 55% or lower, the WRI remains below 1.5, indicating limited efficiency in waste reduction. This aligns with previous studies, which demonstrate that insufficient moisture impairs the biological activity and metabolic processes of BSFL, leading to suboptimal waste degradation (Diener et al., 2011). Conversely, as the moisture content rises to the range of 60-80%, there is a marked increase in WRI, peaking at 2.5. This peak highlight the effectiveness of an optimal moisture range in enhancing the larvae's ability to process organic matter. Similar findings were reported by Zhang et al. (2019), who noted that the metabolic rate and growth of BSFL are positively correlated with moisture content, promoting greater waste reduction. However, it is noteworthy that when the moisture content surpasses 80%, the WRI shows a decline, around 1 or slightly above. This decrease is attributed to anaerobic conditions that arise in overly moist environments, which inhibit the larvae’s growth and waste-processing capabilities (Riptan et al., 2020).

5.5 Effect of temperature on composting process

The findings from the study on the impact of temperature on the composting process reveal insights that align with prevailing literature, elucidating the relationship between temperature and microbial activity in waste decomposition. The results indicate that the Waste Reduction Index (WRI) peaked at 30°C, reinforcing the notion established by several studies that moderate temperatures foster optimal conditions for microbial growth and enzymatic activity, which are crucial for efficient composting (Zhang et al., 2019; Liu et al., 2020). Research has long documented that microbial activity is highly sensitive to temperature fluctuations. At lower temperatures, such as 15°C, the study observed notably slow decomposition rates, which align with existing literature highlighting the detrimental effects of cooler conditions on microbial metabolism. Hargreaves et al. (2008) found that temperatures below 20°C significantly hinder microbial processes, leading to less efficient composting. Conversely, the findings concerning the temperature of 40°C showcase a complex relationship typical of thermophilic composting. While the study indicated an initial increase in decomposition rates at this elevated temperature, a subsequent decline was observed, reflecting dynamics noted in various research works on thermophilic conditions. Hollander et al. (2019) pointed out that although thermophilic bacteria can thrive at higher temperatures, excessive heat can inhibit microbial diversity and activity, potentially compromising the composting process. This is consistent with the observed decline in decomposition of MWS after several days, suggesting that high temperatures encourage rapid initial decomposition, but without careful management, they lead to a slowdown.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The characterization of municipal solid waste designated for decomposition reveals a favorable combination of high moisture content and slightly acidic pH, which supports microbial activity and earthworm health. The preliminary fermentation process enhances the suitability of the waste for vermicomposting by lowering the C:N ratio and optimizing nutrient availability. While the observed temperature is relatively low, indicating the early stages of decomposition, it remains conducive, highlighting the importance of maintaining aerobic conditions without overheating. The effects of BSFL on the decomposition of MSW demonstrates a reduction in weight over the nine-day composting period. The variability in weight reduction among different samples highlights the complex interactions between biological agents and waste materials, indicating that factors such as the activity of the larvae play a crucial role in the efficiency of decomposition. The nine-day compositing process demonstrated significant temperature fluctuations among the samples, highlighting the intricate relationship between microbial activity and waste composition. Moisture content between 60-80% maximizes the WRI, significantly enhancing the larvae's ability to degrade organic matter. In contrast, inadequate moisture levels (55% or lower) impede biological activity, resulting in limited waste processing effectiveness. Conversely, excessive moisture (above 80%) leads to anaerobic conditions, which negatively affect larvae growth and waste management capabilities. Moderate temperatures (around 30°C) significantly improve microbial activity and decomposition rates, while lower temperatures hinder effectiveness and excessively high temperatures can disrupt microbial diversity.

6.2 Recommendations

For effective reduction of MSW using the 5-DOL of BSL, the following are recommended;

- Regularly monitor and maintain moisture levels between 60-80%. This optimum range not only enhances the efficiency of BSFL but also supports microbial activity essential for vermicomposting.
- Maintain the composting temperature at 30°C to optimize microbial activity and enhance decomposition efficiency.

- Consider implementing a preliminary fermentation process for MSW before introducing it to vermicomposting. This can help lower the carbon-to-nitrogen (C:N) ratio and improve nutrient availability, making the waste more suitable for both earthworms and larvae.
- Ensure that aerobic conditions are maintained throughout the composting process. This can be achieved by turning the compost regularly to promote aeration and prevent overheating, which can hinder the composting process.
- Frequently monitor the temperature of the composting samples. Significant temperature fluctuations can indicate varying levels of microbial activity and waste composition, which may require adjustments in composting strategies.
- Keep track of the activity levels of BSFL during the composting period, as this is crucial in optimizing the decomposition process. Adjust conditions as necessary to maximize their efficiency.
- Prevent moisture levels from exceeding 80%, as this can create anaerobic conditions detrimental to both larvae health and waste management effectiveness. Use drainage solutions if necessary.

