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ASSESSING THE POTENTIAL OF USING COAL ASH AND BAGASSE ASH AS INORGANIC AMENDMENT IN THE COMPOSTING PROCESS OF MUNICIPAL SOLID WASTES: IMPROVEMENTS IN COMPOST QUALITY FOR AGRONOMIC APPLICATION

Final Report

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RESEARCH PROJECT REPORT

ASSESSING THE POTENTIAL OF USING COAL ASH AND BAGASSE ASH AS INORGANIC AMENDMENT IN THE COMPOSTING PROCESS OF MUNICIPAL SOLID WASTES: IMPROVEMENTS IN COMPOST QUALITY FOR AGRONOMIC APPLICATION

Part 1: Effects Of Coal Ash And Bagasse Ash In The Composting Process Of Municipal Solid Wastes

Submitted to the
Mauritius Research Council
Ebène, Mauritius

Under the
Research on Coal Ash Management in Mauritius (MRC/RUN-ASH)

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ABSTRACT

Mounting demand of electricity consumption, fuelled by the rapid modernisation and ever-growing population, has risen up the use of coal, with an inclination towards bagasse utilisation as well in the line of sustainable energy consumption. Improper disposal of ashes generated by the combustion of these energy sources is creating havoc and this has resulted in the quest of technologies that would swallow up and stabilise these ashes. In this respect, the use of coal ash and bagasse ash as amendment in the composting process was investigated. 10 composting drums were set up as follows: A -20% bagasse ash with unsorted municipal solid wastes (MSW); B-40% bagasse ash with unsorted MSW; C - unsorted MSW only; D -20% bagasse ash with sorted MSW; E - 40% bagasse ash with sorted MSW; F- sorted MSW only; G -20% coal ash with unsorted MSW; H - 40% coal ash with unsorted MSW; I -20% coal ash with sorted MSW and J- 40% coal ash with sorted MSW. Moisture content was maintained within 53.56-63.12% after first adjustment. Setups D, F, G and I achieved a retention time of at least 3 days above 550C with the following peak temperature: D–620C, F–570C, G–620C and I-580C. D and G resulted in the highest VS degradation of 68.59% and 58.41% to yield the highest volume reduction of 66.07 and 64.29% for the sorted and unsorted category respectively. Compost quality tests were performed on D, G, I and the controls C and F. All the composted masses were within range in terms of electrical conductivity (794-1771µS/cm) and pH (6.69-7.12) and exhibited comparable water holding capacities (183.18 – 216.79%). C/N ratio of sorted wastes was improved by the addition of 20% coal ash and bagasse ash. Higher Germination indices, all above 0.8%, were attributed to the ash-amended compost (D, G, I) as compared to their respective controls, indicating the feasibility and enhancement of using bagasse and coal ash as inorganic amendment in the composting process in the following proportion: 20% bagasse ash in sorted wastes and 20% coal ash in sorted and unsorted wastes. In terms of heavy metal content, while the composting mix G exceeded in final chromium concentration, the other ash amended wastes (D and I) showed compliance with the MS 164 standards indicating no problematic issue in land application of these composted masses.

Keywords: Bagasse ash, coal ash, composting, MSW, sorted, unsorted

1   INTRODUCTION

1.1   The problem

1.1.1   Ash mismanagement

December 22, 2008 imaged one of the largest environmental disasters of its kind in United States with the failing of a dike that had been restraining decade's worth of coal ash (US EPA, 2009a). This breach unleashed 1.1 billion gallons of coal ash slurry that engulfed the whole Tennessee Valley into toxicity in its wake (Luther, 2010). Testing of surrounding water revealed extremely dangerous levels of arsenic, mercury and other toxins, with arsenic level up to 149 times higher than usual, highlighting the gravity of that incident (Luther, 2010; US EPA, 2009a; US EPA, 2009b). The Tennessee incident was not an unprecedented one; the year 2005 saw a dam confining surface impoundment, discharging tons of coal ash in Delaware River and before that, a similar failure was observed at Plant Bowen in Georgia, 2002 (Earth Justice, 2009). Despite such historical teachings, ashes are continually being deposited in precarious surface waste ponds, impoundment and abandoned mines and unfortunately, while people require such dramatic events as eye-openers, the quiet daily seeping of contaminants from coal ash dumps into groundwater remains unnoticed and they continue their pathway to increase the risk of exposing people and wildlife to toxic substances (Earth Justice, 2009). Dumping in landfills as well has been a long common method, though it seemed that realisation of the hazardous characteristics of coal ash and combustion wastes started to sink in for the regulations have raised the costs of landfill disposal, driving the search for new means of ash management (Nurmesniemi *et al*.). Other than landfills, the use of combustion ash is being incorporated in road construction, reclaiming of acid mine sites and reducing acid mine drainage, from which, however, leaching from improperly lined surface is very probable (Bruder-Hubscher *et al*., 2001; Dick *et al*., 1999; Tedesco *et al*., 1999; Luther, 2010). While innovative uses including soil and water remediation through heavy metal adsorption by the ashes also emerged, the disposal of the used adsorbents remained a problem leading back to the same initial issue of ash management (Balsamo *et al*., 2011; Lin *et al*., 2008; Gupta *et al*., 2012).

1.1.2   Rise in energy demand fuelling the problems of ash management

The desire to sustain and continuously improve the well-being of ourselves, our families and our communities has fuelled the consumption of energy to heights whereby a prediction of about 30% raise has been made , out of which electricity generation will account for 40% of global energy consumption (The Outlook for energy, 2012). In accordance to such increasing power demand, the use of coal in thermoelectric power plants is rapidly increasing (Yeon and Kim, 2011), accounting for 57% of the electricity produced in US and more than 40% of the world electricity generation (Bardhan *et al*., 2009). As per The Energy Outlook (2012), within these years, coal along with oil and gas will be the most widely used fuel, with coal reaching its peak demand. However, in this era where

depletion of fossil reserves is shifting our attention to the use of renewable sources, the concept of not infinitely depending on coal and other fossil fuels seems to have finally implanted in the human mind; energy generation form biomass as a sound and friendly alternative is being implemented (Nurmesniemi *et al*.) . The Energy outlook (2012) confirms this environmental- oriented behaviour by stating that though population growth and economic growth will drive demand higher, the world will use energy in more efficient manner, shifting forward to sustainable alternatives.

However, from an environmental point of view, exploiting energy sources may lead to unwanted and damaging by-products; generation of ashes from coal and biomass burning being one of them (Rouhier, 2009). Hence, while energy resource utilisation is increasing, the task of securing the repository of these wastes has become an urgent task (Metha, 1984; Yeon and Kim, 2011).

1.2 Composting as an alternative

1.2.1 Composting as a solid waste management program

Knowingly or unknowingly, the advanced human civilisation with its ever growing tertiary consumers are increasingly contributing to thousands of tons of solid wastes daily, which if not channelled effectively might engulf us within it (Norbu, 2002). Through littering of the land or solid adsorption of leachate, leaching or direct dumping of wastes in our aqueous systems and release of greenhouse gases and other air pollutants to the atmosphere (Environmental guidelines for the USAID Latin America and Caribbean bureau), solid waste mismanagement *ironicall*y proceeds towards a *holistic approach* to pollute the whole environment. While these wastes were traditionally landfilled, being limited in terms of land resources, this tradition is no longer able to cope with the rapid urbanization and industrialisation that keeps flourishing the amount of wastes produced (Asgharipour and Sirousmehr, 2012). Every government in the world is currently focussing on methods to tackle this challenge and many authors have experimented with various technological options in the search for viable alternatives (Schwarz-Herion *et al*., 2008). This brought much focus on **composting** which is one of the most versatile, remunerative, viable and acceptable techniques for handling biodegradable solid wastes (Gajalakshmi and Abbasi, 2008). Under controlled conditions, complex organic materials are transformed into a soil-like material (compost) which found its uses in many agricultural applications to improve soil fertility (Vining, 2002). Hence, composting not only reduces the volume of Municpal Solid wastes (MSW) as landfill siting becomes for difficult and expensive, it as well provides a useful resource for plant growth (Vining, 2002).

1.2.2 Composting as an option to ash management

By overriding the option of wastes incineration, the adoption of composting technology itself reduces the amount of ash produced (Beffa, 2002); Incorporating ash as amendment in composting process is another method. According to Kuba *et al*. (2008) nutrients and micronutrients contents in ashes suggest a use of ash as fertilizers, either in its pure form, pelleted or in combination with other

materials, in particular nitrogen containing compounds. Based on such criteria, various authors have ventured in the domain of using ash like wood ash (Kuba *et al.*, 2008; Bougnom *et al.*, 2010;Tezuka *et al.*, 2012 ;Carpenter and Beecher, 1997) , fuel ash (Koivula *et al.*, 2004), and coal ash (Ravikumar *et al.*, 2008; Gain and Gaur, 2003;Wong *et al.*, 2009; Belyaeva and Haynes, 2009a; Ananthakrishnasamy *et al.*, 2009; Punjwani *et al.*, 2011; Fang *et al.*, 97, 98, 99; Wong *et al.*, 1995; Lau *et al.*, 2001; Chiang *et al.*, 2007) as amendments to improve the composting process and have succeeded in their trials.

1.3 The proposed study

1.3.1 Coal ash and bagasse ash as amendment

Globally, around 500 million tonnes of coal ash is emerging from coal combustion, with Mauritius contributing to load of about 70,500 tonnes per year. Out of these, 20,000 tonnes are being produced from coal burnt by the Sugar Industry during the intercrop season (Oogathoo, 2012). With the advent of a 39% decrease in sugar prices by the European Union Sugar Regime, coupled with the Maurice Ile Durable concept of questing for existing potential for sustainable energy, during the crop season, the sugar industry is also moving towards the use of renewable biomass in the form of bagasse to contribute to the generation of electricity; this results in the generation of about 20,000 tons of bagasse ash yearly (Oogathoo, 2012). Mauritius expects an annual energy growth of 6% with a recorded increase of 43.7% energy imports from the year 2009-2010 (CSO, 2010); targeted visions like 24/7, treble GDP and two-million tourists will continue to stimulate the demand for more energy (Elahee, 2012), increasing the consumption of coal and bagasse as fuel input and as a result increasing the generation of coal and bagasse ashes.

1.3.2 Municipal solid wastes as the main substrate

Commonly known as trash or garbage, MSW refers to those discarded materials that include predominantly residential wastes together with commercial and institutional wastes (Republic of Mauritius, 2010). In 2011, Mauritius recorded an amount of 414, 543 tonnes of wastes being land filled at the Mare Chicose Sanitary landfill which were initially receiving only about 6, 800 tons of wastes (Mohee *et al.*, 2002; CSO, 2011). Such abuse of land capacity led to its saturation and Mauritius, being a small island, is limited in terms of land resources thus writing off the option of a new landfill. Composting then emerged as a helping hand in the alleviation of solid waste management in Mauritius; with a capacity to accept about 300 tons of wastes daily or 90,000 tons of wastes annually, the dawn of a composting facility at la Chaumiere decreased the amount of wastes that were land filled by 16% in 2012 (Mohee *et al.*, 2012). While the plant is actually treating unsorted MSW, it is intended to implement a sorting line with the aim of doubling the plant's capacity and further reducing the amount of wastes being land filled (Mohee *et al.*, 2012). Hence, in the aim of considering both the actual situation and the future targets, this study shall investigate the effect of ash

addition on both sorted and unsorted wastes. Moreover, MSW being the largest proportion of wastes that is composted on large scale in Mauritius, incorporating the ashes in the most largely composted wastes will maximise the quantity of ashes that can be disposed of.

1.3.3   Aims and Objectives

The aim of this study is to assess the potential of using coal ash and bagasse ash as an inorganic amendment in the process of composting. More specifically, the objectives involve:

1. Addition of coal ash and bagasse ash with sorted and unsorted municipal solid wastes in different proportions and composting these mixes in composting drums

2. Monitoring of temperature, pH, moisture content, volatile solids, electrical conductivity, total organic carbon and organic mass reduction rate (decrease on net carbon content), total Kjeldahl nitrogen, heavy metal contents and respiration rate of the composting mix

3. Determining the best composting mix for the composting of sorted and unsorted wastes with coal ash and bagasse ash

4. Assessing the quality of composts produced from the different treatments, in terms of heavy metals, water holding capacity, bulk density, nitrogen content, C/N ratio and phytotoxicity bioassay

2 LITTERATURE REVIEW

2.1 COMPOSTING PROCESS

2.1.1 Microbiology and microorganism

Composting has been termed as a controlled microbiological process mediated by a succession of mixed microbial populations, in the presence of nutrients and oxygen, to break heterogeneous organic materials into a stable organic mass (Keener *et al.*, 1997; Keener *et al.,* 2000; Beffa, 2002). However, many of those microorganisms are individually incapable of full mineralisation; the intermediate products formed will either serve as a substrate for the other microorganism whereby the full mineralisation will be ensured or, they will remain as residue in the composting material (Bardos, 2004). Considering such complexity of substrate and intermediates, microbial diversity and succession of populations is a must for complete biodegradation; such population and community changes is a continuous process dependent on the evolution of temperature, nutrient availability, oxygen concentration, water content and pH during composting (Rebollido *et al.*, 2008; Beffa, 2002).

2.1.2 Phases and microorganisms

Composting phases are delineated by the different temperatures involved, with the mesophilic range of ambient temperatures up to 40^0C defining the first stage of composting (Bardos, 2004; Norbu 2002; Beffa, 2002). At such early stage of the composting process, the microbial population in the fresh wastes is dominated fungi (essentially molds) and acid producing bacteria which initiate the decomposition process and liberate heat as a result of microbial activity (Bardos, 2004; Norbu 2002; Beffa, 2002). The raise in temperature shifts the phase to a thermophilic range, characterised by a temperature of above 45^0C, where thermophilic bacteria and actinomycetes replace the mesogenic microorganisms (Beffa, 2002; Norbu, 2002; Finstein and Morris, 1975). The fungi population holds up only to an optimal growth temperature of 40-50^0C; actinomycetes are more tolerant to higher temperatures with a marked increase in its population at 50-60^0C (Beffa, 2002). Thermophilic phase accelerates the breakdown of protein, fats, starches, and more complex carbohydrates like cellulose, hemi-cellulose (Finstein and Morris, 1975; Norbu 2002; Pace *et al.*, 1995). When these readily degradable substrates are exhausted, the composting phase reaches a phase known as the cooling and maturation phase, where fungal activity will be resumed (Bardos, 2004; Anid, 1986; Beffa, 2002). This phase is involved in the slow degradation of more complex polymers such as lignin and lingo-cellulose mainly through the action of basidomycete fungi (Zach *et al.*, 2000). Also, as the end of maturation phase approaches, the following occurs: abatement of phytotoxicity through degradation of toxic compounds and detoxification of heavy metals through the formation of insoluble salts; oxidation and mineralization of inorganic nitrogen to form nitrates as well as atmospheric nitrogen fixation by nitrifying bacteria and; humification through the polymerisation of simple organic compounds (Zach *et al.*, 2000; Beffa, 2002). As the temperature continues its descent, the composted mass will be invaded by a range of animals that were not able to tolerate the higher temperatures of

the thermophilic stages (Bardos, 2004). The succession of microorganisms throughout the phases is generally an increase of each group to its peak population at optimum conditions; one group of microorganisms dies off while another thrives until the next incremental change in temperature/nutrition occurs (Norbu, 2002).

2.1.3 Composting technologies

Windrow	Aerated Static pile	In-vessel
Composting materials are placed in elongated piles or rows according to a regime that favours maximum rate of degradation: • Wastes are arranged in a triangular cross section of height of 2-3 m and width 3-6m to form a structure large enough to generate heat and maintain the pile temperature and small enough to allow oxygen diffusion through the pile. • Turning is carried out to expose fresh surfaces to the degradation process, to re-introduce air and prevent anaerobic build-up (Bardos, 2004; Beffa, 2002; Norbu, 2002; US EPA, 1995)	• Piles of wastes are arranged on a network of pipes that are connected to a blower installed for controlled aeration. • Presence of blowers write off the need for mechanical turning and the pile, once constructed remains static. • Piles are usually covered with an insulating material like recycled compost to retain the heat during thermophilic conditions as well as to minimise odour and emissions. • Aerated static piles offer the advantage of faster throughout and lower land requirements than windrows with however some hurdles in ensuring adequate moisture level within the pile as well as sufficient aeration and temperature control. (Bardos, 2004l; US EPA, 95)	• Composting materials are enclosed in a vessel referred to as a reactor or bioreactor. • In-vessel composting allows close tailoring of temperature, moisture and air, enabling a better control of composting parameters, odours as well as leachate formation. • The contents are mixed and turned at regular intervals to homogenize the mixture and provide an enhanced rate of oxygen transfer. • After the contents have been discharged from the vessel, further composting (curing) is required to complete the degradation of the remaining materials (Abboud and Heidman, 2002; Bardos, 2004; US EPA, 95)

2.1.4 Parameters influencing composting process

2.1.4.1 Temperature and rate of reaction

The temperature controlling process, termed as a "*central issue in composting process design*" by Finstein *et al*. 1992, is the key factor to achieve maximum microbial activity (Finstein *et al*., 1992; Miller, 1993). Temperature is an indicator of, as well as an influence to microorganisms' activity: Heat developed as a result of exothermal-biological reaction is retained by the composting material which has good insulation properties and is reflected in the form of temperature raise (Norbu, 2002). This increase in temperature influences the biochemical process by doubling its rate with every 10^0C rise, hence enhancing decomposition (Bardos, 2004; Richard *et al*., 1993. A decrease in temperature below 32^0C will on the other hand slow down the degradation process (Norbu, 2002).Temperature changes also affect the microbial composition of the community of organism undertaking the composting process (Bardos, 2004); Composting is governed by two temperature phases namely mesophilic (25- 40^0C) and thermophilic (> 45^0C) which lead to the domination of certain species at a given temperature depending on their activation temperatures (Zeng, 2011).

2.1.4.2 Temperature and pathogen reduction

The mutual interaction between microbial activity and temperature raise is carefully monitored to achieve the principal aim of maintaining a steady thermophilic range where the most rapid and extensive degradation, as well as sanitisation will be ensured (Bardos, 2004; Epstein 1998). Sanitisation is important for the elimination of pathogens such as infectious bursal disease, virus, salmonella, coliform bacteria as well as weeds seeds and fly larvae in the composting mass (Pace *et al*., 1995; CCME, 2005). Desired range of pathogen-destroying temperature has been reported as being between $55^0 – 60^0$C by Finstein *et al*. (1992) and greater than 55^0C by Susan (1994), CCME (2005), US EPA (1995) and Haug (1993). Pathogen reduction, being a function of time and temperature, Finstein *et al*. (1992) also recommended a time period of at least 3 days throughout the whole compost volume. US EPA (1995) agrees with this reporting while additionally precising that a time period of 3 days at temperatures greater than 55^0C applies to in-vessel composting; for windrow composting, a minimum of a 15 days is required to achieve pathogen destruction. CCME (2005) stated a similar time period of 15 days for windrow composting.

While continued temperature build up above 55^0C in the composting matrix will further enhance heat inactivation of pathogens, a trade off between sanitisation and composting rate was found to be necessary as only a limited range of microorganisms are able to tolerate temperature ranges above 65^0C, thereby limiting the reaction rate above 65^0C (Bardos, 2004). In order to maintain the temperature at optimum reported values [65^0C (Norbu, 2002), 60^0 (Bardos and Lopez-Real, 1989; Bardos, 2004)], aeration is usually employed to promote evaporative loss (Finstein and Hogan, 1993).

2.1.4.3 *Temperature and aeration*

Expressed as an "aerobic" process, it goes without saying that composting requires oxygen to function; a need that is accomplished through aeration (US EPA, 1995). The role of aeration is to supply oxygen in amounts sufficient enough to firstly power the microbial activities to such levels that ensure the development of pathogen-destructing temperatures and rapid rate of degradation (Zeng *et al*., 2003). Miller (1993) reported a range of $12 - 14\%$ of minimal interstitial oxygen to warrant the continued progress of microbial activity and a similar range of $10 - 15\%$ was a recommended by US EPA (1995). Being a governing parameter, temperature was found to be a useful indicator to monitor oxygen consumption and oxygen level as well (Fraser, 1997). Based on several studies, Haug (1993) highlighted the behaviour of oxygen consumption increasing with increasing temperature. Related to this observation, he evidenced it with case studies showing an increase in oxygen consumption to an optima of $40\text{-}60^0C$ as well as with cases reporting an increase up to 70^0C; the difference being linked to cellulosic content of substrate. Aeration is also an important parameter to enhance volatilisation as a means of temperature control (Zeng *et al*., 2003).

Aeration is achieved by passive diffusion and natural air convection in the composting mass whereby warm air rises to the top, allowing cool air to be sucked in; by regular turning of the compost to physically break down the composting mass allowing incorporation of cool fresh air and escape of carbon dioxide; by forced aeration (-ve or +ve) to mechanically blow fresh air into or remove exhausted air for odour treatment. (EC Project, 1990; Lofgren, 1979; Sesay *et al.,* 1998; Epstein 1997; Morse, 2001).

While according to Morse (2001) a level of oxygen less than 5% will induce anaerobic conditions inhibiting the microbial activity and leading to odorous and slow degradation (Dougherty, 1999; Keener *et al*., 2000; Kalbasi *et al*., 2005), care must also be taken to avoid excess air supply since this action might cause an excess removal of heat cooling the composting mass to temperature lower than required and as a result slow down the composting rate (US EPA, 1995).

2.1.4.4 *Moisture*

"Microbes only utilize nutrients dissolved in water" (Zeng *et al*., 2003). Water hence acts as an important medium for nutrients transport and chemical exchanges that are necessary to support the growth of microorganism and their metabolic activities (Zeng, 2011; Pace *et al*., 1995). Optimal starting moisture content for MSW appears to be mostly in the range of 50-60% based on the below tabulated literature findings, while some authors went up to 40% as a lower limit and 70% as an upper bar.