6.3 Areas of further research

Further research should focus on a comprehensive lifecycle analysis to evaluate the environmental impacts of using BSFL for waste decomposition compared to traditional composting methods.

References

A. Al-Dailami, I. Ahmad, H. Kamyab, N. Abdullah, I. Koji, V. Ashokkumar, B. Zabara. (2022). Sustainable solid waste management in Yemen: environmental, social aspects, and challenges. *Biomass Conver. Biorefin. (2022), pp. 1-27*

A. Cerda, A. Artola, X. Font, R. Barrena, T. Gea, A. Sanchez. (2018).Composting of food wastes: status and challenges. *Bioresour. Technol., 248 (2018), pp. 57-67*

A. Chrysargyris, A. Stamatakis, K. Moustakas, M. Prasad, N. Tzortzakis. (2018). Evaluation of municipal solid waste compost and/or fertigation as peat substituent for pepper seedlings production. *Waste Biomass Valoriz., 9 (2018), pp. 2285-2294*

Aalok, A., Soni, P., & Tripathi, A. K. (2009). Role of Earthworms in breakdown of different organic wastes into manure: a review. *Dynamic Soil, Dynamic Plant*, *3*(2), 13-20.

Ajekwene, K. K., Aigbokhan, E. E., Akindele, O. E., Yibowei, M. E., Momoh, F. P., & Ugonna, U. K. (2022). Electronic Waste (E-Waste): Sources, Proliferation, Effects & Management in Developing Nations. *IOSR J. Eng*, *12*, 12-27.

Al-Khatib, I. A., Kontogianni, S., Nabaa, H. A., & Al-Sari, M. I. (2015). Public perception of hazardousness caused by current trends of municipal solid waste management. *Waste Management*, *36*, 323-330.

Almalki, F. A., Alsamhi, S. H., Sahal, R., Hassan, J., Hawbani, A., Rajput, N. S., ... & Breslin, J. (2023). Green IoT for eco-friendly and sustainable smart cities: future directions and opportunities. *Mobile Networks and Applications*, *28*(1), 178-202.

Anantanatorn, A., Yossomsakdi, S., Wijaya, A. F., & Rochma, S. (2015). Public service management in local government, Thailand (Case study of solid waste management in Pattaya City). *International Journal of Applied Sociology*, *5*(1), 5-15.

Arinabo, D. (2023). Reconciling multiple forms of flood risk knowledge and institutional responses: insights from Kampala's flood management regime. *International journal of disaster risk reduction*, *94*, 103829.

Arora, S., Sethi, J., Rajvanshi, J., Sutaria, D. and Saxena, S., (2021). Developing “zero waste model” for solid waste management to shift the paradigm toward sustainability. In *Handbook of Solid Waste Management: Sustainability through Circular Economy* (pp. 1-20). Singapore: Springer Singapore.

Aryampa, S. (2021). A framework for assessing the ecological sustainability of waste disposal sites in urban areas.

Ashokkumar, V., Flora, G., Venkatkarthick, R., SenthilKannan, K., Kuppam, C., Stephy, G. M., ... & Ngamcharussrivichai, C. (2022). Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: Emerging circular bioeconomy perspective. *Fuel*, *324*, 124313.

Awuchi, C. G., & Awuchi, C. G. (2019). Impacts of plastic pollution on the sustainability of seafood value chain and human health. *International Journal of Advanced Academic Research*, *5*(11), 46-138.

AZAB, M., KIZILKAYA, R., & AL HAYJA, S. A. (2022). Possibility of using vermicompost to improve oil plants productivity. *EEDINGS*, 60.

Azevedo, B. D., Scavarda, L. F., Caiado, R. G. G., & Fuss, M. (2021). Improving urban household solid waste management in developing countries based on the German experience. *Waste management*, *120*, 772-783.

Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., & Thami Alami, I. (2018). Composting parameters and compost quality: a literature review. *Organic agriculture*, *8*, 141-158.

Aziz, H. A., Rosli, N. A., & Hung, Y. T. (2020). Landfill methane emissions. In *Handbook of environment and waste management: Acid rain and greenhouse gas pollution control* (pp. 397-454).

B. Blumenstein, L. Buhle, M. Wachendorf, D. Moller. (2012). Economic assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) in comparison to different energy recovery, animal-based and non-refining management systems. *Bioresour. Technol., 119 (2012), pp. 312-323*

Banga, M., Lokina, R. B., & Mkenda, A. F. (2011). Households' willingness to pay for improved solid waste collection services in Kampala city, Uganda. *The Journal of Environment & Development*, *20*(4), 428-448.

Barua, S., Kabir, J., Akanda, A. M., & Hoque, E. (2015, December). Production of transportation fuel from municipal solid waste. In *2015 2nd International Conference on Electrical Information and Communication Technologies (EICT)* (pp. 467-470). IEEE.

Barupal, T., Chittora, D., & Meena, M. (2019). Solid waste: characterization, assessment, monitoring, and remediation. In *Advances in Waste-to-Energy Technologies* (pp. 1-19). CRC Press.

Barupal, T., Chittora, D., & Meena, M. (2019). Solid waste: characterization, assessment, monitoring, and remediation. In *Advances in Waste-to-Energy Technologies* (pp. 1-19). CRC Press.

Blair, J., & Mataraarachchi, S. (2021). A review of landfills, waste and the nearly forgotten nexus with climate change. *Environments*, *8*(8), 73.

Bokhorst, S., Metcalfe, D. B., & Wardle, D. A. (2013). Reduction in snow depth negatively affects decomposers but impact on decomposition rates is substrate dependent. *Soil Biology and Biochemistry*, *62*, 157-164.

Boldrin and Christensen. (2010). Seasonal generation and composition of garden waste in Aarhus (Denmark). *Waste Manag., 30 (2010), pp. 551-557*

C. Chenu, D.A. Angers, P. Barré, D. Derrien, D. Arrouays, J. Balesdent. (2019).Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. *Soil Tillage Res., 188 (2019), pp. 41-52*

Ceritoğlu, M., Şahin, S., & Erman, M. (2018). Effects of vermicompost on plant growth and soil structure. *Selcuk Journal of Agriculture and Food Sciences, 32*(3), 607-615.

A. Cesaro, V. Belgiorno, M. Guida. (2015). Compost from organic solid waste: quality assessment and European regulations for its sustainable use. *Resour. Conserv. Recycl., 94 (2015), pp. 72-79*

Chandramohan, A., Weibel, J. A., & Garimella, S. V. (2017). Spatiotemporal infrared measurement of interface temperatures during water droplet evaporation on a nonwetting substrate. *Applied Physics Letters, 110*(4).

Chandrappa, R., & Das, D. B. (2012). *Solid waste management: Principles and practice*. Springer Science & Business Media.

Chhabra, R., & Chhabra, R. (2021). Irrigation water: Quality criteria. *Salt-affected Soils and Marginal Waters: Global Perspectives and Sustainable Management*, 431-486.

Colten, C. E. (1994). Chicago's waste lands: refuse disposal and urban growth, 1840-1990. *Journal of Historical Geography*, *20*(2), 124-142.

D. Adamcova, M. Radziemska, A. Ridoskova, S. Barton, P. Pelcova, J. Elbl, J. Kynicky, M. Brtnicky, M.D. Vaverkova. (2017). Environmental assessment of the effects of a municipal landfill on the content and distribution of heavy metals. *Tanacetum vulgare L Chemosphere, 185 (2017), pp. 1011-1018*

Das, S., Lee, S.H., Kumar, P., Kim, K.H., Lee, S.S. and Bhattacharya, S.S., (2019). Solid waste management: Scope and the challenge of sustainability. *Journal of cleaner production*, *228*, pp.658-678.

Davis, R. (2014). *Looking past the present waste: path dependencies in municipal solid waste management in the US and European Union* (Doctoral dissertation, University of British Columbia).

A. De Boni, F.M. Melucci, C. Acciani, R. Roma. (2022). Community composting: a multidisciplinary evaluation of an inclusive, participative, and eco-friendly approach to biowaste management. *Clean. Environ. Syst., 6 (2022)*

De Guardia, A., Mallard, P., Teglia, C., Marin, A., Le Pape, C., Launay, M., ... & Petiot, C. (2010). Comparison of five organic wastes regarding their behaviour during composting: Part 1, biodegradability, stabilization kinetics and temperature rise. *Waste Management*, *30*(3), 402-414.

DeLaune, P. B., Moore Jr, P. A., Daniel, T. C., & Lemunyon, J. L. (2004). Effect of chemical and microbial amendments on ammonia volatilization from composting poultry litter. *Journal of environmental quality*, *33*(2), 728-734.