Table 2.1: Moisture Ranges

Range	Reference
50 – 60%	(Biddlestone *et al.,* 1981; Finstein and Morris, 1975; Jeris and Regan, 1973; Wiley and Pearce, 1955; Schulze 1961; US EPA 1995; Zeng *et al.*, 2003)
40 – 65%	(Pace *et al.*, 1995)
60 – 70 %	(Tweib *et al.*, 2011)
50 – 65%	(Bardos, 2004)

While Bardos (2004) explained that MSW feedstock are usually already at an optimum moisture content of around 60% by mass, US EPA (1995) stated that most compostable materials have a lower moisture content than the ideal one, requiring the addition of water to ensure a desirable rate of degradation. In any case, the initially set moisture will vary along the composting process. During the process, cell structure of the feedstock breaks down releasing the retained water and as a result, further increases the moisture content of the composting material (Norbu, 2002). An increase in moisture content above the recommended range will inhibit the microbial degradation as excessive water will fill the pores essential for air movement impeding oxygen transfer and as a result, induce anaerobic conditions (giving off obnoxious odours), a lower rise to thermophilic temperatures and a reduced composting rate (Bardos, 2004; US EPA, 1995; Zeng, 2011; Norbu, 2002; Pace *et al.*, 1995; Zeng *et al.*, 2003). Excessive moisture and free flowing water also lead to the occurrence of leachate, adding to the pollution load of the environment (US EPA, 1995). The general trend reported however is a net decrease in moisture content for while the moisture of the feedstock may increase through their cellular breakdown, water is also being lost through evaporation at a rate higher than moisture input (Pace *et al.*, 1995; US EPA, 1995). Reduced moisture content to a level less than about 40 % limits the dissolution of nutrients to an extent that affects the growth of microorganisms thereby hindering microbial activity and degradation (Pace *et al.,* 1995; Zeng *et al.*, 2003). Considering the difficulty involved in in-situ moisture measurement, automatic control of water level is not common; to maintain the ideal range of moisture content, manual addition of water / dry coarse material is employed to raise/decrease moisture and the squeeze test is carried out to judge the appropriateness of the moisture level (Fraser, 1997; Pace *et al.*, 1995; Norbu, 2002).

2.1.4.5   C/N Ratio

The survival and replication of composting microorganism depends on the sufficiency of carbon and nitrogen present (Kalbasi *et al.*, 2005); While microorganisms depend on carbon as a major energy provider for growth, nitrogen, being a component of nucleic acids, amino acids, enzymes and co-enzymes, is utilised for protein production and reproduction (Pare *et al.*, 1998; Tiquia *et al.*, 2002; Zeng, 2011; Pace *et al.*, 1995; Bardos, 2004). Adequacy of available nutrients is determined by the C/N ratio; a parameter critical for nutrient balance, decomposition rate as well as for the final quality

of composts (Pace *et al*., 1995; Boulter *et al*., 2000). Starting C/N ranges considered to be appropriate seem to converge around a ratio of 30:1(US EPA, 1995; Tweib *et al*., 2011; Norbu, 2002; Epstein, 1997), while ranges of 25:1 – 35:1 (Pace *et al*., 1995; Zeng *et al*., 2003) and 25:1 – 40:1 (Keener *et al*., 2000) have also been reported.

A low starting C/N ratio, usually represented by a value of 20 or lower, leads to the full consumption of carbon mater without stabilising all of the nitrogen present, thereby resulting in the release of excess nitrogen in the form of ammonia (Pace *et al*., 1995); an odorous environment will thus be developed (Zeng *et al*., 2003; Pace *et al*., 1995). Excess of nitrogen also entails a rapid growth of microorganisms initially, accelerating decomposition and consumption of oxygen which eventually creates an anaerobic atmosphere and hence odour issues (Norbu, 2002). To avoid such situations, carbon rich materials in grounded or chopped form, e.g. wood chips and shavings, saw dust, straw and corn stalks are usually added to balance the C/N ratio and immobilise the excess nitrogen (Witter and Lopez-Real, 1987; Michel *et al*., 2004; Morse, 2001).Lack of nitrogen in the form of a too high C/N ratio (above 40:1), slows down the growth rate of microorganism and consequently the composting rate (Norbu, 2002; Zeng, 2011; Pace *et al*., 1995). In both cases, the microbial activity suffers, decomposition is reduced and the desirable peak temperature is not attained (Zeng, 2011; Zeng *et al*., 2003).

Finished compost should have a C/N ratio of 15:1 – 20:1 (US EPA, 1995).

2.1.4.6 *pH*

pH affects the availability of nutrients, solubility of heavy metals and the activity of the microbial population on the whole, given their sensitivity to pH changes (US EPA, 1995). Excessive acidic and alkaline conditions are indicators of feedstock imbalances or process problems, with acidic composting mass being closely related to anaerobic environment (Fraser, 1997). Bardos (2004) and US EPA (1995) recommended a pH range of 6-8. Zeng (2011) stated a range of 6.5 to 7.2 and further added that a pH below 6.5 will induce a competition between fungi and bacteria while a pH above 9.0 will retard microbial activity. Though the composting process is self-buffered by the reaction between the released carbon dioxide and water present to yield carbonic acid (though the organic mass is well-buffered), if the need arise, pH may be adjusted by the addition of lime or sulphur (US EPA, 1995).

2.1.4.7 *Particle Size*

Microbial decomposition takes place on the surface of organic wastes (Kalbasi *et al*., 2005). Smaller particle size of the wastes is known to increase the decomposition rate by virtue of the larger surface area provided (Pace *et al*., 1995; Kalbasi *et al*., 2005). The number of times required to turn the pile and the composting time are reduced as well (Kalbasi *et al.,* 2005). While grinding is usually done to promote reduction in size initially, composting process is a natural process of size reduction yielding smaller particles per unit weight as degradation proceeds (Zeng, 2011; US EPA, 1995). Optimum

particle size should be one that is large enough to provide enough void space for effective movement of air and drainage of excess water and small enough to offer sufficient surface area for rapid microbial activity (Pace *et al.*, 1995; Bardos, 2004; US EPA, 1995; Norbu, 2002). Such particle size should be < 50 mm according to Bardos (2004) while according to Pace *et al.* (1995) it ranges from 1/8 – 2 inch. Aesthetically, size reduction is also applied to improve the appeal of the final compost produced (US EPA, 1995).

2.1.4.8 *Starting culture*

Starting culture has proved its stabilising effect on the composting process (Sun, 2006). With the main aim of diversifying microbial species that could help accelerating the process (Nakasaki and Akiyama, 1988), starting culture also dilutes the fresh wastes by decreasing the energy available per unit volume (Sun, 2006). In doing so, the risk of high odours and inhibitory organic acid is reduced (Sun, 2006). Starting culture has also been known to act as a chemical preventing low pH conditions and process inhibition. Both the quality and quantity of the starting culture influence the composting process significantly and they need to be regulated to ensure enhanced process conditions (Sunberg and Jonsson, 2005).

2.1.4.9 *Amendments*

Amendments are materials that added to the composting process to condition the feed mixture by setting up an environment that would beneficially support microbial activities. Conditioning involves provision of sufficient nutrients, moisture control, reduction of odour emission, adjustment of pH level as well as providing structural support for the composting pile and creating void spaces for aeration (Haug, 1980; Norbu, 2002). Such type of amendment may be accomplished by either organic or inorganic material.

2.2 AMENDMENTS USED IN COMPOSTING PROCESS

Various authors have investigated on the use of amendments to improve the composting process. Eklind and Kirchmann (2000) compared the use of straw, leaves, hardwood, softwood, paper and sphagnum peat as amendments to organic household waste composting to reveal that nitrogen losses were least in the case of sphagnum peat. Hua *et al.* (2009) co-composted sludge with **bamboo derived charcoal** and observed a 64% decrease in nitrogen loss at a charcoal application rate of 9% as well as a decrease in heavy metals mobility. Authors have also shown their interest in the application of inorganic amendments. Wong and Fang (2000) deduced a reduction in heavy metal availability and effective pH buffering when **lime** was used as amendment at a rate of less than 1.0 weight % to compost sewage sludge; the work Fang and Wong (1999) additionally reported a decline in electrical conductivity when lime was applied to sewage sludge at the same rate. Qiao and Ho (1997) found that addition of **red mud** as amendment reduced metal leachability and linked this point

to the adsorption and complexation of heavy metals onto the inorganic components. Incorporation of amendment in composting process also yielded a higher reduction in volume and weight of composting mass as explained by Michel *et al.* (2004) during his investigation on the composting of **sand**-bedded manure. The usage of **wood ash** as amendment has also been studied; Kuba *et al.* (2008) concluded that addition of wood ash to organic wastes improved the compost and its performance; Bougnom *et al.* (2010) stated that application of wood ash amended compost at moderate dose was found to be beneficial to soil microbiota; Tezuka *et al.* (2012) deduced that wood ash application increased the compost pH and promoted the inactivation of pathogens while Carpenter and Beecher (1997) explained that when applied to sludge, wood ash increased the porosity of sludge, improved aeration and increased the micro- and macro- nutrients in the final product. **Fuel ash derived from incinerated sorted wastes** also found its use in composting to yield better aeration, reduced hydrogen sulphide formation and decreased nitrogen loss (Koivila *et al.*, 2004).

2.3   BAGASSE AND COAL ASH AS COMPOSTING AMENDMENTS

2.3.1   Coal fly ash V/S coal bottom ash

A clear domination of utilisation of coal fly ash over coal bottom ash as agricultural amendment has been observed throughout literature as reported in the table below:

Table 2.2: Studies on coal fly ash

Co-composting of Coal Fly Ash	
with	*Reference*
Organic residues	Ravikumar *et al.* (2008)
Wheat straw	Gain and Gaur (2003)
Sewage sludge	Fang *et al.*(97, 98, 99); Lau *et al.* (2001); Chiang *et al.* (2007); Wong *et al.* (1995)
Municipal green waste	Belyaeva and Haynes (2009a)
cow dung	Ananthakrishnasamy *et al.* (2009)
Water hyacinth (organic manure)	Punjwani *et al.* (2011)
Food wastes	Wong *et al.* (2009)

While studies on amendments with coal bottom ash alone were absent, co-composting of **coal ash** with food wastes (An *et al.*, 2012), municipal solid wastes (Zeng *et al.*, 2003) and cow manure (Beaver, 1995) were mentioned. However, only Beaver (1995) clarified that the coal ash comprised both the fly ash and bottom ash; no such information was provided from the other two papers dealing with coal ash.

Such observation tallies with the characteristics of coal ash and bottom ash: bottom ash, being defined as coarse, gritty and agglomerated ash particles that are too large to be carried away in the flue gas and as a result settles at the bottom (Luther, 2010), already have a useful application as construction material and is rarely considered as soil/compost amendments (Pels *et al.*, 2005); bottom ash has found its way as a replacement to sand and fills in the construction industry, favouring their bulk utilization in civil engineering applications that require large volumes of fills and backfill materials (Pels *et al.*, 2005; Marto *et al.*, 2011). However, while having a well-established market in the construction industry, bottom ash may also be incorporated into co-composting of ashes as a bulking agent as suggested by Sun (2006) who mentioned that the coarse structure of **bottom ash would improve aeration**.

Captured in the chimney stack through particulate control technologies, fly ash has a powder-like consistency and such small size characteristics make it unsuitable for bulk-building material as an alternative to sand and gravel (Pels *et al.*, 2005; Luther, 2010). Fly ash is also richer in heavy metals content as compared to bottom ash, which would make leaching from concrete structures due to weathering and erosion over time more hazardous than if bottom ash were applied (Bridgen and Santillo, 2002). In terms of production and disposal rate, fly ash again dominates as shown in table 3, increasing the difficulty of its handling and disposal.

Table 2.3: Fly ash to bottom ash ratio

Ratio of fly ash/bottom ash generation and disposal rate	Reference	Country
80% : 20%	Kim *et al.* (2005a); Kim *et al.* (2005b); Marto *et al.* (2011)	Indianna (US)
80% :20%	Sathyanathan (2011)	-
70% : 30%	Luther (2010)	US
Fly ash: 88%	Bridgen and Santillo (2002)	Philippines
75% : 25%	Tennessee Valley Authority (2009)	US
Fly ash : 70-85%	Laudyn *et al.* (2000)	Poland

Because of such high generation rate and disposal problems associated with fly ash, the latter has **a greater preference** in the application of composting as ash stabilisation and disposal method as highlighted by table 3.
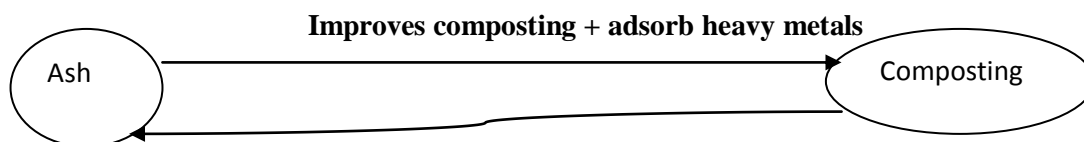
2.3.2 Bagasse fly ash v/s bagasse bottom ash

Researchers have characterised bagasse ash as a good source of micronutrients like Fe, Mn, Zn and Cu, with the capacity to contribute to plant growth (Anguissola *et al*., 1999; Carlson and Andriano, 1993). Though lacking in terms of N, their high content in Phosphorus and Potassium denotes a potential for their beneficial usage in crop production (Page *et al*., 1979).

Similar to coal ashes, bagasse ashes are generated as bagasse bottom ash and bagasse fly ash. According to Pels *et al*. (2005), biomass bottom ash is most easily used as building material (similar to coal bottom ash), while, the fly ash, being a carbon rich, soft, compressive, and highly adsorptive material is usually excluded from inclusion in concrete.(Pels *et al*., 2005; Baguant and Mohamedbhai, 1990). Texeira *et al*. (2011) reported a high carbon content of up to 35% in sugarcane bagasse fly ash and as per French and Smithan (2007) an unburnt carbon content of greater than 3% limit the use of fly ash in concrete applications. Once again, fly ash seems to pose greater disposal problems than bottom ash, requesting for better disposal and stabilisation technologies.

2.4 MUTUALLY BENEFICIAL CONCEPT

"*Fly ash in general makes a good amendment to compost and compost can be regarded as a diluent of fly ash*" – Menon *et al*. (1992)

Improves composting + adsorb heavy metals

Ash → Composting

Lock down heavy metals in ash and in substrate + means disposal of ash

2.4.1 Effects of coal ash in composting process

Fermentation of carbohydrates and fats during composting of food wastes lowers the pH of the composting mass and retards the decomposition process (Nakasaki *et al*., 1998). Such situations require the need for alkaline stabilisation and this is where the role of coal fly ash has been emphasized throughout literature; being an alkaline waste, the use of coal ash has been trialled successfully in various studies to buffer acid generation during composting and has even been considered as potential alternative to lime (Wong *et al*., 2009; An *et al*., 2012; Zeng *et al*., 2003). Coal ash also demonstrated the ability to improve water holding capacity of the end product when Belyaeva and Haynes (2009a) investigated on the feasibility of co-composting municipal green waste with coal ash to produce manufactured top soil for landscaping. Significant improvement in water holding capacity also resulted when coal fly ash was vermi-composted with organic residues (Ravikumar *et al*., 2008). Koivula *et al*. (2004) found that the presence of coal ash in a composting substrate of source-separated cattle waste increased the rate of mineralization of compost and formation of humic acids. Coal ash may also reduce metal stability of the composting mass through

formation of insoluble carbonates, adsorption of metals on alkaline particles or formation of organometallic composts as suggested by Wong and Fang (2000), Ravikumar *et al*. (2008) and Fang *et al*. (97, 98, 99). Coal ash has also proved to be a moisture regulator in a study of Zeng *et al*. (2003) by absorbing excess water in the composting mixture of MSW; the same study emphasized on the rough porous nature of coal ash that helped to improve ventilation. Coal ash addition favoured nutrient retention as well: Ravikumar *et al*. (2008) and Punjwani *et al*. (2011) observed an increase in the content of macro and micro-nutrients with addition of coal fly ash in the composting of organic residues while Goldstein (1997) and Beaver (1995) mentioned an enhancement in nutrient value in final composts that led to an improved plant growth and soil fertility.

2.4.2 Effects of bagasse ash in composting process

While no such case of bagasse ash composting was discussed in literature, Jameel *et al*. *(2003)* did investigate on the application of bagasse ash in calcareous soils to improve the yield of wheat. He noted a favorable impact of the soil physical conditions and nutrient availability that led to an enhanced yield of straw and grain.

2.4.3 Effect of composting on ash: fate of heavy metals

When in contact with water, the metallic constituents of the ash (arsenic, selenium, lead and other contaminants) leach out of the waste to contaminate groundwater and surface water and by nature. These recalcitrant and persistent metals bioaccumulate in the living tissues throughout the food chains until they reach the top ladder where humans are waiting to endure all the complications associated with heavy metal toxicity including damage of nerves, livers and bones as well as mal functioning of vital enzymes (Volesky, 2001). As such, US EPA (2007) has reported the presence of 600 coal ash sites with at least 67 proven potential cases in at least 23 States, with a highlight that exposure to coal combustion wastes is more harmful than smoking a pack of cigarettes per day (Earth Justice, 2009).

In the field of mine rehabilitation, Chaney *et al*. (1995) once mentioned that the unique quality of some organic materials or residuals is that they not only lock the heavy metals found in the residuals but also within the spoil substrate; these organically bonded heavy metals are less likely to cause environmental contamination. Similar line of thought is being applied behind the concept of ash co-composting. Heavy metals exist in a variety of fractions: the exchangeable and water soluble fractions which are affected by water ionic composition as well as sorption and desorption processes; the carbonate bound fractions which is susceptible to pH changes; those metals that are bound or precipitated with Fe and Mn oxides and which are affected by anoxic conditions; the organically bonded metals which are influenced by oxidation and the residual fractions comprising of those metals that are incorporated in the crystal lattice of primary and secondary minerals (Emmerich *et al*., 1982; Lake *et al*., 1984; Petruzzelli, 1989; Zorpas *et al*., 2000; He *et al*., 1992; Iwegbue *et al*., 2006b,c). Unlike organic materials there is no quantitative lessening of the metallic components in the feed and their concentration may even increase as a result of loss of carbon; however the

bioavailability of these metals may be reduced (Chaney *et al*., 1993; Barker and Bryson, 2002). In the composting process, the thermophilic phase may be termed as a reduction phase for heavy metals; the oxidation processes occurring and the formation of organo-metallic complexes lessen the soluble contents of the metals while the humic substances bind with exchangeable and carbonate fractions of the metals, decreasing their solubility (He *et al*., 2009; Fang and Wong, 1999; Singh and Kalamdhad, 2012). Furthermore, a study carried out by Amir *et al*. (2005) on heavy metals bioavailability from sewage sludge composted with straw, reached to the conclusion that largest proportions of metals existed as residual fractions and, residual fractions being the fractions the most resilient to extraction, gave an indication of the stability of heavy metals and their unavailability for plant uptake. This study quantified the amount of potentially biovailable metals to a value of less than 2%. Other studies also emphasized on the reduction of biovailable metals through composting. When municipal solid wastes was composted with biosolids, Pare *et al*. (1999) noted a decrease in soluble components and an increase in residuals that were organically bounded; it was suggested that as the composting process proceeds, the stabilised organic matter formed complexes with the present metals, binding them and thereby restricting their mobility and bioavailability (Pare *et al*., 1998; Pare *et al*., 1999). Hsu and Lo (2000) reported a low leaching level of Cu, Zn and Mn from composted hog manure and linked this observation to interactions between Cu, Zn, Mn and organic materials.

Thus, while ashes may increase heavy metals stability through adsorption of metals from the substrate, the composting process locks down the bioavailability of heavy metals from the whole mixture being composted leading to a proper and safer disposal of ashes.

2.5 PAST STUDIES JUSTIFYING THE IMPORTANCE OF RIGHT APPLICATION RATES

Some studies however did point out that the other facet of ash amendment revealed a different image. Wong *et al*. (1995) showed that the high salts content and pH of coal ash led to a lower respiration rate of coal ash-amended soil when coal ash was added in high amounts. According to Fang and Wong (2000) this high alkalinity and salinity characteristic led to a decrease in population and diversity of thermophilic species present in the composting mixture of sludge and coal ash. He also noted a decrease in metabolic activity in the sludge amended compost. Adriano *et al*. (1980) and Page *et al*. (1979) talked about potential adverse effects on crops and environment owing to too high concentration of trace metals in coal ash. Wang *et al*. (2006), in his study on soil amendments, observed an improvement in growth and nutrient uptake due to ash addition but he emphasized that the though the yield was higher than the control, the increase was not significant.

On the same wavelength as Wong *et al*. (1995) who linked the effects of ash addition to the amount of ash being added and based on the above covered negative aspects associated with usage of ash, it can

be said that application rate of ashes to the composting materials is critical for it may overturn the benefits associated with ash amendment to yield undesirable, inhibitory or insignificant effects. Table 4 summaries past studies done on coal ash amendment laying emphasis on the mixes utilised.

For sewage sludge, a ratio of < 25 wt % is being shown as favourable, while for organic wastes and municipal solid wastes, optimum level of ash may vary from $40 - 60\%$. Nonetheless wheat straw alone, though being very much organic, required an optimum proportion of ash less than 25%. Based on the findings below, the appropriate mix seems to be varying with the type substrate used.