Dickson-Gomez, J., Nyabigambo, A., Rudd, A., Ssentongo, J., Kiconco, A., & Mayega, R. W. (2023). Water, sanitation, and hygiene challenges in informal settlements in Kampala, Uganda: a qualitative study. *International Journal of Environmental Research and Public Health*, *20*(12), 6181.

S. Diener, S., Zurbrügg, C., & Tockner, K. (2009). Conversion of organic material by black soldier fly larvae: Establishing optimal feeding rates. Waste Management & Research, 27(6), 603-610. https://doi.org/10.1177/0734242X09345526

Dumontet, S., Dinel, H., & Baloda, S. B. (1999). Pathogen reduction in sewage sludge by composting and other biological treatments: a review. *Biological agriculture & horticulture, 16*(4), 409-430.

E. Barriuso, P. Benoit, I.G. Dubus. (2008). Formation of pesticide nonextractable (bound) residues in soil: magnitude, controlling factors and reversibility. *Environ. Sci. Technol., 42 (2008), pp. 1845-1854*

E. Castán, P. Satti, M. González-Polo, M.C. Iglesias, M.J. Mazzarino.

Emerick, R. J., & Olson, O. E. (1962). Effect of nitrate and nitrite on vitamin A storage in the rat. *The Journal of Nutrition*, *78*(1), 73-77.

Engler, M. E. (2004). *Designing America's waste landscapes*. JHU Press.

Environ. Technol. Innovat., 26 (2022), Article 102342

Ermolaev, E., Sundberg, C., Pell, M., Smårs, S., & Jönsson, H. (2019). Effects of moisture on emissions of methane, nitrous oxide and carbon dioxide from food and garden waste composting. *Journal of cleaner production*, *240*, 118165.

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

Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: A review of global issues. *International journal of environmental research and public health*, *16*(6), 1060.

Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: A review of global issues. *International journal of environmental research and public health*, *16*(6), 1060.

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M. A., Munch, J. C., & Beese, F. (2002). Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany. *Agriculture, Ecosystems & Environment*, *91*(1-3), 175-189.

G. Bueno, I. Latasa, P. Lozano. (2015). Comparative LCA of two approaches with different emphasis on energy or material recovery for a municipal solid waste management system in Gipuzkoa. *Renew. Sustain. Energy Rev., 51 (2015), pp. 449-459*

Garg, P., Gupta, A., & Satya, S. (2006). Vermicomposting of different types of waste using Eisenia foetida: A comparative study. *Bioresource technology*, *97*(3), 391-395.

Gautam, M., & Agrawal, M. (2021). Greenhouse gas emissions from municipal solid waste management: A review of global scenario. *Carbon footprint case studies: municipal solid waste management, sustainable road transport and carbon sequestration*, 123-160.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner production*, *114*, 11-32.

Giusti, L. (2009). A review of waste management practices and their impact on human health. *Waste management*, *29*(8), 2227-2239.

Godfrey, L., Ahmed, M. T., Gebremedhin, K. G., Katima, J. H., Oelofse, S., Osibanjo, O., ... & Yonli, A. H. (2019). Solid waste management in Africa: Governance failure or development opportunity. *Regional development in Africa*, *235*(10.5772).

Gökbel, F. (2015). *Energy balance and biodegradability assessments for food waste composting under various c: n ratios and air flow rates* (Master's thesis, Middle East Technical University).

Grandhi, B., & Appaiah Singh, J. (2016). What a waste! A study of food wastage behavior in Singapore. *Journal of Food Products Marketing*, *22*(4), 471-485.

H.I. Abdel-Shafy, M.S. Mansour. (2016)Solid waste issue: sources, composition, disposal, recycling, and valorization. *Egypt. J. Petrol., 27 (2018), pp. 1275-1290*

Inglezakis, V. J., & Moustakas, K. (2015). Household hazardous waste management: A review. *Journal of environmental management*, *150*, 310-321.

Jackson, S. B. (2004). An in-depth report on the development, advancement, and implementation of pneumatic waste collection systems and a proposed program for the practical evaluation of such a system in terms of waste disposal parameters, engineering design, and economic costs *(Doctoral dissertation, Monterey California. Naval Postgraduate School).*

Joshi, R., Singh, J., & Vig, A. P. (2015). Vermicompost as an effective organic fertilizer and biocontrol agent: effect on growth, yield and quality of plants. *Reviews in Environmental Science and Bio/Technology*, *14*, 137-159.