Table 2.4: Application rates of coal ash and their effects

Substrate/ash	Application rate of ash	Observation	Reference
Organic residues/fly ash	50- 100 wt %	Higher nutrient availability was achieved at a % ash addition of 50 and 60% in a vermi-composting process	Ravikumar *et al.* (2008)
Wheat straw/fly ash	Up to 60 %	An application rate of 20 wt% produced the lowest C/N Ratio and Highest available phosphorus when fly ash was co-composted with wheat straw. Also an increase in application rate up to 40-60 wt % did not cause any inhibition to the process.	Gain and Gaur (2003)
Sewage sludge/fly ash	0 – 50 wt % (combined range)	Fang *et al.* (97, 98, 99) ventured in several studies related to fly incorporation to sewage sludge and all observations converged to the following points: Reduction in DTPA – extractable Cd, Cu, Zn, Mn and Pb contents at increased level of ash, but inhibition occurred at: 25% ash amendment level and above in terms of reduced thermophilic bacterial growth and CO_2 production 35% amendment level where significant loss of NH_4-N occurred along with interference with nitrification and phosphorus transformation process reflected by a lower amount of NO_3-N and PO_4-P in the ash-amended sludge	
Sewage sludge/fly ash	0 – 20 wt %	Increased addition of fly ash decreased the DTPA-Pb contents in the sludge	Chiang *et al.* (2007)
Municipal solid waste/ Coal ash	0 – 75 wt %	Favorable thermophilic temperatures of 50-65^{0}C were generated at an ash application range of 40-60%, with the optimum level being 45%; thermophilic temperature attained increased with increasing ash level up to 45% and decreased afterwards.	Zeng *et al.* (2003)

2.6 INFERENCES FROM LITERATURE

1. Mix of bottom/fly ash

In order to:

- Bring the study to an international level (considering worldwide generation rate)
- Maximise the use of fly ash in co-composting (fly-ash being the more difficult material to dispose)
- Exploiting the bulking nature of the bottom ash to improve aeration and
- Maximising the ease of utilisation of disposed coal ash by using them directly (i.e at the rate they are being disposed),

A mixing ratio of 80% fly ash and 20% bottom ash will be applied.

For comparison purposes, similar mix ratio of 80% fly ash and 20% bottom ash will be utilised for bagasse ash.

2. Mix ash/waste

This study is concerned with the use of unsorted and sorted municipal solid waste as substrate, corresponding more closely to literature data on municipal solid waste (for unsorted wastes) and organic residues (for sorted wastes) provided in Table 2.4. This gives rise to the possibility of investigating up to 40-50% of ash application. **Moreover, in the point of view of maximising the use of coal ash in composting as a means of disposal, investigating the effect of ash addition at high dosage may prove to be important**.

No literature findings was obtained on co-composting of bagasse ash with other substrates; an observation that emphasizes on the innovativeness of this study. For the purpose of this study, **same application rate will be applied as for coal ash to enable comparison between the two types of ashes.**

3   METHODOLOGY

3.1   Introduction

The aim of this study was to assess the suitability of coal ash and bagasse ash as amendment in the composting process. This section covers the techniques and procedures adopted to achieve the desired objectives. All the tests and setups were carried out at Solid Waste Recycling Limited for a period of 2 months.

3.2   Procurement of Substrates

100 - 200 kg of Bagasse fly ash, 50 kg of bagasse bottom ash and 50 kg of coal bottom ash was collected from Beau Champs Thermal Power Plant while 100- 200Kg of coal fly ash was obtained from FUEL Thermal Power Plant. The municipal solid wastes were provisioned by Solid Waste Recycling Limited itself from which sorting was carried out to yield sorted MSW whenever required.

Figure 3.1: Different types of ashes utilised

3.3   Choice of mixes and ratios

Inferring from literature, the following 10 set-ups were chosen to englobe the current handling of unsorted wastes, future prospects of treating sorted wastes, and current and future increasing utilisation of coal and bagasse as energy sources.

Table 3.1: Application rates of bagasse and coal ash

Main Substrate	Control	Application of Bagasse ash		Application of Coal ash	
	(0%)	Application Rate 1 (20%)	Application rate 2 (40%)	Application Rate 1 (20%)	Application rate 2 (40%)
unsorted MSW (S)	0% ash; 100% sorted MSW (C)	20% bagasse ash: 80% unsorted wastes (A)	40% bagasse ash: 60% unsorted wastes (B)	20% coal ash: 80% unsorted wastes (G)	40 % coal ash: 60 % unsorted wastes (H)
sorted MSW (U)	0% ash; 100 % sorted MSW (F)	20% bagasse ash: 80% sorted wastes (D)	40% bagasse ash: 60% sorted wastes (E)	20% coal ash: 80% sorted wastes (I)	40 % coal ash: 60 % sorted wastes (J)

The coal ash comprised of 80% coal fly ash and 20% coal bottom ash; the same mix was applied for bagasse ash.

3.4   Ash characterisation

The ashes were assessed in terms of their moisture content, volatile solids content, nitrogen content, bulk densities, pH and Electrical Conductivity.
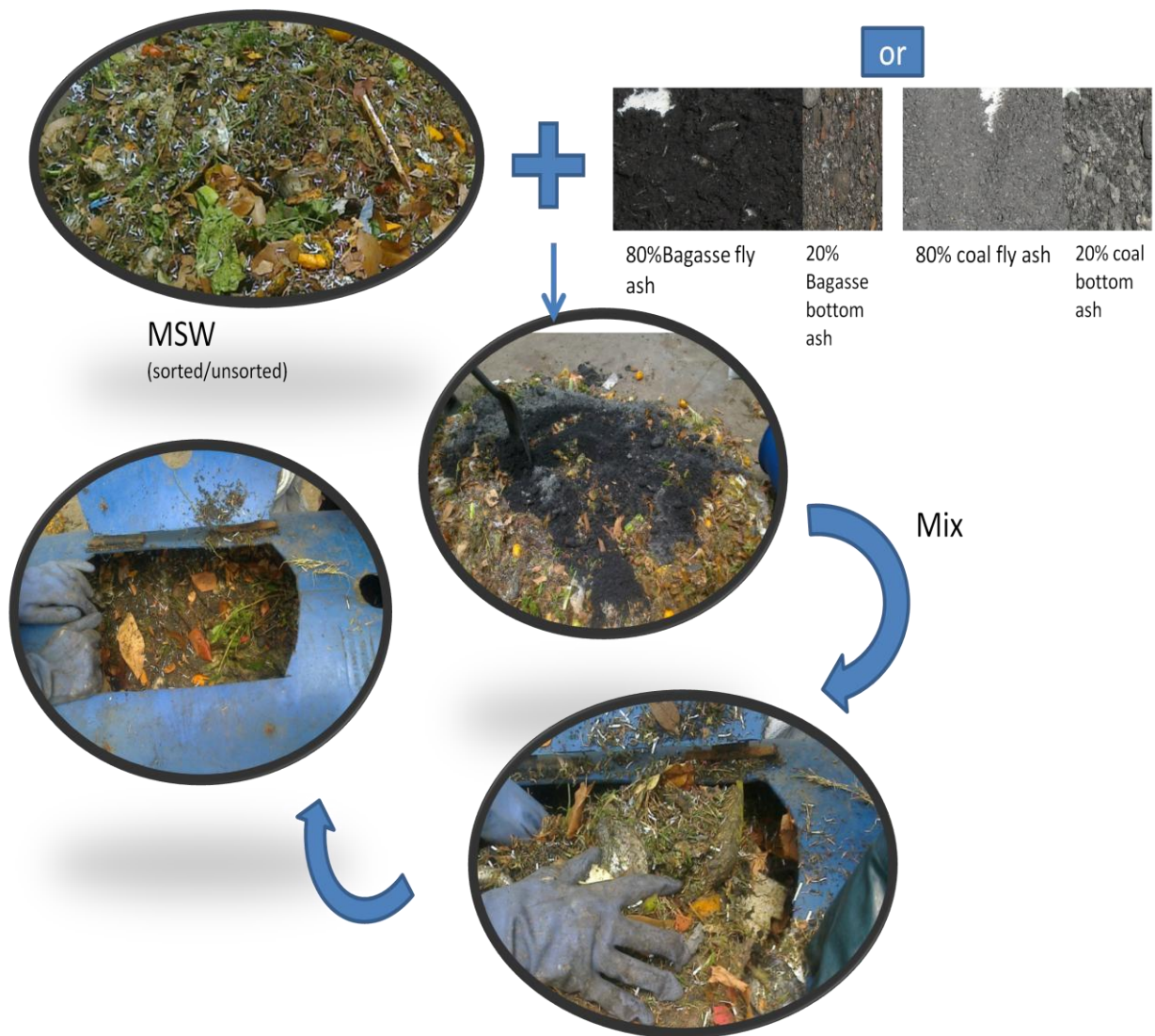
3.5   Setting up of composting drums

The mass requirement of MSW, fly ash and bottom ash were calculated so that the whole composting mass could fit the 200L composting drums while at the same time maintaining the desired ratio of ash application. The results are shown in Table 3.2 below, based on which, required amount of ashes were added to pre-weighed quantities of municipal solid wastes. Manual and homogeneous mixing of the different substrates followed to output a uniform blend of the composting mass.

Table 3.2: Calculated masses of each substrates

Setups	Description	Mass of MSW (Kg)		Mass of bagasse ash (Kg)		Mass of coal ash (Kg)	
		sorted	unsorted	Bagasse fly ash	Bagasse bottom ash	Coal fly ash	Coal bottom ash
A	20% bagasse ash/unsorted MSW	-	64.74	12.95	3.24	-	-
B	40% bagasse ash/unsorted MSW	-	52.57	28.12	7.03		
C	Control for unsorted MSW	-	75	-	-	-	-
D	20% bagasse ash/sorted MSW	82.55	-	16.51	4.13	-	-
E	40% bagasse ash/sorted MSW	63.96	-	34.11	8.53	-	-
F	Control for sorted MSW	100	-	-	-	-	-
G	20% coal ash/unsorted MSW	-	68.31	-	-	13.66	3.42
H	40% coal ash/unsorted MSW	-	59.49	-	-	29.38	7.35
I	20% coal ash/sorted MSW	84.7	-	-	-	16.94	4.24
J	40% coal ash/sorted MSW	67.50	-	-	-	36.00	9.00

The drums were then filled to compaction, with regular shakings to ensure even placement of the wastes. Figure 3.2 gives a pictorial description of the process flow.
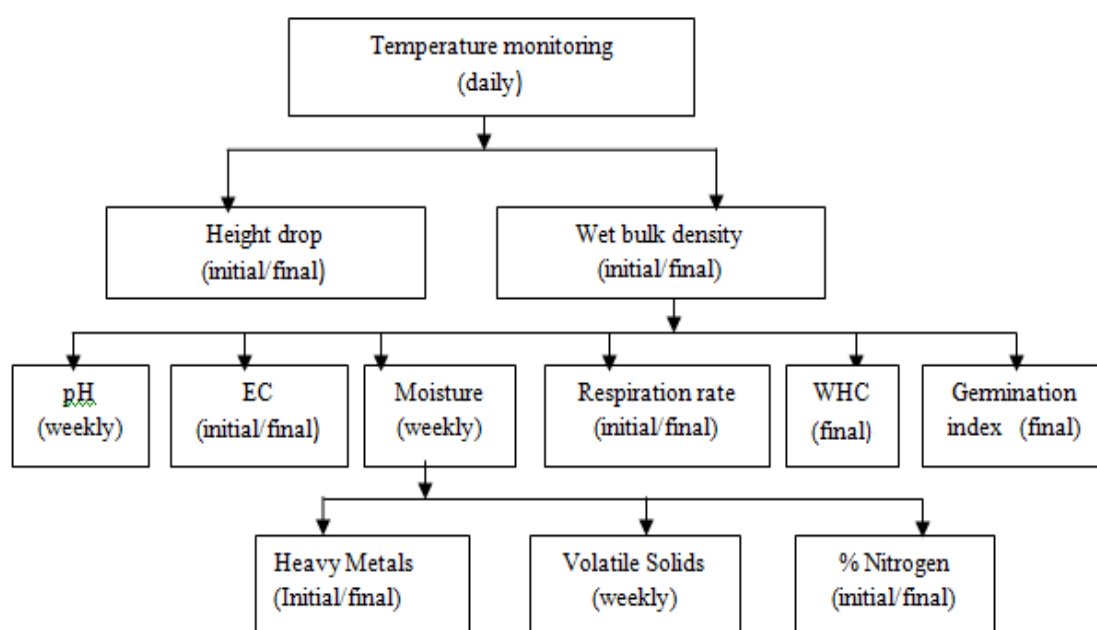

Figure 3.2: pictorial description of filling of drums

Table 3.2 only served as a theoretical guide for mixing; the amount used was either enough to fill the drums completely or were in excess by a small amount. Because innoculum addition depended on the total composting mass, any excess wastes were measured and subtracted from the mixed mass. Table 3.3 gives the actual total mass of substrates. The bioculum, being in a powdered and insoluble form, was mixed with water before being irrigated throughout the whole composting mass.

Table 3.3: Actual mass of substrates in composting drums

	Mixed mass (kg)	Excess (kg)	Actual mass
A	81	5	76
B	88	2	86
C	70		70
D	103	3	100
E	107	negligible	107
F	85		85
G	84	3	81
H	95	1	94
I	108	4	104
J	118	5	113

3.6   Monitoring of drums

Figure 3.3: Breakdown of analyses

3.6.1 Sampling

Samples were taken from the core and the sides of the drums to a depth halfway within the composting mass as far as possible. The samples were homogeneously mixed in a tray before being utilized for the different analyses below.

3.6.2 Aeration

Aeration was achieved through weekly turning of the composting drums.

3.6.3 Moisture

Moisture was adjusted weekly during the turning of the drums to ensure even moisture distribution. The drums were emptied to about half of its volume and water was added to each halved portion; the portion outside was mixed manually with a shovel while the contents remaining in the drums were turned. The drums were emptied to ensure enough buffer space within the drum, thus allowing for proper turning and mixing. After returning the outside wastes into the drums, the drums were turned once again. The moisture content of the composting mass was verified using the oven drying method at $105^{0}C$ for 24hrs.

3.6.4 pH

200 ml of 0.01M calcium chloride was added to 20g of fresh samples from each composting drums and the mixture was stirred at regular intervals for a period of 2hr. The pH of the suspension was measured using a calibrated glass electrode pH meter.

3.6.5 VS

VS analyses were made on the dried sample obtained from weekly moisture monitoring. The dried materials were ground and about 5g of each sample that passed through a 2mm sieve was weighed in a crucible and ignited at $550^{0}C$ for 2hrs in a muffle furnace. % VS was calculated as follows:

$$VS\% = \left(\frac{M_{s1} - M_s}{M_{s1} - M_c}\right) x 100$$

Where: M_c = mass of empty crucible, g

M_{s1} = mass of sample + mass of empty crucible, g, before burning

M_s = mass of sample + mass of empty crucible, g, after burning

3.6.6 Respiration rate

The composting masses were analysed for their respiration rate during the first week and final days.

25 g of fresh sample was placed together with beaker containing 25ml of 1M sodium hydroxide in a tightly sealed bell jar. The sodium hydroxide was titrated against 1M hydrochloric acid daily to determine the carbon dioxide evolution as follows:

$$CO_2.C = 12\ (HCL_b - HCL_s)$$

Where $CO_2.C$ = mass of CO_2 carbon generated (mg)

    HCL_b = titre value for blank (ml)

    HCl_s = titire value for sample (ml)

The Stability index was calculated from the equations below:

$$\textbf{Stability Index} = \frac{\textbf{mass } CO_2.C\ (\frac{\textbf{mg}}{\textbf{day}})}{\textbf{organic carbon (g)}}$$

$$\% \textbf{ carbon} = \frac{\% \textbf{ Organic Matter (Volatile Solids)}}{\textbf{1.8}}$$

$$\textbf{organic Carbon (g)} = (\textbf{wet weight of sample}) x\ (\textbf{100} - \% \textbf{ moisture}) x\ (\% \textbf{ carbon})$$

3.6.7 Temperature

Daily recordings of the core temperature were carried out. Maximum temperatures were retrieved by varying the depth to which the probe's tip was dipped, allowing the probe to stabilise and recording the maximum temperature read.

3.6.8 Wet Bulk density

Wet Bulk Density was measured by dividing the mass of samples placed in a recipient by the volume of water that the recipient can hold.

3.6.9   Height drop

Figure 3.4: Measurement of loss in height

A threaded rod equipped with a nut was placed perpendicularly in the drums and the nut was rolled till it touched the surface of the composting substrates. A Centimeter was used to measure the distance from the tip of the rod till the nut.

3.7   Compost quality tests

3.7.1   Electrical Conductivity

200 ml of distilled water was added to 20g of fresh samples from each composting drums and the mixture was mixed at regular intervals for a period of 2hr. Each suspension was filtered and the EC of the filtrate was measured using a calibrated glass conductivity meter. Analysis was repeated in triplicates.

3.7.2   Water holding capacity

Triplicate analyses were performed to determine the water holding capacity of the compost samples. A PVC cylinder, with a close-meshed plastic net bottom, was wrapped at the bottom with a moistened filter paper and was weighed as M_0. The cylinder was filled with the compost sample and was weighed as M_c. The cylinder was placed in a beaker in which water was slowly added until it covered the cylinder and the sample floated as mulch. The setup was allowed to stand for 24 hours, after which the cylinder was removed from the water, dried from the outside and placed on a sieve to allow excess of water to drain. After 2 hours, the cylinder was continuously weighed and allowed to drain until a constant mass was obtained. The final mass was measured as M_{moist}. The water holding capacity was calculated from the equation below:

$$\text{Water holding capacity} = \frac{(\text{Mmoist} - \text{Mo}) - [(\text{Mc} - \text{Mo}) \text{x} \left(1 - \frac{\text{WC}}{\text{100}}\right)]}{[(\text{Mc} - \text{Mo}) \text{x} \left(1 - \frac{\text{WC}}{\text{100}}\right)]} \text{ x 100}$$

Where, WC = moisture content of fresh samples (%)

3.7.3 Nitrogen content
The initial and final nitrogen content of the composting substrates were determined in duplicates.

About 0.5 – 1.0g of dried and ground sample was digested with sulphuric acid and Kjedahl tablets for a period of 1hour at 350^0C. 20ml of water was added to the digested contents and the resultant mixture was distilled together with a conical flask containing 50 ml of boric acid that acted as a receiver of the distillate. After 4 minutes of distillation, the boric acid was titrated against 0.1M of Hydrochloric acid and the % N was calculated as follows:

$$\%\text{N} = \frac{(\text{M} - \text{m}) \text{ x 100 x F}}{\text{E}}$$

Where N = nitrogen content (%)

M= titre volume for sample (ml)

m = titre volume for blank

F = 1.4 for 0.1M HCL

E = mass of sample used (g)

3.7.4 Phytotoxicity bioassay
The water content of the compost sample required for extraction was calculated by the following equations:

$$\text{g wet compost} = 100\text{g dry} \frac{\text{compost}}{\text{moisture content of sample}}$$

$$(\text{or ml})\text{distilled water} = 850\text{ g total} - \text{g of wet sample}$$

The mixture was stirred and allowed to settle for 20 minutes, after which, 200ml of the mixture was decanted and the rest filtered to obtain the filtrate as extract.

The germination assays were conducted in duplicates on a filter paper in petri dishes, to which 1ml of the extract was added. 5 mustard sheets were placed on the wet filter paper and the glass dish was covered and incubated in the dark for 48 hours. Experiment was repeated with diluted extract (1/10

v/v), and with distilled water. The length of radicles formed after 48 hours was measured with a vernier calliper.

The following formulas were applied to calculate the Germination index:

$$\% \, G = \left(\frac{G_t}{G_c}\right) x100$$

Where % G = Percent germination, G_t = Mean germination for treatment, G_c = Mean germination for distilled water control

$$\% \, L = \left(\frac{L_t}{L_c}\right) x100$$

Where % L = Percent germination, L_t = Mean germination for treatment, L_c = Mean germination for distilled water control

$$GI = \frac{\% \, G * \% \, L}{10000}$$

Where GI = Germination Index

3.7.5 Heavy metals content

Composts derived from the 20% bagasse ash amended sorted wastes (D), 20% coal ash amended unsorted wastes (G) and 20% coal ash amended sorted wastes (I) had their heavy metals content analysed and quantified through the microwave acid digestion method by the Mauritius Standard Bureau.

4 RESULTS AND DISCUSSION

4.1 INTRODUCTION

Chapter 4 brings about the consequent results obtained following the methodology detailed in chapter 3, accompanied by supporting arguments and explanations to pour some light on the resultant behaviours of the following monitored parameters: Temperature, pH, moisture, VS, Bulk density, Respiration rate and volume reduction. Date of setups depended on the availability of ashes; in this respect A, B and C was prepared on the 5th of November, D, E and F on the 6th of November while the setups for coal ash were conducted on the 19th of November.

4.2 ASH CHARACTERISATION

Table 4.1: Characterisation of the ashes used

	Bagasse fly ash	Bagasse bottom ash	Coal fly ash	Coal bottom ash
Moisture content	22.24%	0.88%	41.06%	1.02%
Volatile solids	20.4%	1.15%	32.20%	18.61%
Bulk density	480 kg/m^3	1436 kg/m^3	798.22 kg/m^3	821 kg/m^3
Nitrogen content	0.154%	N/A	0.21%	N/A
pH	9.24	8.90	8.45	8.74
Electrical conductivity	1249	N/A	756	N/A

Electrical conductivities of the coal and bagasse ashes were already within limit when considering the compost EC range of < 3.5 dS/m; a fact that may explain their direct application in agricultural industry. However, the low nitrogen content of the ashes tallies with the remarks made in the work of Ravikumar *et al*. (2008) whereby it was stated that ashes need to be composted with organic wastes to improve the available ranges of nutrients and increase their effectiveness as soil amendment. Also, the high alkalinity of the ashes is one the many contributing factors that led to the focus on safe disposal of fuel ashes; composting being the disposal method considered in this study. Regarding the volatile solids content, though bagasse ash was termed as an organic waste by Jameel *et al*. (2004), the characterisation study showed that the bagasse ash used for this study was very low in organic content, supporting the fact that the characteristics of ashes may differ according to feed characteristics and process technologies (Teixeira *et al*., 2011). Similarly, moisture content will depend on the source and technology of ash collections as well as atmospheric conditions since the sugar factories stored their ashes on-site in an open environment.
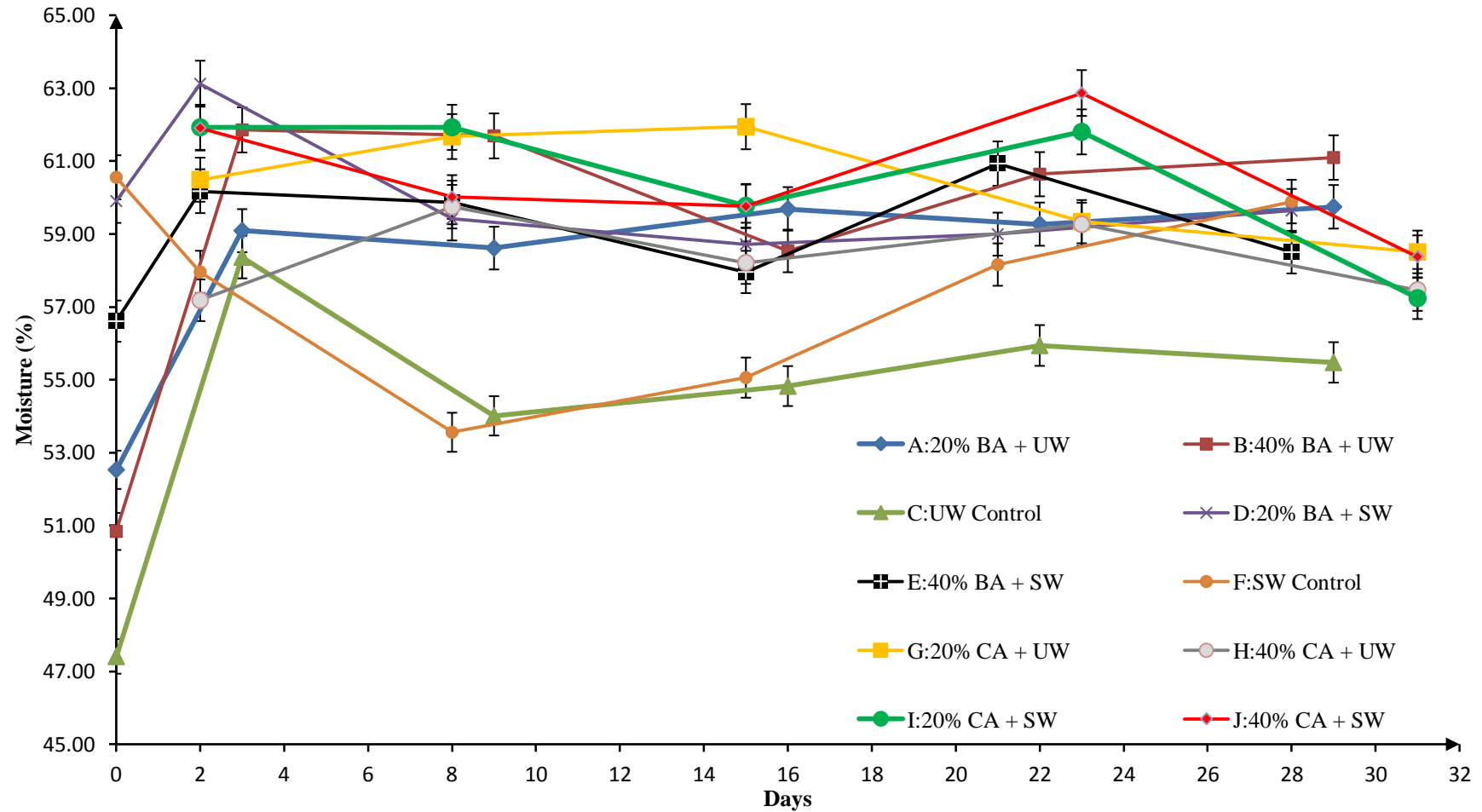
4.3 PROCESS PARAMETERS

4.3.1 Moisture content

Figure 4.1: Moisture variation

Literature data recommended a range of 50-60% for optimum moisture content, with flexible extents up to 40 – 65% (Pace *et al.*, 1995; Zeng *et al.*, 2003). First analysis of the moisture content was carried out on setups A – F on day 0 after the moisture was adjusted and the drums filled. All 6 composting mass were found to be within the literature range with the following observations however: A and B, though having a moisture content of 52.53 and 50.84% respectively, felt lacking in terms of the desired moist touch. Such condition may be attributed to a high moisture absorption capacity of the fly ash that impartially absorbed the water supplied, leaving the parts of the substrates lacking in moisture. A study on the properties of bagasse ash for their application in cement use aspect also observed the high water demand by the bagasse ash and they related it to the highly porous nature of the bagasse ash (Suvimol and Daungruedee, 2008). Because composting will occur more rapidly in thin films of water on the surfaces of the particles, further water adjustment was made on A and B until the whole composting mass felt moist to the touch. Samples were thereafter taken and analysed for moisture content to yield values of 59.09 and 61.86%. Drum C, having a moisture content near to the lower limit, was adjusted as well and taking into consideration the absorption capacity of the bagasse ash and the hot climate at La Chaumiere, the other drums were also adjusted.

For coal ashes, Zeng *et al.* (2003) emphasized on the role of fly ash in excess moisture absorption in a study of composting coal fly ash with MSW. In another point of view, this might as well means absorbing too much water content and depriving the substrate with moisture, similar to the case of bagasse ash. Coal fly ash has also been categorised as being highly porous with high water absorption capacity by Rai *et al.* (2010). Hence, for drums G-I as well, the moisture content were kept to high upper range as far as possible. To ensure proper functioning of the composting process, water adjustment was made each week during turning to ensure even moisture distribution.

Figure 4.1 shows that after initial moisture adjustment, the moisture content of the composting substrates was successfully maintained at 53.56 – 63.12%. Hence**,** at any point in time, moisture content was not a limiting factor. A slight demarcation between the ash-amended wastes and controls was noted on the graph showing that ash-amended wastes required a somewhat higher water demand.
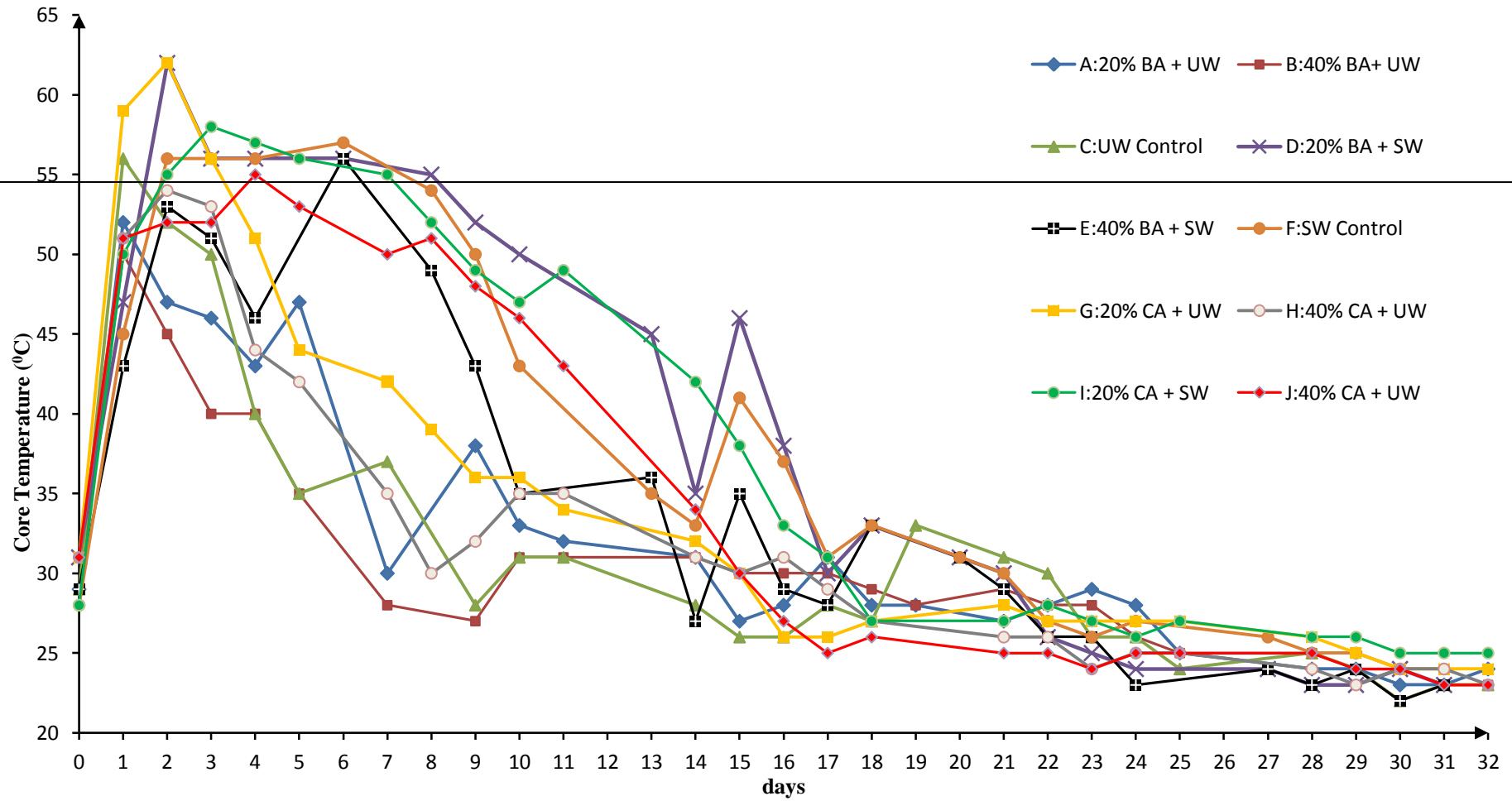
4.3.2 Temperature

Figure 4.2: Temperature Variations

4.3.2.1 General Trend

Starting temperatures for setup A-J ranged between 28- 31^{0}C; such high temperatures are characteristics of atmospheric temperature of La Chaumiere, where a dry and hot climate prevails. Rapid rise of temperature was initiated as soon as the setup was completed as implied by the steep slope from day 0 to day 1. This denotes a high microbial activity from the start itself which may be accounted by the use of bioculum that wrote off the need for acclimatization time required by bacteria. The bioculum had as aim to diversify the microbial population and to increase the composting process (Nakasaki and Akiyama, 1988); a target that proved to be successful as the composting mass reached the thermophilic stage (with some even attaining their peak point) within a period of 1 day itself. The temperature profile shown in **Figure 4.2** followed typical profiles reviewed in literature (Mohee *et al*., 2008; Menez and Garcia, 1992; Inbar *et al*., 1993; Tiquia *et al*., 1997; Belyaeva and Haynes, 2009a): a rapid rise to the thermophilic range fuelled by rapid breakdown of organic matter and nitrogenous compounds through microbial activity; a retention time of few days at peak temperatures to ensure destruction of pathogenic organism and; a decrease in temperature thereafter, as a result of depletion of rapidly biodegradable components (Bardos, 2004; An *et al*., 2012). However, regarding the attainment of pathogenic destruction temperatures, only C, D, E, F, G, I surpassed the barrier of 55^{0}C, with only D, F, G and I achieving a retention time of at least 3 days at > 55^{0}C.

Fluctuations in the temperature recordings may be related to the turnings and moisture addition carried out weekly, as well as regular samplings that might have either disturbed the temperature or provide fresh nutrients and carbon source to the microorganism, thereby enhancing the temperature.
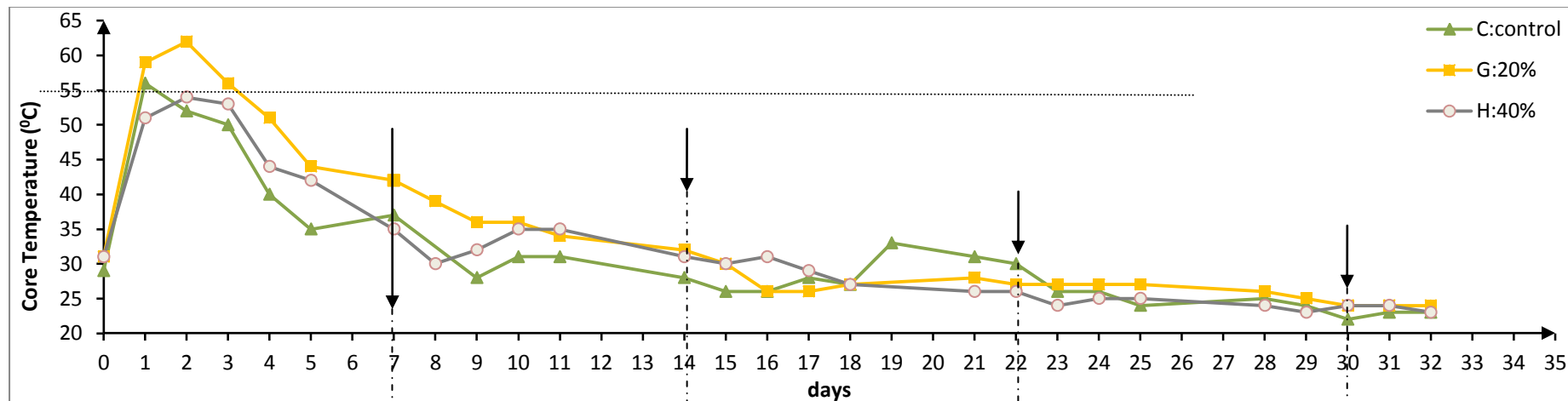
4.3.2.2 Wastes amended with coal ash

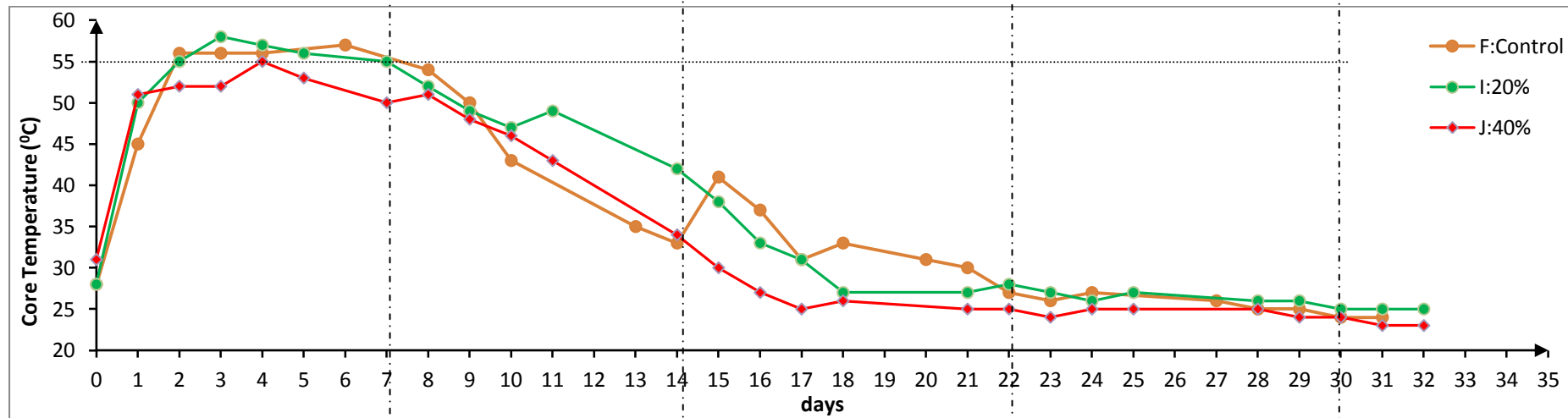**Figure 4.3: Temperature profile for unsorted wastes amended with coal ash**

Figure 4.4: temperature profile for sorted wastes amended with coal ash

From **Figure 4.3**, it can be observed that setup G and H reached their peak temperature within a period of 2 days before exhibiting a drop in temperature, while the control, C attained its peak within the first day itself. For the sorted wastes, the control reached its peak after 6 days, while I and J took 3 and 4 days respectively, as illustrated in **Figure 4.4**. Setup G lasted for 7-8 days within the thermophilic range, setup H lasted for about 5-6 days and the unsorted control for 4 days. F and J remained in the thermophilic range up to 11 days, with I going up to 15 days.

Turning and moisture addition was conducted on day 7, 14, 22 and 30 after the daily temperature was recorded. After 24 hours of turning, all the setups, except F, continued their trend indicating normal composting conditions. The rise in temperature for setup F after day 14 is an indicator of previous inhibition that might have been caused by lack of aeration or uneven moisture distribution. After 2 days of 1st and 2nd turning, drum H showed a rise in temperature which may be associated to a delayed effect of turning.

Application of 20% of coal ash to unsorted wastes (G) enhanced the peak temperature from 56^{0}C achieved by the control to 62^{0}C while a 40% application of coal ash (H) lowered the peak temperature to 54^{0}C. A similar trend was observed with the utilisation of sorted wastes, whereby 20% coal ash amended wastes (I) reached a peak temperature of 58^{0}C which is slightly higher than what the control attained i.e 57^{0}C. 40% coal ash amended wastes(J) demonstrated inhibition here as well by producing a lower peak temperature of 54^{0}C. An uncharacteristic observation of higher peak temperature attainment by the addition of 20% coal ash to unsorted (62^{0}C) wastes as compared to sorted (58^{0}C) was made. This could have been because the sorted mass was more compact that the unsorted mass, resulting in lower aeration and hence lower degradation rate. Addition of 20% coal ash in both cases (G and I) also ensured a retention time of more than 3 days above 55^{0}C, thus ensuring pathogen destruction.

The rise in temperature and heat detainment may be explained by several approaches. One contributing aspect might be the high absorption capacity of the coal ash that limits evaporative losses of moisture and consequently reduces heat losses as explained by Zeng *et al*. (2003) in a study on co-composting coal ash with MSW. Secondly, the ash is known to retain its porous structure, by virtue of which, ventilation is ensured even when rotting is causing the substrate to become denser; such aeration favours continued rapid degradation yielding high peak temperatures (Zeng *et al.,* 2003; An *et al.,* 2012). The rise in temperature was also related to an increase in heat capacity of the composting mass through ash addition by Koivula *et al.* (2004).

While 20% application rate seemed to bring about these favourable changes, 40% ash application appeared to be too high a dose. Indeed An *et al. 2012* found that coal ash -amended setups slightly lowered the number of thermophilic microorganism due to its alkalinity and salinity. However, the study did mention that as soon as the microorganism adapted to this new environment, the

microorganism content in the ash amended ones outnumbered the non-amended ones. In our study, the adaption part did not occur. This could be because the lowered organic content of H and J as a result of too much ash addition might have provided an unfavourable condition for the adaptation and growth of the microorganisms; initial VS analyses provided a value of 55.01% for H, 51.68% for J with their respective controls having an initial VS content of 69.25% and 79.80% respectively.