K. Brimo, S. Ouvrard, S. Houot, F. Lafolie, P. Garnier. (2018). Modelling the fate of PAH added with composts in amended soil according to the origin of the exogenous organic matter. *Sci. Total Environ., 616–617 (2018), pp. 658-668*

Katusiimeh, M. W. (2012). Public and private service provision of solid waste management in Kampala, Uganda. *Wageningen University and Research*.

Khan, M. S., Mubeen, I., Caimeng, Y., Zhu, G., Khalid, A., & Yan, M. (2022). Waste to energy incineration technology: Recent development under climate change scenarios. *Waste Management & Research*, *40*(12), 1708-1729.

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

Kinobe, J. R., Gebresenbet, G., Niwagaba, C. B., & Vinnerås, B. (2015). Reverse logistics system and recycling potential at a landfill: A case study from Kampala City. *Waste Management*, *42*, 82-92.

Komakech, A. J. (2014). *Urban waste management and the environmental impact of organic waste treatment systems in Kampala, Uganda*. Department of Energy and Technology, Swedish University of Agricultural Sciences.

Kondusamy, D., & Kalamdhad, A. S. (2014). Pre-treatment and anaerobic digestion of food waste for high rate methane production–A review. *Journal of Environmental Chemical Engineering*, *2*(3), 1821-1830.

Kulabako, R. N., Nalubega, M., Wozei, E., & Thunvik, R. (2010). Environmental health practices, constraints and possible interventions in peri-urban settlements in developing countries–a review of Kampala, Uganda. *International journal of environmental health research*, *20*(4), 231-257.

Kulyanyingi, V. (2002). Economic losses/gains attributed to the water hyacinth.

Kumar, S., Dheeran, P., Singh, S. P., Mishra, I. M., & Adhikari, D. K. (2013). Cooling system economy in ethanol production using thermotolerant yeast Kluyveromyces sp. IIPE453. *Am J Microbiol Res*, *1*(3), 39-44.

Kumartasli, S., & Avinc, O. (2020). Recycling of marine litter and ocean plastics: A vital sustainable solution for increasing ecology and health problem. *Sustainability in the Textile and Apparel Industries: Sourcing Synthetic and Novel Alternative Raw Materials*, 117-137.

L. Abbey, M. Ijenyo, B. Spence, A.O. Asunni, R. Ofoe, V. Amo-Larbi. (2021). Bioaccumulation of chemical elements in vegetables as influenced by application frequency of municipal solid waste compost. *Can. J. Plant Sci., 101 (2021), pp. 967-983* https://www.sciencedirect.com/science/article/pii/S2949919423000389

Li, W., Sun, Y., Li, G., Liu, Z., Wang, H., & Zhang, D. (2017). Contributions of nitrification and denitrification to N2O emissions from aged refuse bioreactor at different feeding loads of ammonia substrates. *Waste Management*, *68*, 319-328.

Liebeschuetz, W. (2015). Rubbish Disposal in Greek and Roman Cities. In *East and West in Late Antiquity* (pp. 1-18). Brill.

Liebeschuetz, W. (2015). 1 Rubbish Disposal in Greek and Roman Cities. In *East and West in Late Antiquity* (pp. 1-18). Brill.

Lim, S. L., Lee, L. H., & Wu, T. Y. (2016). Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: recent overview, greenhouse gases emissions and economic analysis. *Journal of cleaner production*, *111*, 262-278.

Louis, G. E. (2004). A historical context of municipal solid waste management in the United States. *Waste management & research*, *22*(4), 306-322.

Louis, G. E. (2004). A historical context of municipal solid waste management in the United States. *Waste management & research*, *22*(4), 306-322.

M.I. Al-Sari, M.A.A. Sarhan, I.A. Al-Khatib. (2018). Assessment of compost quality and usage for agricultural use: a case study of Hebron, Palestine. *Environ. Monit. Assess., 190 (2018), p. 223*

M.K. Awasthi, A.K. Pandey, J. Khan, P.S. Bundela, J.W. Wong, A. Selvam. (2014). Evaluation of thermophilic fungal consortium for organic municipal solid waste composting. *Bioresour. Technol., 168 (2014), pp. 214-221*

Malandrino, P., Russo, M., Gianì, F., Pellegriti, G., Vigneri, P., Belfiore, A., ... & Vigneri, R. (2020). Increased thyroid cancer incidence in volcanic areas: a role of increased heavy metals in the environment?. *International journal of molecular sciences*, *21*(10), 3425.

Medina, M. (2010). Solid wastes, poverty and the environment in developing country cities. *World Institute for Development Economic Research (UNUWIDER) Working Papers*.