Hence, low thermophilic microbial activity in H and J might have resulted in lower peak temperatures. Fang *et al*. (97, 98, 99) also debated on reduced on thermophilic bacteria at high dosage of ash amendment. Belyaeva and Haynes (2009a) provided another line of thought, whereby the decrease in temperature was attributed to the coating effect of the coal ash which increased with increasing ash amendment, defying the aerative purpose of the ash at high dose; such event might have diminished the availability of the wastes to microbial contact as well, thereby decreasing the rate of degradation and hence heat generation.
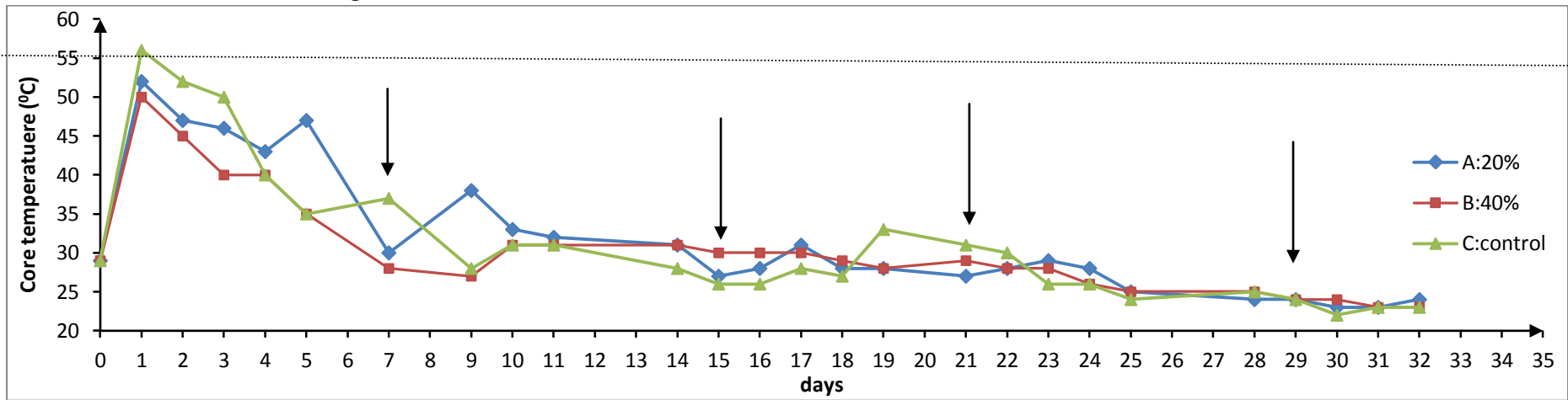
4.3.2.3 Wastes amended with bagasse ash

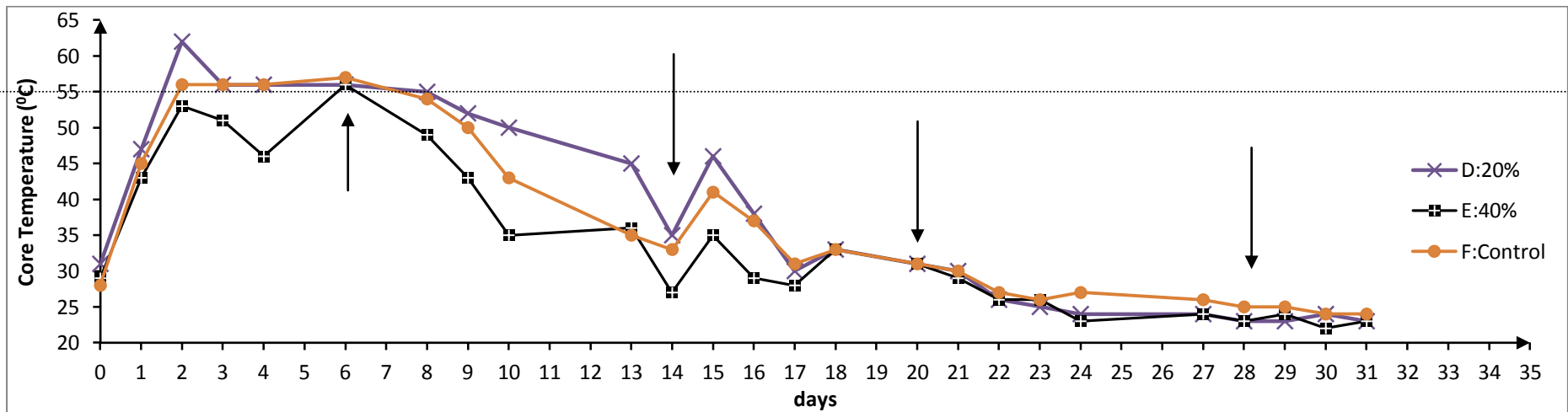**Figure 4.5: temperature profile for unsorted wastes amended with bagasse ash**

Figure 4.6: temperature profile for sorted wastes amended with bagasse ash

Turning+ moisture adjustment

For the unsorted setups amended with bagasse ash, **Figure 4.5** shows that all three drums reached their peak temperature within a period of one day and started exhibiting a drop in temperature immediately after. Setup B and C lasted 4 days within the thermophilic range, while A lasted for a period of 5 days. For the sorted composting mass, D reached its peak after 2 days, while E and F took 6 days according to **Figure 4.6**. E remained in the thermophilic range for 9 days, D, 13 days and F 10 days. These data are summarised and compared in **Table 4.2.**

Turning and moisture addition for the unsorted setup was conducted on day 7, 15, 21 and 29 while for the sorted setups turning was done on day 6, 14, 20 and 28. A rise in temperature in setup A was observed after turning on day 7, implying that the composting process might have been inhibited by conditions like: uneven moisture distribution, lack of aeration or accessibility to fresh wastes/nutrients which was corrected by turning. Similar raise in temperature, though much lower, was noted on day 15's turning. Setup B and C continued their trend and did not show any raise in temperature as a result of turning, indicating normal composting conditions. For sorted setups all 3setups continued their decreasing trend indicating normal operating conditions after the first, third and fourth turning. However, after the second turning, a rise in temperature was noticed for all 3 drums, denoting previous inhibition.

For the sorted bagasse ash amended wastes, 20% application rate and 40% application rate demonstrated similar patterns to that of coal ash amended wastes in the sense that, 20% bagasse ash amended sorted wastes (D) reached a higher peak temperature than the control (F), and the 40% bagasse ash amended sorted wastes (E) reached a slightly a lower temperature: D: 62^0C; E: 56^0C; F:57^0C. However, unlike the coal ash effect, both application of 20% (A) and 40% (B) bagasse ash to unsorted wastes produced lower peak temperatures of 52^0C and 50^0C as compared to the higher peak temperature of 56^0C obtained by the control. Also, only the sorted wastes amended with 20% bagasse ash (D) and the control for sorted wastes (F) achieved a retention time of more than 3 days above 55^0C favouring pathogens elimination.

Improvements at 20% bagasse ash on sorted wastes may be justified by the similar arguments provided for coal ash: the high moisture absorption capacity of bagasse ash as stated by Suvimol and Daungruedee (2008) could have limited evaporative heat loss; the porous nature of the ash improved ventilation, and as proposed by Koivula *et al*. (2004) for coal fly ash, the addition of bagasse ash may have increased the heat capacity of the composting mass.

Similarly, 40% in both sorted (E) and unsorted (B) wastes inhibition may be accounted by the following: the coating effect of the bagasse ash on the substrates, as confirmed by visual observation, would have blocked aeration and the lowered organic content of the composting mass due to excessive dosage of bagasse ash would have restricted the development of thermophilic bacteria;

initial VS content of B and E were found to be 45.40% and 53.19%, with their respective controls having an initial VS content of 69.25% and 79.20% respectively.

Interestingly, application rate of 20% of bagasse ash on unsorted wastes (A) did not lead to temperature enhancement as expressed by 20% coal ash on unsorted wastes (G). This might be because of the lower organic content of composting mass A (VS: 60.48%) compared to G (VS: 67.91%) which did not boost the adaptation and growth of thermophilic bacteria as G did. Another aspect that could be considered is the difference in the specific gravity of the bagasse bottom ash and coal bottom ash, quantified as 1436 kg/m^3 and 821 kg/m^3 respectively. Literature emphasised on the role of bottom ash as bulking agent that would improve aeration. Because of the difference in weight/volume, on a similar mass basis, more of coal bottom ash was employed compared to bagasse bottom ash, hence improving aeration, and consequently degradation, to a greater extent in the coal-ash setups.

4.3.2.4   *Summary of Temperature findings*

Table 4.2: compiled findings on temperature variations

Temperature profiles criteria	A	B	C	D	E	F	G	H	I	J
Peak temperature reached(^0C)	52	50	56	**62**	56	**57**	**62**	54	**58**	55
Time spent > 55^0C	0	0	1	**4**	1	**3**	**3**	0	**3**	0
Time spent in thermophilic range	4	4	4	**13**	9	**11**	**7**	5	**15**	11

From the table above, it can be concluded that based on temperatures criteria, D, F, G and I thrived, implying improved composting when 20% bagasse ash was added to sorted wastes and 20% coal ash was applied to sorted and unsorted wastes.

In both bagasse ash and coal ash utilization scenario, short retention time achieved by the unsorted wastes within the thermophilic range as compared to the sorted setups may be attributed to the wastes characteristics, whereby unsorted wastes are lower in organic content and higher in more difficultly degradable materials like cellulose (An *et al*., 2012).

4.3.3 pH
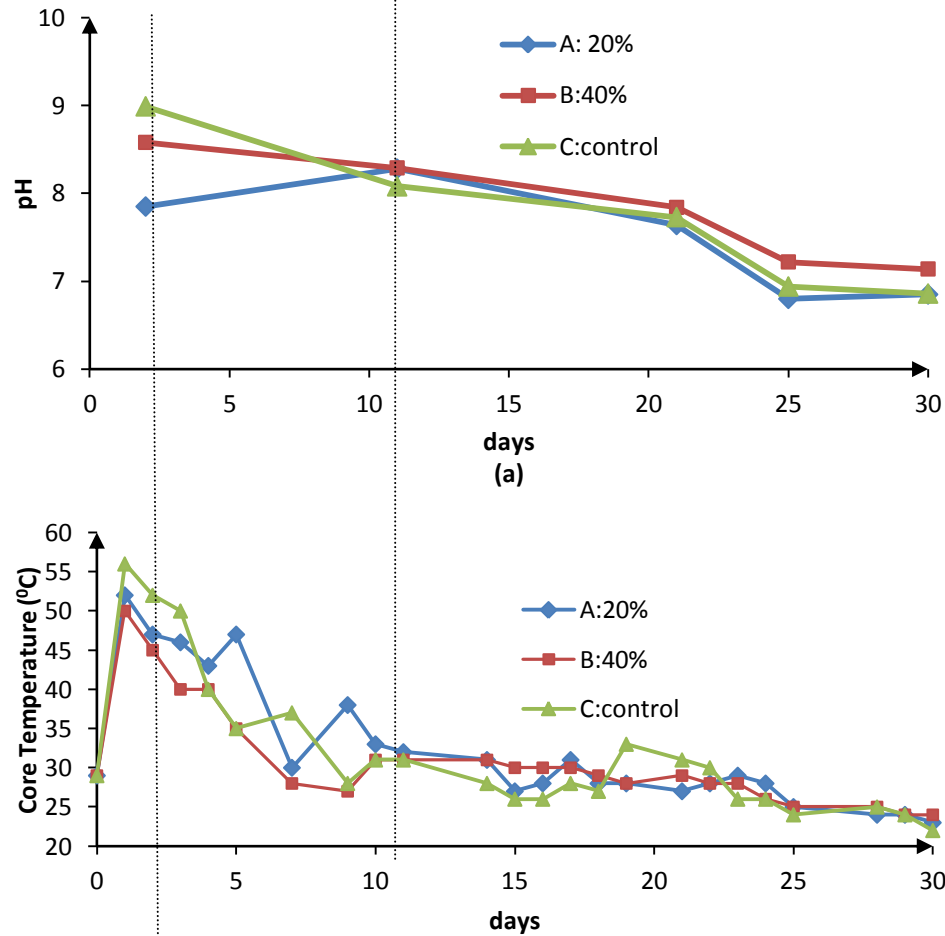
4.3.3.1 Wastes amended with bagasse ash

Figure 4.7: (a) pH and (b) temperature variations for unsorted wastes amended with bagasse ash
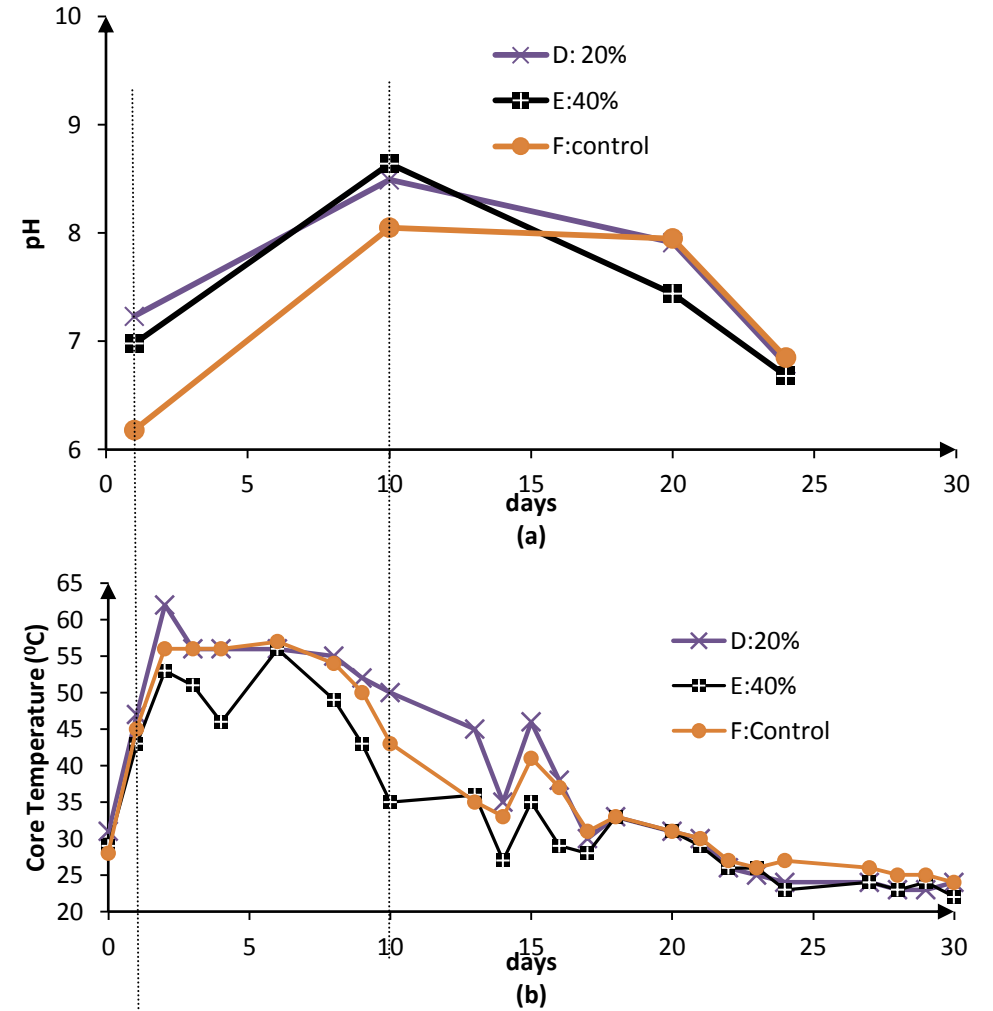

Figure 4.8: (a) pH and (b) temperature variations for sorted wastes amended with bagasse ash

For setups A, B and C initial sampling was carried out on day 2 which crossed the peak temperature reached by the three unsorted setups as shown in **Figure 4.7 (a,b)**, while for the sorted ones, initial sampling was done on day 1, before peak temperature attainment as **Figure 4.8(a,b)** depicts.

The ascent to peak temperature is usually accompanied by organic acid formation like amino acids and volatile fatty acids as a result of bacterial digestion of the organic matter (Hagerty *et al.,* 1973). Consequently, reduced initial pH is a normal behaviour, though excessive acid accumulation may be adverse to the composting process given the sensitivity of microorganism to pH fluctuations. According to EPA (1994), in this region, the pH may fall up to 4-5 and as per Nakasaki *et al*. (1993) a pH < 6.0 will lead to inhibitory effect.

D, E and F had a pH of 7.23, 6.98 and 6.18 respectively indicating that acid accumulation was not an issue here. However, the pH of the unammended mass is very close to the lower limit suggesting that buffering might be desirable. Addition of bagasse ash to D and E on the other hand, successfully buffered the pH drop to around neutral values emphasising on the buffering capacity of bagasse ash. **Such buffering might have been an additional contribution to the improved composting achieved by setup D as covered in temperature variation dissection** .While according to Lau *et al.* (2001) the increase in pH should correspond to the application rate of ash, E showed a lower increase than D and this could be attributed to the difference in initial pH characteristics of composting masses. This reduced pH stage was not observed in setups A, B and C because sampling occurred after this acid formation stage and peak temperature.

After the composting process crosses the peak temperature, organic acids generated start to be utilised as substrates whereby they are decomposed and volatised with the formation of carbon dioxide. Proteins and other nitrogen sources are microbially broken down as well to release ammonium ions; a process known as ammonification which is accompanied by release of OH^- (Haynes and Swift, 1989). Correspondingly, a rise in pH is observed as demonstrated by the increasing trend of graph D E and F to reach a higher pH of 8.49, 8.64 and 8.05 respectively on day 10.

High pH obtained on day 2 for the 3 unsorted masses A, B, C indicated that organic acid mineralization was already in process. The increasing trend for A implied that depletion of organic acids continued prevailing to reach a higher pH of 8.28 on day 11. For B, and C the decreased pH may be explained as follows: at high pH, the ammonium ions formed are either volatilised in the atmosphere in the form of ammonia, or nitrified to nitrate ions which is accompanied by the release of H^+ ions (Belyaeva and Haynes, 2009a). The composting mass is thus returned to a lower pH medium (Witter and Lopez-Real, 1988). According to Figure **4.7 (a)** , A started this stage after 11 days to reach a lower pH of 6.85 on day 30, while B and C started exhibiting a decrease in pH from day 2 itself to reach a pH of 7.14 and 6.86 on day 30 respectively. For D, E and F, ammonia volatilisation

and/or nitrification phase started to manifest itself after day 10 whereby the pH of the composting mass decreased to 6.82, 6.75 and 6.86 respectively.

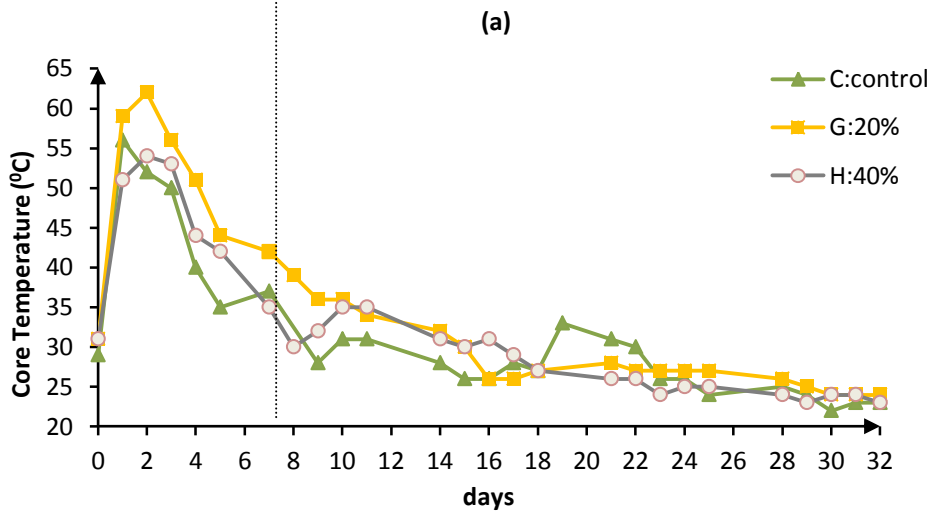### 4.3.3.2 Wastes amended with coal ash

(a)

(b)

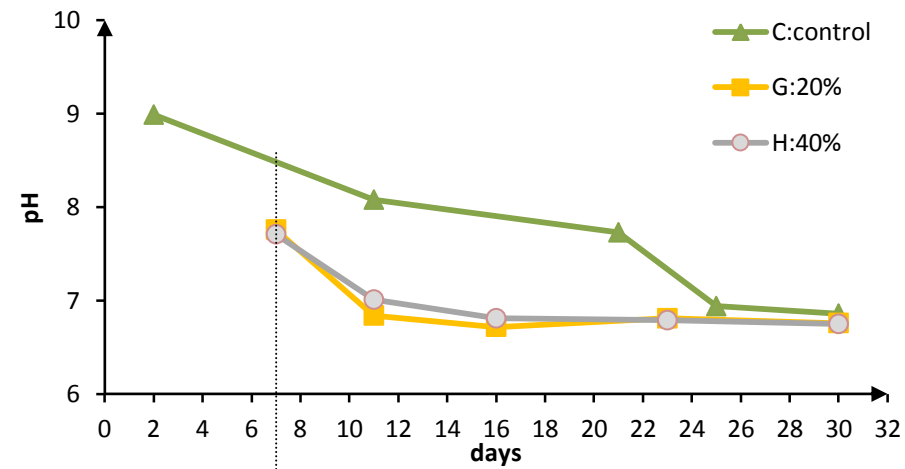**Figure 4.9: Correlation between (a) pH and (b) Temperature variations for unsorted wastes amended with coal ash**
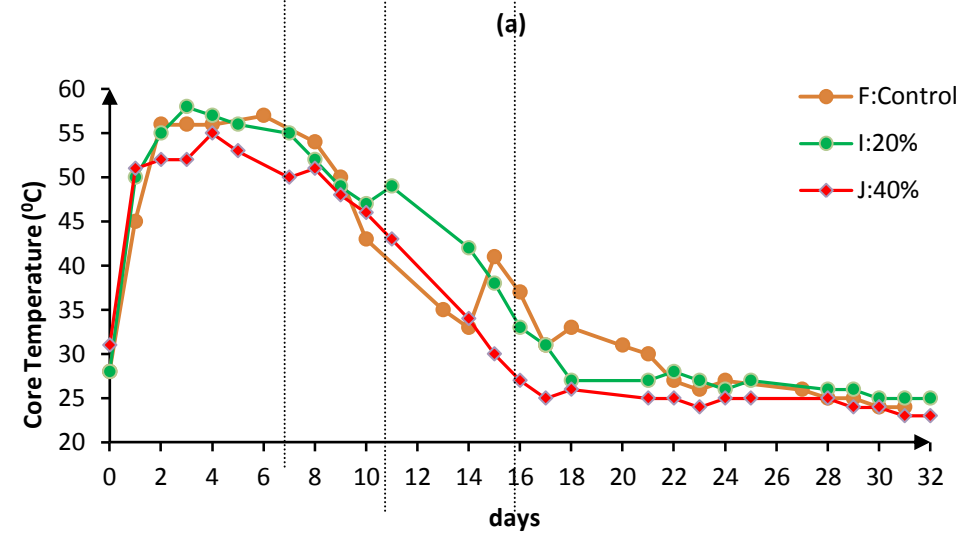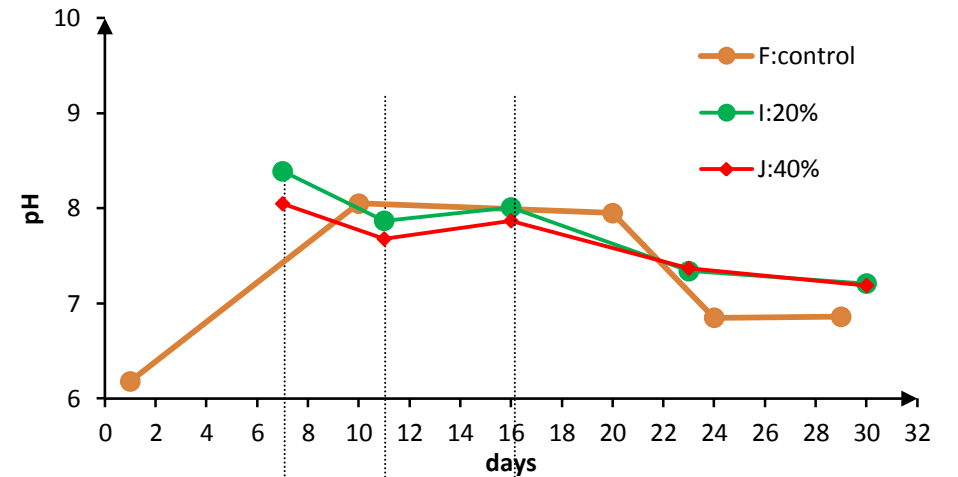

(a)

(b)

Figure 4.10: Correlation between (a) pH and (b) Temperature variations for sorted wastes amended with coal ash

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Samplings for coal ash setups started 7 days after the setups were completed, which surpassed the acid formation and peak temperature period. For the unsorted wastes G and H, the decreasing trend in **Figure 4.9 (a**) suggests that the phase whereby organic acids are utilised as substrates leading to pH rise was also completed. Day7 and onwards denotes an NH_3 volatilisation and/or nitrification event which corresponded to the decrease in pH from 7.76 to 6.76.

For I and J, the corresponding temperature profile during which initial samples were taken indicated a quasi-stable fluctuation within high temperature region, suggesting an on-going acid formation process as a result of continuous degradation of abundant readily biodegradable substrates. This situation has been reflected in terms of an initial decreasing pH trend obtained by these two setups. According to **Figure 4.10 (a),** organic acids depletion may have occurred as from day 10, explaining the rising pH profile. From day 16 and onwards, the pH decreased to 7.21 and 7.16 for I and J respectively, most probably denoting an NH_3 volatilisation and/or nitrification event.

According to MS 164 specifications as well as US EPA (1995), finished compost should have a pH between 6 - 8; a target that the composting masses seems to be achieving given the final values ranging within 6.71 – 7.14.
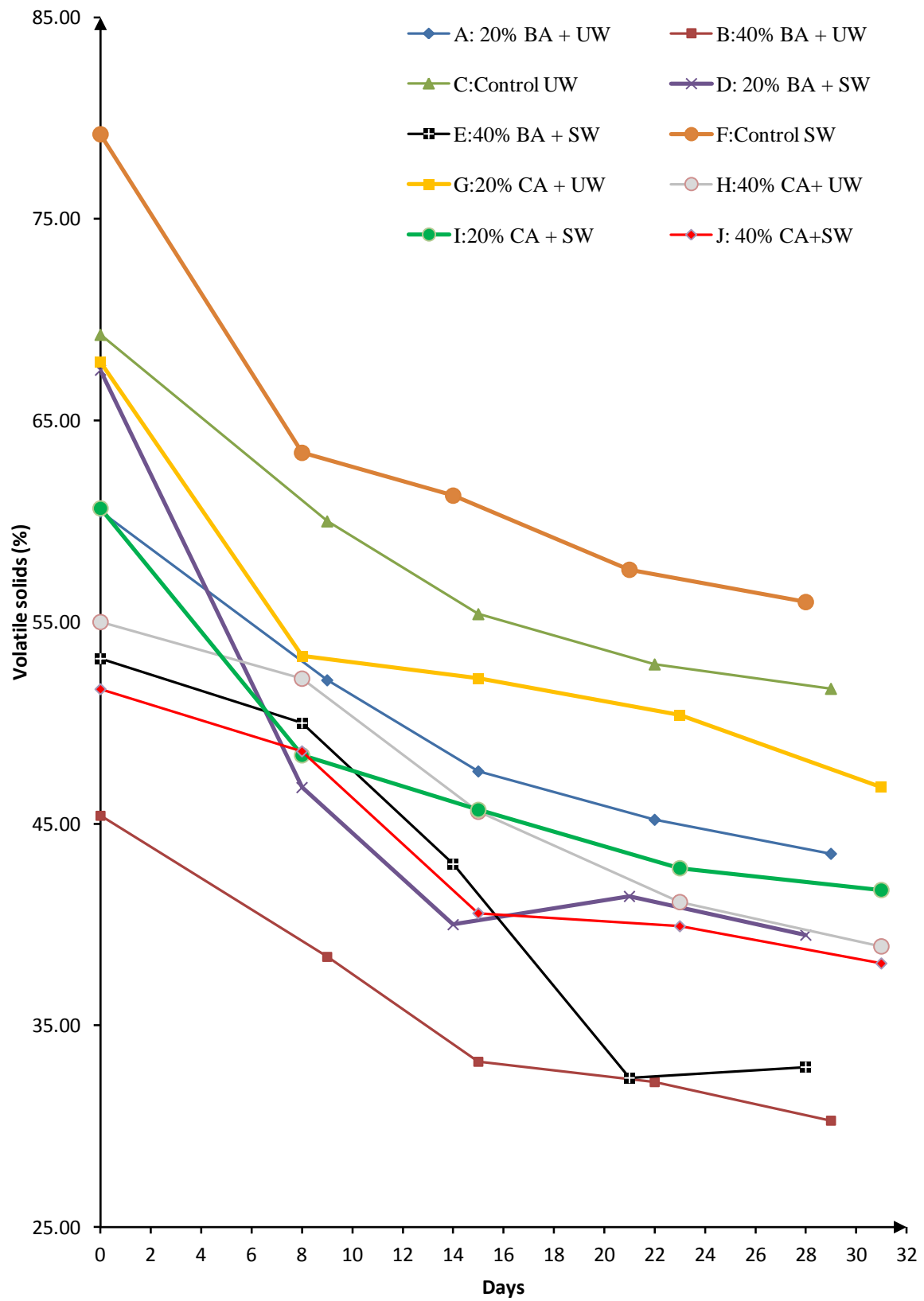
4.3.4 Volatile Solids

Figure 4.11: VS Variation

Table 4.3: Correlation between VS change and Temperature

	Initial VS %	Final VS %	Net % VS Change (fixed ash basis)	Peak Temp reached	Retention time > 55^{0}C
A	60.48	43.51	49.66	52	0
B	45.40	30.28	47.77	50	0
C	69.25	51.70	52.48	56	1
D	67.50	39.48	68.59	**62**	**4**
E	53.19	32.93	56.79	54	0
F	79.20	56.00	66.57	**57**	**3**
G	67.91	46.81	58.41	**62**	**3**
H	55.01	38.92	47.88	54	0
I	60.65	41.72	53.66	**58**	**3**
J	51.68	38.08	42.50	54	0

One of the first observations made during VS analyses was the lowered VS content of the composting mass in accordance to increased application rate of coal ash and bagasse ash; all the ash amended mixtures had lower VS as compared to their respective controls, with the 40% application rate producing the lowest VS content. This may be related to the low volatile solids content of the ashes itself as obtained from the characterization study detailed in **Table 4.1**. A similar observation was made by Zeng *et al*. (2003) who stated that total organic matter of the composting mass decreased with increasing coal ash addition as a result of its inorganic nature. One present anomaly, however, was the higher VS content of unsorted wastes amended with coal ash as compared to sorted wastes amended with coal ash; such irregularity may have occurred either due to the presence of non-homogeneous pockets within the drums leading to sampling that might not be a representative of the whole composting mass, or due to presence of inert plastic particles that have been ignited and hence measured as organic matter (California compost quality council, 2001).

During the composting process, the VS% of composting masses A-I decreased from 79.20% - 45.40% to 56.00 -30.28% after a composting period of 5 weeks. The decreasing trend of volatile solids may be attributed to the statements offered by Mao *et al*. (2006) and Gajalakshmi and Abassi (2008) whereby according to them, transformation of organic wastes is achieved through mineralisation and humification during the composting process which is accompanied by emissions of metabolic by-products like biomass, inorganic materials and volatile organic compounds.

According to Morel *et al*. (1986) and Chen and Bar (1996), because of the availability of a large proportion of initial organic matter, the rate of decrease is usually faster at the beginning whereby the

degradation of the most easily biodegradable organic matter occurs. Similar trend was exhibited by all the setups except E which showed higher rate of degradation afterwards. This may be probably because of its higher resistant organic contents than rapidly biodegradable substrates (Bernal *et al.*, 2009). Furthermore, according to the **Figure 4.11**, fastest initial decrease was demonstrated by the curves D, F, G and I.

In terms of VS change, for sorted wastes, setup D (20% bagasse ash) achieved the highest degradation as implied by the highest net VS change of 68.59% shown in **Table 4.3**, while for the unsorted category, setup G (20% coal ash) showed a highest VS change of 58.41%. Temperature, being an influence to the rate of biochemical processes (Norbu, 2002), might have been the key factor for setup D and G. Though having initial lower VS than their control due to ash addition, the high degradation rate and net VS change by D and G may be attributed to the high peak temperature of 62^0C attained along with a 4 and 3- day retention time respectively above 55^0C as a result of improved composting as discussed previously. The fact that ash amendment leads to a better degrading performance was also proved in studies made by An *et al.* (2012) and Wong *et al.* (2009) on coal ash amendment.

High degradation rate in setup F may have largely depended on the abundant available organic matter (as denoted by the high initial VS of 79.20%), leading to a more intense process of mineralisation and consequently resulting in more loss of volatile organic matter as suggested by An *et al.* (2012). While I reached a higher peak temperature than its control (F) as well, the control showed higher degradation characteristics. Such behaviour may be explained by that fact that both F and I reached similar high temperature characteristics with similar retention time above 55^0C, but with an additional advantage of having a higher initial VS content, F showed a better degradation rate.

On the other hand, the lower degradation rate of A, B, E, H and J as compared to their controls, may be linked to the inhibition caused by ash addition as explained before during temperature analyses.

According to MS 164 Specifications, volatile solids (organic matter) content of composts should typically be greater than 25%. Experimental results show that all the final VS lie above 25% though B and E is very near to the lower limit. The lower final VS content of the ash-amended wastes may be attributed to the fact that their VS content was already low from the start as a result of ash addition.
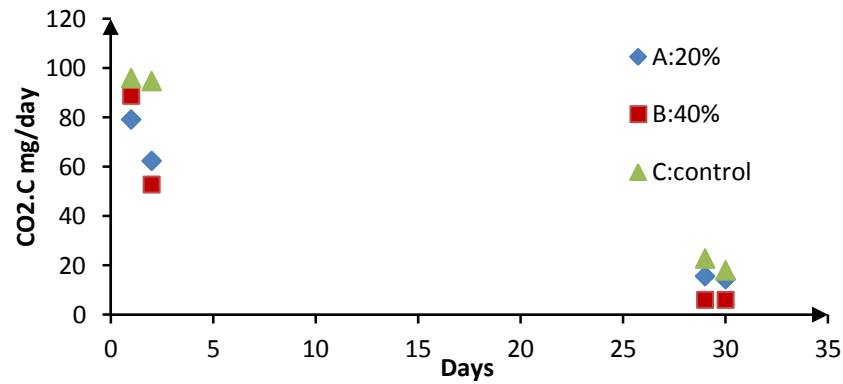
4.3.5 Respiration

Figure 4.12: Respiration rate for Unsorted wastes amended with bagasse ash
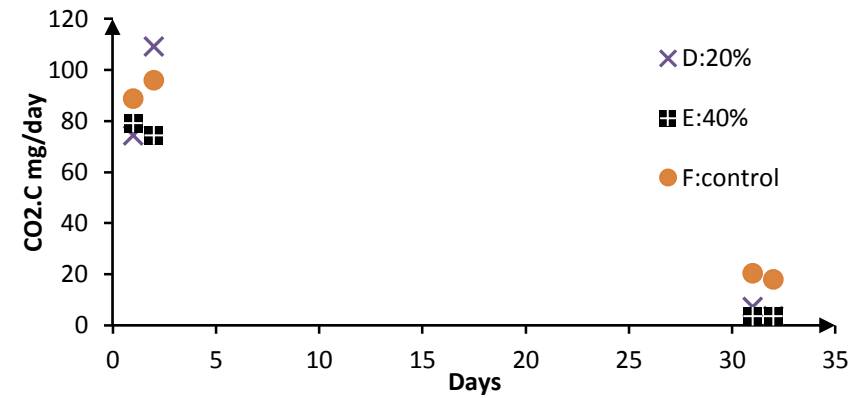

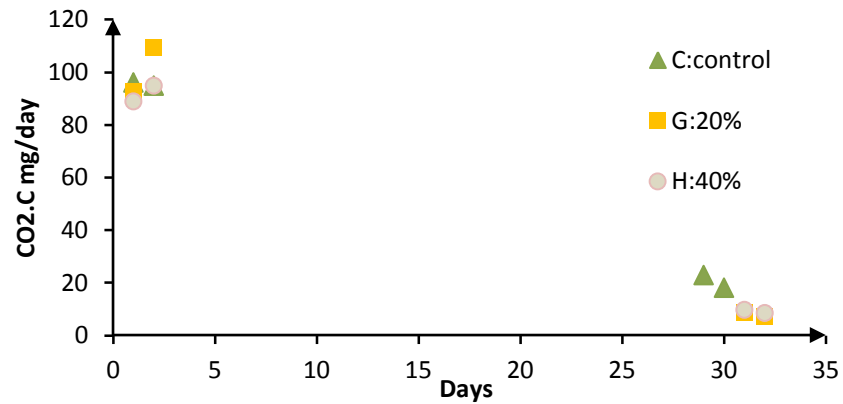**Figure 4.13: Respiration Rate for Sorted wastes amended with bagasse ash**

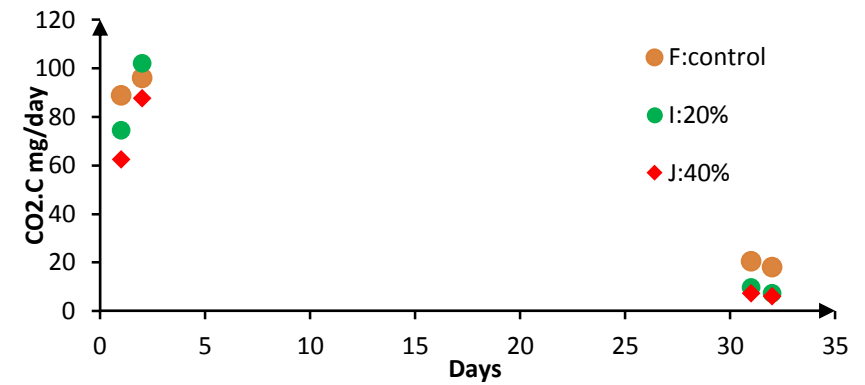**Figure 4.14: Respiration rate for unsorted wastes amended with coal ash**

Figure 4.15: Respiration rate for sorted wastes amended with coal ash

High initial rates for all the setups confirm the immediate action of the biocculum added whereby an increase in microbial activity was initiated on the first day itself. From **Figure 4.12**, the lower respiration rates of A and B as compared to C further support the inhibitive effect of the ash amended mass to adaptation of microbial population. Similarly, higher respiration rates achieved by D, G and I as compared to their controls, as shown in **Figure 4.13, 4.14 and 4.15**, emphasise on the favourable conditions provided by the 20% bagasse/coal ash in terms of aeration and buffering of the composting mass during organic acids formation as discussed previously. Lower microbial activity displayed by E, H and J as compared to their controls was related to the innapropriate medium, characteristed by low VS% and excessive dosage of the 40% ash, that reduced the availability of food subsrates to microorganisms and thereby disturbed their growth. As reported previously, Fang *et al.* (97, 98, 99) also observed a similar lowered thermophilic bacterial activity as a result of adverse effect of high dosage of fly ash amendment.

A-C showed initial decreasing trend of microbial activity that may be correlated to the fact that they started showing sign of temperature drop after 1day only. The intial increasing trend of microbial activity for D, F, G, H, I and J may be related the continual rise in temperature upto day 2, 6, 2, 2, 3 and 4 respectively where each composting mass achieved its peak temperaure before temperature drop started occuring. The correlation of microbial activity to temperature has been justified by Zimmerman (1991), who stated that heat released as a result of microbial metabolism could infact be considered as an indicator of respiration rate. One irregularity obtained was that while E experienced its peak temperature on day 2, the CO_2 evolution obtained for day 2 decreased. One plausible explanation might be that the sample taken for E failed to represent the conditions prevailing within the composting drum.

After 30 days of composting for A-C and 32 days for D-I the respiration rate of the microbial population for A-Iwas measured and rated according to the stability index as tabulated below:

Table 4.4: Respiration Rating Index

Respiration rate (mg CO_2.C/g organic carbon/day)	Rating
< 2	Very Stable
2 – 5	Stable
5 – 10	Moderately Stable
10 – 20	Unstable
>20	Extremely stable

Table 4.5: Reparation Rate and Rating

	Respiration rate (mg CO_2 C/g organic carbon/day)	Rating
A (20% BA +UW)	5.91	Moderately stable
B (40% BA + UW)	3.65	Stable
C (control UW)	5.61	Moderately stable
D (20% BA + UW)	1.62	Very stable
E (40% BA + UW)	1.89	Very stable
F (Control SW)	5.71	Moderately stable
G (20% CA + UW)	2.67	Stable
H (40% CA + UW)	3.64	Stable
I (20% CA + SW)	2.90	Stable
J (40% CA + SW)	2.71	Stable

The descent from peak temperature to room temperature usually brings about the degradation of complex polymers like lignin and ligno-cellulose throuh fungal activity (Zach *et al*., 2000). D had undergone maximum degradation during the thermophilic phase thus resulting in a probably lower about of subsrates to be degraded afterwards; a fact that may explain its fastest stabilisation. From the VS% graphs, during cooling-phase degradation, E showed the highest rate of complex subsrates breakdown as suggested by the steep slope from day 14 to 27 which may have led to a fast stabilisation and correspondingly a fast decline in microbial activity. Among the unsorted wastes, G achieved the highest stability and this may be correlated to its high peak temperature achieved that resulted in maximum VS degradation for the unsorted catergory, as achieved by D for the sorted category. The rapid decline of microbial activity in the following 40% ash amended wastes: B, H and J, may be associated with the low VS content and high dosage of ash of the composting mass that either resulted in a limited food supply to the microorganisms and hence rapid depletion leading to a shorter period of microbial activity; or the unfavorable conditions produced by the high ash dose and low VS content might have inactivated the microorganisms before complete stabilisation of the composting substrates. The higher stability index for for setup A, C and F denotes a slower procress of the complex substrates breakdown, though degradation was sufficient enough to classify these setups as moderately stable.
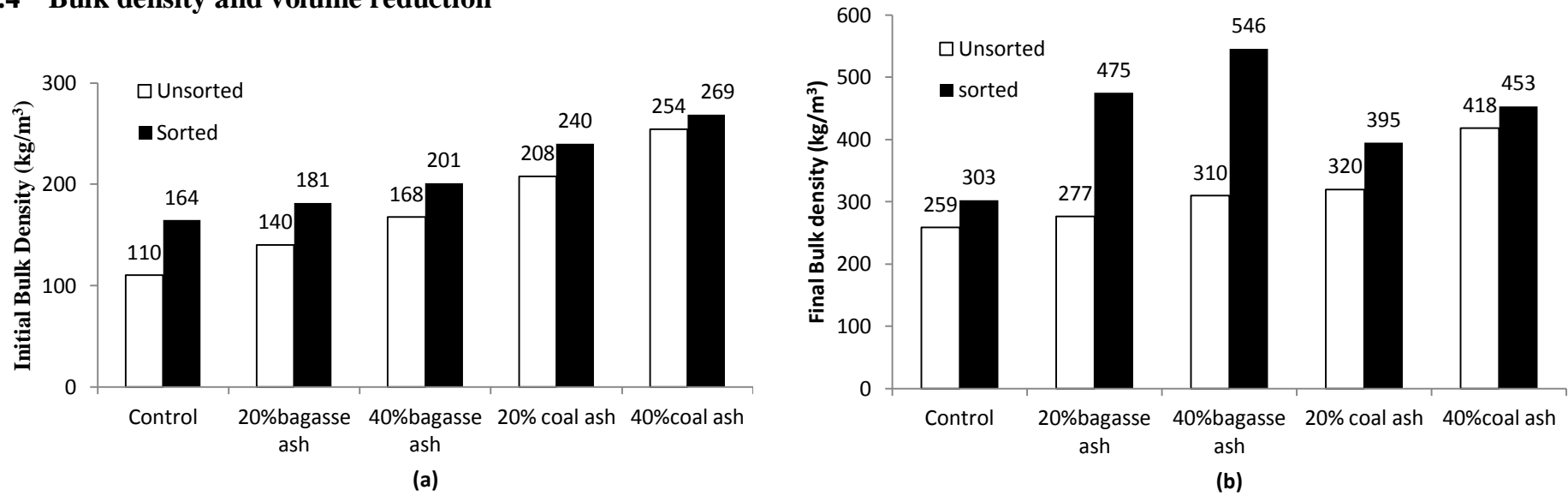
4.4   Bulk density and volume reduction