Melikoglu, M. (2013). Vision 2023: Assessing the feasibility of electricity and biogas production from municipal solid waste in Turkey. *Renewable and Sustainable Energy Reviews*, *19*, 52-63.

Melosi, M. V. (2004). *Garbage in the Cities: Refuse reform and the Environment*. University of Pittsburgh Pre.

Meneguz, M., Schiavone, A., Gai, F., Dama, A., Lussiana, C., Renna, M., & Gasco, L. (2018). Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (Hermetia illucens) larvae. *Journal of the Science of Food and Agriculture*, *98*(15), 5776-5784.

Minakshi, M. (2014). Solid Waste as a Major Environment Problem in Major Cities: A Case Study of Chandigarh. *Int. J Rec Res Asp*, (2), 278-282.

Minakshi, M. (2014). Solid Waste as a Major Environment Problem in Major Cities: A Case Study of Chandigarh. *Int. J Rec Res Asp*, (2), 278-282.

Moehring, E. P. (1998). Joanne Abel Goldman. Building New York's Sewers: Developing Mechanisms of Urban Management.(History of Technology Series.) West Lafayette, Ind.: Purdue University Press. 1997. Pp. xvii, 228. $29.95.

Morse, W. F. (1908). *The collection and disposal of municipal waste*. Municipal Journal and Engineer.

Muheirwe, F., Kombe, W. J., & Kihila, J. M. (2024, March). Solid waste collection in the informal settlements of African cities: a regulatory dilemma for actor's participation and collaboration in Kampala. In *Urban Forum* (Vol. 35, No. 1, pp. 1-22). Dordrecht: Springer Netherlands.

Muthuraman, L., & Ramaswamy, S. (2019). *Solid Waste Management*. MJP Publisher.

Navarro, R. A. (2003). A Systems Approach on Solid Waste Management in Metro Manila, Philippines. *Unpublished thesis for Masters in Environmental Science, Lund University Sweden*.

Ngatia, L., Grace III, J. M., Moriasi, D., & Taylor, R. (2019). Nitrogen and phosphorus eutrophication in marine ecosystems. *Monitoring of marine pollution*, *1*, 1-17.

Nicholas, W. (2018). Effects of solid waste management practices on the local people's general health: A case study of Makindye Division, Kampala Uganda (*Doctoral dissertation, Nkumba University*).

Noor, T., Javid, A., Hussain, A., Bukhari, S.M., Ali, W., Akmal, M. and Hussain, S.M., (2020). Types, sources and management of urban wastes. In *Urban ecology* (pp. 239-263). Elsevier.

P. Castaldi, D. Demurtas, M. Silvetti, S. Deiana, G. Garau. (2017). Interaction of the water soluble fraction of MSW-composts with Pb(II) and Cu(II) ions. *J. Environ. Manag., 192 (2017), pp. 39-47*

Panhota, R. S., da Cunha Santino, M. B., & Bianchini Jr, I. (2023). Oxygen consumption and formation of recalcitrant organic carbon from the decomposition of free-floating macrophyte leachates. *Environmental Science and Pollution Research*, *30*(45), 101379-101391.

Parkar, S., Mulukh, R., Narhari, G., & Kulkarni, S. (2021, May). An insight into treatment, reuse, recycle and disposal of biodegradable and non-biodegradable solid waste. In *Proceedings of the 4th International Conference on Advances in Science & Technology (ICAST2021)*.

Pawan, M. (2014). Impacts of Global Warming on Environment. *International Research Journal of Environmental Sciences*, *3*(3), 72-78.

Pollans, L. B. (2021). *Resisting garbage: The politics of waste management in American cities*. University of Texas Press.

Pongrácz, E. (2002). Re-defining the concepts of waste and waste management: Evolving the Theory of Waste Management.

Pongrácz, E. and Pohjola, V.J., (2004). Re-defining waste, the concept of ownership and the role of waste management. *Resources, conservation and Recycling*, *40*(2), pp.141-153.

Purkayastha, D., & Sarkar, S. (2022). Black soldier fly larvae for treatment and segregation of commingled municipal solid waste at different environmental conditions. *Journal of Environmental Management*, *302*, 114060.

Puyol, D., Batstone, D. J., & Krömer, J. O. (2017). Resource recovery from wastewater by biological technologies: opportunities, challenges, and prospects. *Frontiers in microbiology*, *7*, 218193.

Qiu, Y., Wang, P., Guo, Y., Zhang, L., Lu, J., & Ren, L. (2023). Enhancing food waste reduction efficiency and high-value biomass production in Hermetia illucens rearing through bioaugmentation with gut bacterial agent. *Science of The Total Environment*, *904*, 166488.