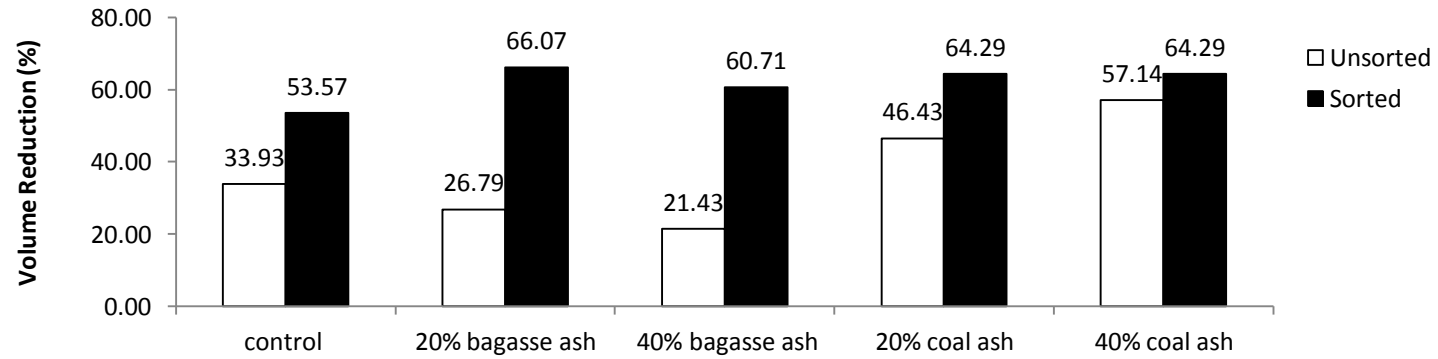**Figure 4.16: (a) Initial and (b) Final Bulk densities**

Figure 4.17: Volume reduction

Initial bulk density increased with increasing ash addition as shown in **Figure 4.16 (a)** and this may be related to the high bulk densities of coal fly ash (798.22 kg/m^3) and bagasse fly ash (480 kg/m^3). Such behaviour tallies with the observations made by Belyaeva and Haynes (2009a) who noticed a similar increase in bulk densities when coal fly ash were added to green wastes and attributed this raise to the high bulk density of coal fly ash. On the same note, the higher bulk densities exhibited by coal ash mixtures as compared to bagasse ash mixtures can be explained by coal fly ash having a greater bulk density than bagasse fly ash.
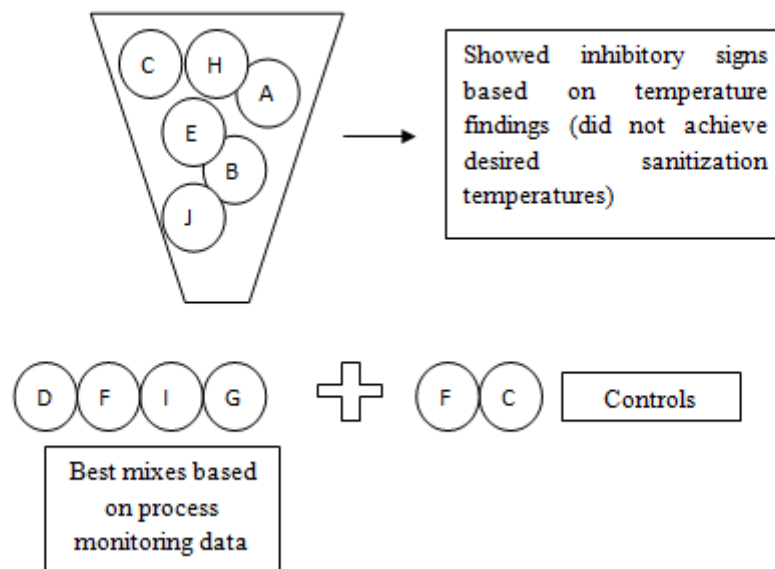
A volume reduction ranging from 21.43 – 66.07% coupled with an increase in bulk density from 110 – 268.89 kg/m^3 to 258.57 – 546 kg/m^3 indicated the occurrence of settlement which may be ascribed to the effects of subsidence and compressive settlement; to mass loss settlement due to organic matter degradation and to changes in mechanical property of the composting material at increased temperature conditions (Van Lier *et al.*, 1994; Van Ginkel *et al.*, 1999; Bowders *et al.*, 2000; Chan and Veeken, 2004). Reduction in mass and volume is a key parameter to the design of composting facility in terms of space availability (Breitenbeck and Schellinger, 2004).

Sorted wastes were characterised by higher bulk densities and volume reduction as compared to unsorted wastes. High bulk density is an inherent trait of sorted wastes whereby similar substrates pack up more easily reducing the void spaces unlike the assorted substrates of unsorted wastes leading to a very porous medium. Higher volume reduction, on the other hand, would be a consequence of higher retention time of the sorted wastes above 55^{0}C and at thermophilic range leading to more degradation as shown in **Table 4.3**. Among these sorted wastes, 20% addition of bagasse ash (D) led to the highest volume reduction of 66.07% as illustrated in **Figure 4.17**. The highest peak temperature achieved by this mixture along with highest net VS change of 68.59% might have contributed to enhanced changes in mechanical property at high temperatures and mass loss, favouring a greater degree of settlement.

Similar to initial bulk densities, a positive correlation between final bulk density and ash application rate was observed as indicated in **Figure 4.16 (b),** whereby higher ash application rate achieved a higher bulk density; however, in contrast to initial scenario, final data showed that sorted wastes amended with bagasse ash demonstrated higher bulk density characteristics as compared to the sorted wastes amended to coal ash. This can be correlated to the higher net VS changes, hence greater degradation, attained by bagasse ash amended setups as compared to the coal-ash amended setups.

4.5 COMPOST QUALITY TESTS

4.5.1 Funnel Approach to select the best mixes for compost quality tests

Figure 4.18: Filtering of non-conforming composted mass

After 30-32 days of composting, all the 10 setups were at least moderately stable, with D achieving the highest stability, followed closely by G and I. Those composting masses that did not meet the process regulatory requirements, with **the attainment of sanitization temperatures being the main criteria here,** were filtered. On a preliminary analysis, D, F, G and I thrived as those composting masses that were deemed to be suitable for agricultural application. To further assess the feasibility of their application, theses composted masses were additionally analysed in terms of their final pH and conductivity; Nitrogen content and C/N ratio; water holding capacity and Germination indexes. For comparison purposes, their controls were tested as well.

4.5.2 Final pH

Figure 4.19: Final pH Values

The pH trend of the above 6 setups converged toward pH values that lies within the MS 164 specifications as well as US composting council, implying no alkaline or acidic inhibition to plant growth. Considering the high pH characteristics of the ashes, it might as well be deduced that the acid formation phase of the composting process has counteracted this high pH, thereby indicating that composting is a suitable means of disposing coal and bagasse ashes in a safe manner.

4.5.3 Final Electrical Conductivity

Figure 4.20: Final ECs values

Bagasse ash amended composts showed higher electrical conductivities (ECs) as compared to the coal-ash amended composts and this may be correlated to the higher electrical conductivity of bagasse fly ash (1249) as compared to that of the coal ash (756). Final ash-amended composts had higher ECs than the EC of the fly ashes most probably because of concentration of mineral cation occurring as a result of loss of organic carbon during composting (Francou *et al.*, 2005). While compost phytotoxicity has been linked with ECs higher than 3.5dS/m by MS 164 specifications and higher than 5 dS/m by US composting council, the rise in ECs was not dramatic, resulting in final ECs within the threshold of regulations. Maintenance of within-range electrical conductivities may have been caused by in-process reduction through precipitation of soluble salts due a high retention time with the carbon dioxide released during composting, and binding of the salts to the stable organic contents (Francou *et al.* 2005, Fang *et al.*, 1998). Such simultaneous mechanisms of salt concentration together with salt precipitation and salt binding might have lowered the rise in EC, resulting in composted masses fit for agricultural use.

4.5.4   Nitrogen content and C/N ratio

Figure 4.21: initial and final N content in (a) sorted and (b) unsorted setups

Figure 4.8: Initial and Final C/N ratio in (a) sorted and (b) unsorted setups

– – – – Final desired limit

– – – – Initial desired limit

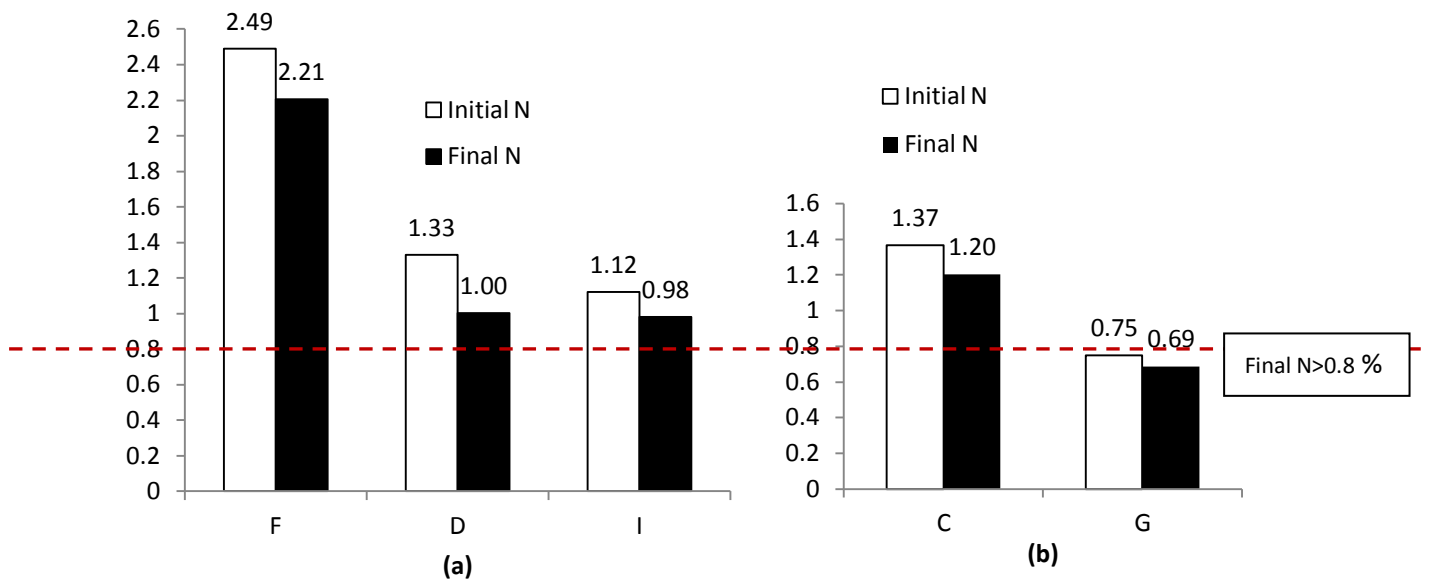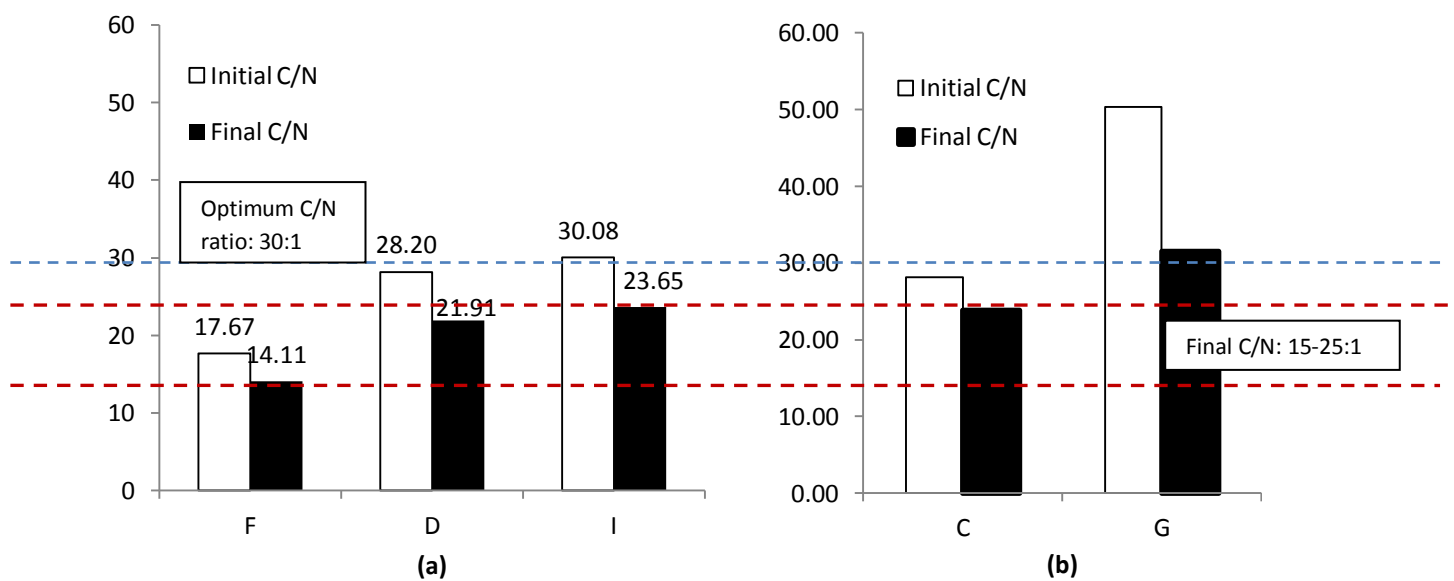From **Figure 4.21(a),** it appeared that addition of ashes to the municipal solid wastes (sorted and unsorted) decreased the overall nitrogen content of the mixture. This could be explained by the low nitrogen content of the coal and bagasse fly ash which were characterised with 0.3 and 0.15% nitrogen respectively. Such reduction was found to be detrimental to setup G (20% coal ash in unsorted wastes) as while the composting standard (MS 164) specified a nitrogen content greater than 0.8% in the final product, G exhibited a nitrogen content lower than 0.8% (0.75%) at the beginning of the process itself. This unfavourable effect might be linked to the already low nitrogen content in the unsorted wastes (1.37% as compared to 2.49% in sorted wastes) which was further reduced during coal ash addition.

A decrease in Nitrogen content was observed for all the analysed samples; a behaviour that reflects the trait of a normal composting process. The decrease in nitrogen content is generally a consequence of partial nitrogen assimilation by the microorganisms for the synthesis of proteins and substantial loss of nitrogen through ammonia volatilisation (An *et al*., 2012; Morisaki *et al*., 1989). According to Martins and Dewes (1992), Rao Bhamidimarri and Pandey (1996) and Tiquia and Tam (2000), about 20-70% of the initial nitrogen content may be lost through ammonia volatilisation, leaching and run off; leaching and runoff being insignificant losses in this study given that the composting was conducted in drums. Hence the main nitrogen loss mechanism may be attributed to ammonia volatilisation. Another cause of nitrogen loss could be the presence of anaerobic pockets within the composting mass that may have led to the microbial denitrification of NO_3^-/NO_2^- to release nitrogen gas, nitrogen oxide and dioxides into the atmosphere (Wong *et al*., 2009; Tiquia, 2002). However, given the regular turnings carried out coupled with the porous nature of the ashes even at high moisture, denitrification process might have been very low as compared to ammonia volatilisation.

The final N content of the analysed samples met the MS 164 regulations by being greater than 0.8%, except G since its initial N content were already lower than 0.8%. Such observations implied that 20% coal ash (I) and bagasse ash (D) in sorted wastes mixtures, though having lower final nitrogen content than the sorted control (F), were not deficient in terms of nutrient content for plant growth. On the other hand, ash addition to unsorted wastes was not favourable in terms of nitrogen availability for plant growth. However, from another point of view, it was proved that ash-amended composts are more nitrogen rich as compared to fly ashes alone implying that co-composting of fly ashes with MSW enhances the effectiveness of fly ashes in agricultural field as stated by Ravikumar et al. (2008).

The control for sorted wastes (F) was characterised with a very low C/N ratio (17.67) which is a result of its very high nitrogen content. Such low starting C/N gave composting mass F an odourous

characteristic that was less obvious in the other setups. Addition of the low nitrogen content ashes to the sorted wastes improved the C/N ratio by increasing it to values close to the optimum one (30:1) as shown by the composting mass D (28.20) and I (30.08), and thus diminished the odour emanation as compared to the sorted wastes control. Furthermore, Koivula *et al.* (2004) also talked about the ability of ash to suppress odours formed during composting period as well as the odour of the final product by virtue of the carbon present in the ashes that act as active carbon filters. As for the unsorted wastes, since the control was already at its optimum C/N ratio, addition of coal ash raised the C/N ratio to a highly unfavourable one. Hence one deduction that can be made from these data would be that coal and bagasse ash could favourably be used as an amendment to low C/N substrates

While nitrogen is utilised only partially for protein synthesis, a much larger portion of carbon is being consumed as an energy source by the microbial population leading to a higher rate of carbon reduction as compared to nitrogen reduction (An *et al*., 2012). This gives rise to a decrease in C/N ratio as demonstrated by the change in data from **Figure 4.22 (a) to 4.22 (b)**. A decreased C/N ratio would indicate a proper mineralization of carbonaceous material while at the same time suggesting that nitrogen losses were not occurring at a too vigorous rate that could detriment the quality of the end-product.

The ash-amended composted mass D and I had a final C/N value corresponding to the MS 164 range of 15-25:1 as compared to their control (F) which falls slightly outside the range. For the case of unsorted setups, the control (C) showed better final C/N value as compared to the coal ash-amended setup which largely exceeded the desired range.

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4.5.5 Water holding capacity

Figure 4.93: Water holding capacities

Table 4.6: Correlation between Water holding capacity, organic content and bulk density

Composting mass	Volatile solids	Bulk density	WHC
C	51.70	258.57	216.79
F	56.00	302.50	197.88
I	41.72	395.00	194. 94
D	39.48	475.00	186.21
G	46.81	320.00	183.18

Water holding capacity is the outcome of a combined influence of the bulk density, the organic content and the porosity of the analysed material. According to the United States Department of Agriculture, water holding capacity is favoured by an increase in organic matter content and porosity and a decrease in bulk density. This may be further supported by Agodzo and Adama (2003) who found a positive correlation with highest water holding capacities and least bulk densities in soil characterization studies and by Gupta *et al.* (2010) who noted that water holding capacities were positively related to organic content. Highest water holding capacity was achieved by the setup consisting of unsorted wastes only given its lowest bulk density and quite high organic content. Addition of ash decreased the organic content and increased the bulk density of the composting mixture, hence yielding to lower final organic content and higher final bulk density as tabulated above in **Table 4.6**. The influence of lowered VS and raised bulk density was reflected in terms of lowered water holding capacities whereby the ash-amended compost showed a lower water holding capacity

than the non- amended composted mass. However it can be observed that the decrease in water holding capacities was not drastic; the values are very much comparable each other as depicted in **Figure 4.23**. This may be explained by the porosity of the mixture. According to Haynes and Belyaeva (2009b), an increase in mesopores and a decrease in macropores would lead to an increase in water holding capacity. The same study characterized fly ash as fine texture, with a % of mesopores being greater than thrice the macropores content. Addition of fly ash to the mixtures would have filled the larger pores of the composting mass, diminished the macroporosity and increased the mesoporosity of the mixture, thereby creating favorable conditions for high water holding capacity (Haynes and Belyaeva, 2009b). Such event might have counteracted the negative effect of lowered organic content and high bulk density and maintained a high water holding capacity, explaining the similarity between the experimental data obtained. Setup G did not seem to follow the above explained trend as it exhibited a lower water holding capacity than I, despite having a higher organic content and lower bulk density; this may be attributed to heterogeneity in samplings and experimental conditions.

4.5.6 Germination Assays

Table 4.7: Germination Indices

Composted mass	Unsorted			Sorted	
	C- control	G – 20% coal ash	F - control	D – 20% bagasse ash	I – 20% coal ash
Full strength extract	0.33	1.25	0.36	0.89	0.99
X10 dilution	1.45	1.73	1.01	1.37	1.76

Ash-amended wastes led to composts exhibiting higher germination potential as compared to the unammended wastes, with no inhibitive characteristics when the extract was utilised at full strength. Factors leading to such observations might firstly be an improved sanitization of the composting material given the higher temperatures and retention time at pathogen destruction temperatures achieved by the ash-amended composts.

According to Haynes and Belyaeva(2009a, 2009b) , limitations to plant growth may be caused by a high pH, high level of soluble salts and extractable phosphorus, deficiency of Nitrogen and accumulation of NH_4^+ - N. ECs and pH are within the compost quality range while ammonium toxicity might be rarefied by the NH_3 volatilisation event discussed in pH variation section. Regarding the phosphorus content, Hue *et al*. (1994) characterised wholly organic material of containing high levels of extractable P, given that organic material have insignificant P sorption capacity. While P is important for plant growth at concentrations of 15-30 mg/L, extremely high level of P are considered to be harmful (Haynes and Belyaeva, 2009b). Fly ashes on the other hand, consist of mineral surfaces (e.g. Fe and Al) with high P adsorptive characteristics, and are hence able to reduce the too high extractable levels of P by converting them into non-extractable forms through adsorption of P on their surfaces (Haynes and Belyaeva, 2009b; Gupta *et al*., 2002). This might have contributed in higher GI indices in ash-amended composts as compared to the controls. Haynes and Belyaeva (2009b) also noted higher GI indices when green wastes – derived compost was mixed with fly ashes as compared to composted green wastes alone and related this behaviour to lower extractable P levels in ash-amended compost.

In terms of Nitrogen content, all the compost produced contained the at least the minimum amount of nutrient required for plant growth, except G. However, despite unfavourable N content and final C/N ratio, G showed better germination performance as compared to its control (C). Sanitization temperatures achieved by G as compared to C coupled with higher VS degradation and stabilisation than might have favoured germination under the effect of compost G. G was also characterised by a

higher final organic content as compared to bagasse ash amended products, which might explain higher germination of the seeds.

Coal-ash amended composts demonstrated higher germination indexes which may be associated to their lower salt content as compared to bagasse-ash amended composts, causing a lower hindrance during water intake (Koivula *et al*., 2004).