R. Barrena, X. Font, X. Gabarrell, A. Sanchez. (2014). Home composting versus industrial composting: influence of composting system on compost quality with focus on compost stability. *Waste Manag., 34 (2014), pp. 1109-1116*

R. Couth, C. Trois. (2012). Sustainable waste management in Africa through CDM projects. *Waste Manag., 32 (2012), pp. 2115-2125*

Rafiq, A., Rasheed, A., Arslan, C., Tallat, U., & Siddique, M. (2018). Estimation of greenhouse gas emissions from Muhammad wala open dumping site of Faisalabad, Pakistan. *Geology, Ecology, and Landscapes*, *2*(1), 45-50.

Rajpal, L. (2002). An investigation into solid waste management practices in residential areas the case of the Phoenix township (*Doctoral dissertation*).

Richard, T. L. (1992). Municipal solid waste composting: physical and biological processing. *Biomass and bioenergy*, *3*(3-4), 163-180.

Richard, T. L. (1992). Municipal solid waste composting: physical and biological processing. *Biomass and bioenergy*, *3*(3-4), 163-180.

Roberts, G. K. (2005). Technologies of water, waste and pollution. In *American Cities and Technology* (pp. 141-172). Routledge.

Rodić, L., & Wilson, D. C. (2017). Resolving governance issues to achieve priority sustainable development goals related to solid waste management in developing countries. *Sustainability*, *9*(3), 404.

Saha, L., Kumar, V., Tiwari, J., Rawat, S., Singh, J., & Bauddh, K. (2021). Electronic waste and their leachates impact on human health and environment: Global ecological threat and management. *Environmental Technology & Innovation*, *24*, 102049.

Salam, M., Alam, F., Dezhi, S., Nabi, G., Shahzadi, A., Hassan, S. U., ... & Bilal, M. (2021). Exploring the role of Black Soldier Fly Larva technology for sustainable management of municipal solid waste in developing countries. *Environmental Technology & Innovation*, *24*, 101934.

Sánchez, Ó. J., Ospina, D. A., & Montoya, S. (2017). Compost supplementation with nutrients and microorganisms in composting process. *Waste management*, *69*, 136-153.

Sarc, R., & Lorber, K. E. (2013). Production, quality and quality assurance of Refuse Derived Fuels (RDFs). *Waste management*, *33*(9), 1825-1834.

Sardar, H., Ali, M. A., Anjum, M. A., Nawaz, F., Hussain, S., Naz, S., & Karimi, S. M. (2017). Agro-industrial residues influence mineral elements accumulation and nutritional composition of king oyster mushroom (Pleurotus eryngii). *Scientia Horticulturae*, *225*, 327-334.

Sezer, K., Albay, M. K., Ozmen, O., Haligur, M. E. H. M. E. T., Sahinduran, S., Mor, F., & Koker, A. (2011). Haematological, biochemical and thyroid gland investigations in pregnant cows and in calves chronically intoxicated with nitrate. *Revue Med. Vet*, *162*(5), 223-228.

Sharholy, M., Ahmad, K., Mahmood, G., & Trivedi, R. C. (2008). Municipal solid waste management in Indian cities–A review. *Waste management*, *28*(2), 459-467.

Sharma, B., Vaish, B., Srivastava, V., Singh, S., Singh, P., & Singh, R. P. (2018). An insight to atmospheric pollution-improper waste management and climate change nexus. *Modern age environmental problems and their remediation*, 23-47.

Sharma, K., & Garg, V. K. (2019). Vermicomposting of waste: a zero-waste approach for waste management. In *Sustainable resource recovery and zero waste approaches* (pp. 133-164). Elsevier.

Sharma, K., & Garg, V. K. (2019). Vermicomposting of waste: a zero-waste approach for waste management. In *Sustainable resource recovery and zero waste approaches* (pp. 133-164). Elsevier.

Sharma, K., & Garg, V. K. (2023). Vermicomposting technology for organic waste management. In *Current Developments in Biotechnology and Bioengineering* (pp. 29-56). Elsevier.

Shekdar, A. V. (2009). Sustainable solid waste management: An integrated approach for Asian countries. *Waste management*, *29*(4), 1438-1448.

Shekdar, A. V. (2009). Sustainable solid waste management: An integrated approach for Asian countries. *Waste management*, *29*(4), 1438-1448.

Singh, N., Hui, D., Singh, R., Ahuja, I. P. S., Feo, L., & Fraternali, F. (2017). Recycling of plastic solid waste: A state of art review and future applications. *Composites Part B: Engineering*, *115*, 409-422.

Sinha, R. K., Herat, S., Bharambe, G., Patil, S., Bapat, P., Chauhan, K., & Valani, D. (2009). Human waste-apotential resource: Converting trash into treasure by embracing the 5 r's philosophy for safe and sustainable waste management. *Environ. Res. J, 3*, 143.

Sophie, K. (2019). *Street vending and the economic development of Kampala City* (Doctoral dissertation, Kampala International University: College of Humanities and Social Sciences).

Srivastava, R. K., Shetti, N. P., Reddy, K. R., & Aminabhavi, T. M. (2020). Sustainable energy from waste organic matters via efficient microbial processes. *science of the total environment*, *722*, 137927.

Stokes, S., La, M., & Lowe, M. (2014). This research was prepared on behalf of Environmental Defense Fund.

T. Cestonaro, R.T. de Vasconcelos Barros, A.T. de Matos. (2022). Municipal composting facility: is it possible to produce a compost that complies with legislation over time?

T. Cestonaro, R.T.D.V. Barros, A.T.D. Matos. (2019). Spatial and temporal variability of the chemical characteristics of food waste and green waste: influence on their sampling and composting. *Int. J. Environ. Waste Manag., 24 (2019), pp. 1-20*

Townsend, T. G., Ingwersen, W. W., Niblick, B., Jain, P., & Wally, J. (2019). CDDPath: A method for quantifying the loss and recovery of construction and demolition debris in the United States. *Waste management*, *84*, 302-309.

Trivedi, M., Mathur, M., Johri, P., Singh, A., & Tiwari, R. K. (2020). Waste management: A paradigm shift. *Environmental Concerns and Sustainable Development: Volume 2: Biodiversity, Soil and Waste Management*, 337-363.

V. Asensio, C.H. Abreu-Junior, F.C. da Silva, J.C. Chitolina. (2018). Evaluation of chemical extractants to assess metals phytoavailability in Brazilian municipal solid waste composts. *Environ. Pollut., 243 (2018), pp. 1235-1241*

Vaish, B., Srivastava, V., Singh, P., Singh, A., Singh, P. K., & Singh, R. P. (2016). Exploring untapped energy potential of urban solid waste. *Energy, Ecology and Environment*, *1*, 323-342.

W.Y. Chia, K.W. Chew, C.F. Le, S.S. Lam, C.S.C. Chee, M.S.L. Ooi, P.L. (2020). Show Sustainable utilization of biowaste compost for renewable energy and soil amendments. *Environ. Pollut., 267 (2020), Article 115662*

Wamalwa, K. (2016). Heavy metals, phosphates and nitrates levels in vegetables: A case study of Kitale Municipality, Trans-Nzoia County, Kenya. *Phosphates and Nitrates Levels in Vegetables: A Case Study of Kitale Municipality, Trans-Nzoia County, Kenya (April 9, 2016)*.

Wang, X., Lu, X., Li, F., & Yang, G. (2014). Effects of temperature and carbon-nitrogen (C/N) ratio on the performance of anaerobic co-digestion of dairy manure, chicken manure and rice straw: focusing on ammonia inhibition. *PloS one*, *9*(5), e97265.

Watson, R. T., Boudreau, M. C., Chen, A., & Huber, M. (2008). Green IS: Building sustainable business practices. *Information systems*, *17*.

Wolf, U. (2014). *Emission of NH3, N2O and CO2 following the application of differently treated digestates from biogas production* (Doctoral dissertation, Dissertation, Braunschweig, Technische Universität Braunschweig).

Yang, Z., Muhayodin, F., Larsen, O. C., Miao, H., Xue, B., & Rotter, V. S. (2021). A review of composting process models of organic solid waste with a focus on the fates of C, N, P, and K. *Processes*, *9*(3), 473.

Zhou, X., Potoka, D. A., Boyle, P., Nadler, E. P., McGinnis, K., & Ford, H. R. (2002). Aminoguanidine renders inducible nitric oxide synthase knockout mice more susceptible to Salmonella typhimurium infection. *FEMS microbiology letters*, *206*(1), 93-98.

Zuberer, D. A., & Zibilske, L. M. (2021). Composting: The microbiological processing of organic wastes. In *Principles and applications of soil microbiology* (pp. 655-679). Elsevier.

Appendices

Appendix 1: Sorting oof Municipal Solid Waste

Appendix 2: Shredding of waste