4.5.7   Final heavy metals content

Table 4.8: Final Heavy metal concentrations in composts derived from ash amended wastes

Toxic Element	MS:164 Requirements (mg/kg)	Coal fly ash	20% Coal ash in sorted wastes (I)	20% Coal ash in unsorted wastes (G)	Bagasse fly ash	20% bagasse ash in sorted wastes (D)
Arsenic	≤ 10	N/D	N/D	N/D	N/D	N/D
Cadmium	≤ 3	N/D	N/D	N/D	N/D	N/D
Chromium	≤ 50	44.23	38.82	**55.28**	**59.68**	44.32
Copper	≤ 200	34.61	36.06	33.86	50.58	37.36
Lead	≤ 100	25.91	16.17	15.28	16.25	12.37
Mercury	≤ 0.15	**0.2**	0.08	0.15	0.15	0.1
Nickel	≤ 50	35.13	20.33	27.64	34.07	28.7
Zinc	≤ 300	86.97	89	84.02	212.9	111.3

According to the above tabulated **(Table 4.8)** preliminary analyses of heavy metals content, initial characterisation of ashes demonstrated that bagasse fly ash exceeded the Composting Standard (MS 164) stipulated norm of chromium concentration while in the case of coal fly ash, mercury content was above the limit value of contamination. Addition of 20% coal ash to sorted and unsorted MSW and 20% bagasse ash to sorted MSW lessened the too high amount of mercury and chromium respectively to values in line with the MS 164. Similar quantitative lessening of metal contents was observed for the entire metallic constituent in bagasse fly ash when 20% bagasse fly ash was composted with sorted wastes; for the case of coal ash, Lead, Nickel and Mercury showed such significant decrease. Such observation may be attributed to the municipal solid wastes acting as diluents to the coal ash and bagasse ash thereby reducing the metallic concentrations of the mixture (Menon *et al*., 1992).

A slightly above-range final chromium concentration was recorded in unsorted wastes composted with 20% coal ash. The composted mix D (20% bagasse ash in sorted wastes) and I (20% coal ash in

sorted wastes) on the other hand yielded heavy metals concentrations below the threshold setup by the MS 164 standard; accordingly these composted masses should not lead to any hindrance and hazard during their application as organic fertilizers. Similar compliance to heavy metals limit value of contamination was observed in past studies whereby co-composting of coal fly ash and lime with food wastes to enhance efficiency of decomposition (Wong *et al*., 199) and addition of fuel ash to source-separated catering wastes prior to composting resulted in final heavy metal concentrations that did not restrict the use of the composts produced (Koivula *et al*., 2004).

4.5.8 Summary of findings
Table 4.9 compiles all the important findings of the study carried out.

Table 4.9: Summary of findings

	Unsorted			Sorted		Requirement
Composted mass	*C-control*	*G – 20% coal ash*	*F - control*	*D – 20% bagasse ash*	*I – 20% coal ash*	*MS 164 unless otherwise specified*
Peak temperature	56	62	57	62	58	
Time above 55	1	3	3	4	3	≥ 3 (US EPA, 1995)
Time spent in thermophilic range	4	7	11	13	15	
Net VS change	52.48	58.41	66.57	68.59	53.56	
Final VS	51.70	46.81	56.00	39.48	41.72	> 25%
Initial C/N	28.12	50.37	17.67	28.20	30.08	30:1 (US EPA, 1995)
Final C/N	23.85	31.52	14.11	21.91	23.65	15-25:1
Final Nitrogen content	1.20	0.69	2.21	1.00	0.98	> 0.8%
Final pH	6.86	6.69	6.86	6.82	7.12	5.5-8.0
Final EC	1771	794	1142	1588	1009	<3500μS/cm
WHC	216.79	183.18	197.88	186.21	198.84	
Stability after 30/32 days	5.61	2.67	5.71	1.62	2.90	
GI (full strength)	0.33	1.25	0.36	0.89	0.99	
GI (x10 dilution)	1.45	1.73	1.01	1.37	1.76	> 0.8
Final Heavy metals content	-	Cr exceeded	-	All within range	All within range	

5 CONCLUSION

20% bagasse ash in sorted wastes and 20% coal ash in both sorted and unsorted wastes favoured higher peak temperatures and ensured a retention time of at least 3 days above 55^0C; such improvement was related to an enhanced aeration and buffering of the composting process due to the porous structure and alkalinity of the coal ash and bagasse ash. Considering sorted wastes, highest net VS change (68.59%) and volume reduction (66.07%) was achieved when 20% of bagasse ash was added to these sorted wastes, while for the case of unsorted wastes, 20% coal ash addition attained the highest VS change (58.41%) and volume reduction (64.29%). All the composting mix that were deemed to be suitable for crop application, (D, F, G and I) along with the sorted (F) and unsorted control (C) had their final product analysed for compost quality. All the setups were within range in terms of final pH and electrical conductivities and exhibited high and comparable water holding capacities. Addition of 20% coal ash and 20% bagasse ash amended the low starting C/N ratio of sorted wastes to optimum starting C/N ratio, leading to less odour emanation. Within the same composting period, ash-amended wastes reached a higher stability than non-amended composting masses, with 20% bagasse ash in sorted wastes reaching the highest stability. 20% coal ash amended sorted and unsorted wastes and 20% bagasse ash amended sorted wastes also improved the Germination Indices inferring to the favourability of using coal and bagasse ash as amendment in the composting process. Regarding the abatement of coal ash and bagasse ash pollution in the environment, while the initial concentrations of some metallic components in bagasse and coal ashes exceeded the MS 164 norms, incorporating 20% of coal ash and bagasse ash in sorted MSW prior to the composting process lessened the concentrations of all metallic component to values in line with the Mauritius composting standard (MS 164). Such preliminary analyses emphasize on the potential of composting as a remediating process to coal ash and bagasse ash toxicity.

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6   REFERENCES

1.   ABBOUD, S. AND HEIDMAN, A. 2002. Curing partially co-composted municipal soil waste and biosolids. *In: Presentation to 2002 Compost Council of Canada Conference Halifax, Nova.*

2.   ADRIANO, D.D., PAGE, A.L., ESEEWI, A.A., CHANG, A.C AND STRAUGHAN, I., 1980. Utilisation and disposal of fly ash and other coal residues in terrestrial ecosystems: A review. *Journal of Environmental Quality*, 9, 333 – 344.

3.   AGODZO, S.K. AND ADAMA, I., 2003. Bulk density, cone index and water content relations for some Ghanians soils. *In: Lecture given at the College on Soil Physics Trieste, 3-21 March 2003, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.*

4.   ANGUISSOLA, S., SILVA, S. AND BOTTESCHI, G., 1999. Effect of fly ash on the availability of Zn, Cu, Ni and Cd to chicory. *Agriculture, Ecosystems and Environment*, 72, 159–63

5.   AMIR, S., HAFIDI, M., MERLINA, G. AND REVEL, J.C., 2005. Sequential extraction of heavy metals during composting of sewage sludge. *Chemosphere*, 59, 801 – 810.

6.   AN, CJ., HUANG, JH., YAO, Y., SUN, W. AND AN, K., 2012. Performance of in-vessel composting of food waste in the presence of coal ash and uric acid. *Journal of Hazardous Materials*, 203-204, 38-45.

7.   ANANTHAKRISHNASAMY, S., SAROJINI, S., GUNASEKARAN, G. AND MANIMEGALA, G., 2009. Flyash – a lignite waste management through vermi composting by indigenous earthworms Lampito Mauritii. *American-Eurasian Journal of Agricultural and Environmental Sciences*, 5 (6), 520 - 524.

8.   ANID, P.J., 1986. Evaluating Maturity and Metal Transfer of NSW Compost. *BioCycle*, 27(1), 46-47.

9.   ASGHARIPOUR, M.R. AND SIROUSMEHR, A.R., 2012. Comparison of three techniques for estimating phytotoxicity in municipal solid waste compost. *Annals of Biological Research*, 3(2), 1094 – 1101.

10. BAGUANT, B. K.. AND MOHAMEDBHAI, G.T.G, Mauritius: A study of the potential use of Mauritian bagasse ash in concrete. *In: Third International seminar of the African Network of Scientific and Technological Institutions, 1990 University Of Mauritius*.

11. BALSAMO, M., DI NATALE, F., ERTO, A., LANCIA, A., MONTAGNARO, F. AND SANTORO, L., 2011. Cadmium adsorption by coal combustion ashes-based sorbents— Relationship between sorbent properties and adsorption capacity. *Journal of Hazardous Materials*, 187 (1-3), 371-378.

12. BARDHAN, S., CHEN, Y. AND DICK, W.A., 1999. Recycling for Sustainability: Plant Growth Media from Coal Combustion Products, Biosolids and Compost. *International Journal of Civil and Environmental Engineering*, 1(4), 177-183.

13. BARDOS, P., 2004. *Composting of mechanically segregated fractions of Municipal Solid Wastes – A Review.*

14. BARDOS, R.P. AND LOPEZ-REAL, J.M., 1989. The composting process: Susceptible Feedstocks, Temperature, Microbiology, Sanitisation and Decomposition. *In*: W. BIDHINGMAJER, P. L'HERMITE, eds. *Proc. CEC Workshop on "Compost Processes in Waste Management", 13-15 September 1988, Neresheim, Germany*. SA Belguim: 179-190.

15. BARKER, A.V. AND BRYSON, G.M., 2002. Bioremediation of Heavy metals and Organic Toxicants by Composting. *The Scientific World Journal*, 2, 407-420.

16. BEAVER, T., 1995. *Adding coal ash to the composting mix* [online]. Available from: http://infohouse.p2ric.org/ref/39/38109.pdf [Accessed 19 October 2012]

17. BEFFA, T., 2002. *The composting biotechnology: A microbial aerobic solid substrate fermentation complex process* [online]. Available from: http://www.compag.ch/pdf/THE%20COMPOSTING%20BIOTECHNOLOGY%20COMPLE TE.pdf [Accessed 2 November 2012]

18. BELYAEVA, O.N., AND HAYNES, R.J., 2009. Chemical, microbial and physical properties of manufactured soils produced co-composting municipal green waste with coal fly ash. *Bioresource Technology*, 100, 5203 – 5209.

19. BERNAL, M.P., ALBURQUERQUE, J.A. AND MORAL, R., 2009. Composting of animal manures and chemical criteria for compost maturity assessment: A review. *Bioresource Technology*, 100, 5444–5453.

20. BIDDLESTONE, A.J., BALL, D., AND GRAY, K.R., 1981. Composting and Urban Waste Recycling. *In*: J.T. MANASSAH, E.J. BRISKEY, eds. *Advances in Food Producing Systems for Arid and Semi Arid levels*. Academic Press, 191-224.

21. BOUGNOM, B.P., KNAPP, B.A., ELHOTTOVÁ, D., KOUBOVÁ, A., ETOA, F.X., AND INSAM, H. 2010. Designer compost with biomass ashes for ameliorating acid tropical soils: Effects on the soil microbiota. *Applied soil ecology*.

22. BOULTER, J.I., BOLAND, G.J. AND TREVORS, J.T., 2000. Compost: A study of the development process and end-product potential for suppression of turfgrass disease. *World Journal of Microbiology and Biotechnology*, 16, 115-134.

23. BOWDERS, J.J., BOUAZZA, M., LOEHR, E. AND RUSSELL, M. 2000. Settlement of municipal solid waste landfill. *In: Proceedings of Fourth Kansai International Geotechnical Forum, Creation of New Geo-Environment Kyoto, Japan, 24- 26 May*. 101–106.

24. BREITENBECK, G.A. AND SCHELLINGER, D., 2004. Calculating the reduction in material mass and volume during composting. *Compost Science and Utilization*, 12, 365–371.

25. BRIGDEN, K. AND SANTILLO, D., 2002. *Heavy metal and metalloid content of fly ash collected from the Sual, Mauban and Masinloc coal-fired power plants in the Philippines*. Greenpeace research laboratories, Department of biological sciences, University of Exeter.

26. BRUDER-HUBSCHER, V., LAGARDE, F., LEROY, M. J. F., COUGHANOWR, C. AND ENGUEHARD, F., 2001. Utilisation of bottom ash in road construction: evaluation of the environmental impact. *Waste Management & Research*, 19, 545 - 556.

27. CALIFORNIA COMPOST QUALITY COUNCIL, 2001. *Compost Maturity Index* [online]. Available from: http://www.calrecycle.ca.gov/organics/products/quality/compmaturity.pdf [Accessed 7 December 2012]

28. CANADIAN COUNCILS OF MINISTERS OF THE ENVIRONMENT (CCME), 2005. *Guidelines for Compost quality* [online]. Available from: ttp://www.ccme.ca/assets/pdf/compostgdlns_1340_e.pdf [Accessed 10 December 2012]

29. CARPENTER, A. AND BEECHER, N., 1997. Wood ash finds niche in biosolids composting. *BioCycle*, 38 (1), 37–39.

30. CARLSON, C.L. AND ADRIANO, D.C., 1993. Environmental impacts of coal combustion on residues. *Journal of Environmental Quality*, 22, 227–47

31. CENTRAL STATISTICS OFFICE, 2010. *Economic and Social Indicators, Energy and Water Statistics.*

32. CENTRAL STATISTICS OFFICE, 2011. *Environment Statistics*.

33. CHANG, Z.Z. AND VEEKEN, A., 2004. Effects of temperature on the structure of a compost bed-compress, porosity and permeability. *Journal of Agro-environmental Science,* 23, 791–795.

34. CHANEY, R.L. AND RYAN, J.A., 1993. Heavy metals and toxic organic pollutants in MSW composts: research results on phytoavailability, bioavailability, fate, etc. *In*: H.A.J. HOITINK, H.M. KENNER, eds. *Science and Engineering of Composting*. Worthington, OH, 451–506.

35. CHANEY, R.L., BROWN, S., LI, Y-M., ANGLE, J.S., HOMER, F. AND GREEN, C., 1995. Potential use of metal hyperaccumulators. *Mining Environment Magazine*, 3(3), 9-11.

36. CHEN, Y., AND INBAR, Y., 1993. Chemical and Spectroscopial analysis of organic matter transformations during composting in relation to compost maturity. *In*: H.A. HOITINK, H.M. KENNER, eds. *Science and Engineering of Composting*. The Ohio State of University, 551-600.

37. CHIANG, KY., HUANG, HJ., AND CHANG, CN., 2007. Enhancement of Heavy metal stabilization by different amendments during sewage sludge composting process. *Journal of Environmental Engineering and Landscape Management*, 17 (4), 249 – 256.

38. DICK, W.A., KOST, D.A., CHEN, L., STEHOUWER, R.C., HOUSER, T.A., BIGHAM, J.M. AND HAO, Y. 1999. Land application uses of FGD for mine land reclamation and

agriculture: arsenic. *In: Proceedings – 16th Annual International Pittsburgh Coal Conference.* 448-461.

39. DOUGHERTY, M. (Ed), 1998. Composting for municipalities: planning and design considerations. *Natural Resource, Agriculture and Engineering Service (NRAES).*

40. EARTH JUSTICE, 2009. *Coal ash: A national problem needs a national solution* [online]. Available from: http://www.sierraclub.org/coal/downloads/2009-07-coal-ash.pdf [Accessed 17 October 2012]

41. EKLIND, Y., AND KIRCHMANN, H., 2000. Composting and storage of organic household waste with different litter amendments. II: nitrogen turnover and losses. *Bioresource Technology*, 74 (2), 125-133.

42. ELAHEE, 2012. MID: Multidisciplinary Integrated Development. *In:* D.K. HURREERAM, ed. *Journal of the Institution of Engineers Mauritius*, 2012. 1-5.

43. EMMERICH, W.E., LUND, L.G., PAGE, A.L., AND CHANG, A.C., 1982. Solid phase forms of heavy metals in sewage sludge-treated soils. *Journal of Environmental quality*, 11, 178-181.

44. ENVIRONMENTAL GUIDELINES FOR THE USAID LATIN AMERICA AND CARIBBEAN BUREAU. *Environmental issues and best practices for solid waste management* [online]. Available from: http://www.usaid.gov/locations/latin_america_caribbean/environment/docs/epiq/chap5/lac-guidelines-5-solid-waste-mgmt.pdf [Accessed on 17 November 2012]

45. EPSTEIN, E., 1998. Pathogenic health aspects of land application. *BioCycle*, 39(9), 62-64.

46. EPSTEIN, E., 1997. *The Science of Composting*. Lancaster, Pennsylvania, USA: Technomic Publishing Company.

47. EUROPEAN COMMISSION PROJECT, 1990. *Waste separation and composting plant in the Municipality of Kalamata* [online]. Available from: http://dbs.cordis.lu/cordis-cgi/srchidadb?ACTION=D&SESSION=15412003-10-2&DOC=1&TBL=EN_PROJ&RCN=EP_RCN:15695&CALLER=EISIMPLE_EN_PROJ [Accessed on

48. FANG, M., WONG, J.W.C., LI, G.X. AND WONG, M.H., 1997. Effect of coal ash residues on the microbiology of sewage sludge composting. *Studies in Environmental Sciences*, 66, 511-523.

49. FANG, M., WONG, J.W.C., LI, G.X. AND WONG, M.H., 1998. Changes in biological parameters during co-composting of sewage sludge and coal fly ash residues. *Bioresource Technology*, 64(1), 55-61.

50. FANG, M., WONG, J.W.C., MA, K.K. AND WONG, M.H., 1999. Co-composting of sewage sludge and coal fly ash: nutrients transformations. *Bioresource Technology*, 67 (1), 19-24.

51. FANG, M., AND WONG, J.W.C., 1999. Effects of lime amendment on availability of heavy metals and maturation in sewage sludge composting. *Environmental Pollution*, 106 (1), 83-89.

52. FANG, M., AND WONG, J.W.C., 2000. Changes in Thermophilic Bacteria Population and Diversity during Composting of Coal Fly Ash and Sewage Sludge. *Water, Air and Soil Pollution*, 124 (3-4), 333 – 343.

53. FINSTEIN, M.S. AND MORRIS, M.L., 1975. Microbiology of Municipal Solid Waste Composting. *Advances in Applied Microbiology*, 19, 131- 157.

54. FINSTEIN, M. S., 1992. Composting in the Context of Municipal Solid Waste Management. *Environmental Microbiology*, 355-374.

55. FINSTEIN, M.S. AND HOGAN, J.A., 1993. Integration of Composting Microbiology, Facility, Structure and Decision-Making: Science and Engineering of Composting Design, Environmental, Microbiological and Utilization aspects. *In*: H.A.J. HOINTINK, KEEPER, H.M, eds. *Proceedings of the International Composting Research Symposium, May 1992, Columbus, USA.*

56. FRANCOU, C., POITRENAUD, M. AND HOUOT, S., 2005. Stabilisation of Organic Matter during Composting: Influence of process and feedstocks. *Compost and Science Utilization*, 13(1), 72- 83.

57. FRASER, B.S., 1997. *An investigation of in-vessel composting process control strategies.* Thesis (Master). University of Columbia.

58. FRENCH, D., AND SMITHAN, J., 2007. Fly ash characteristics and feed coal properties. *Cooperative Research Centre for Coal in Sustainable Development, Research Report 73*.

59. GAIND, S. AND GAUR, A.C., 2003. Quality assessment of compost prepared from fly ash and crop residue. *Bioresource Technology*, 87(1), 125–127

60. GAJALAKSHMI, S. AND ABASSI, S.A., 2008. Solid Waste Management by Composting: State of the Art. *Critical Reviews in Environmental Science and Technology*, 38 (5), 311- 400.

61. GOLDSTEIN, J., 1997. Industrial waste as fertilizer: What's wrong? What's right? *BioCycle*, 38 (8), 63–66.

62. GUPTA, D.K, RAI, U.N., TRIPATHI, R.D. AND INOUHE, M., 2002. Impacts of fly-ash on soil and plant responses. *Journal of Plant Research*, 115, 401-409.

63. GUPTA, R.D., ARORA, S., GUPTA, G.D. AND SUMBERIA, N.M., 2010. Soil physical variability in relation to soil erodibility under different land uses in foothills of Siwaliks in N-W India. *Tropical Ecology*, 51(2), 183 – 197.

64. GUPTA, V.K., MITTAL, A., JHARE, D. AND MITTAL, J. 2012. Batch and bulk removal of hazardous colouring agent Rose Bengal by adsorption techniques using bottom ash as adsorbent. *RSC Advances*, 2 (22), 8381-8389.

65. HAGERTY, J.D., PAVONI, J.L. AND HEER, J.E., 1973. *Solid Waste Management*. New York, USA: Van Nostrand Reinhold Company.

66. HAUG, R.T., 1980. *Compost engineering: principles and practice*. Ann Arbor Science Publishers.

67. HAUG, R.T., 1993. *The Practical Handbook of Composting Engineering*. USA: Lewis Publishers.

68. HAYNES, R.J. AND SWIFT, R.S., 1989. Effects of rewetting air-dried soils on soil pH and accumulation of mineral nitrogen. *Journal of Soil Science*, 40, 341 – 347.

69. HAYNES, R.J. AND BELYAEVA, O.N., 2009b. Use of municipal green wastes as the basis for production of manufactured soil in Australia. *In: Proceedings of the 11th International*

Conference on Environmental Science and Technology, 3-5 September 2009, Chania, Crete, Greece.

70. HE, X.T., TRAINA, S.J., LOGAN, T.J., 1992. Chemical properties of municipal solid waste compost. *Journal of Environmental Quality*, 21, 318-329.

71. HE, M., TIAN, G., AND LIANG, X., 2009. Phytotoxicity and speciation of copper, zinc and lead during the aerobic composting of sewage sludge. *Journal of Hazardous Materials*, 163, 671–677.

72. HSU, J.H. AND LO, S.L., 2000. Characterization and extrability of copper, manganese, and zinc in swine manure composts. *Journal of Environmental Quality*, 29**,** 447–453.

73. HUA, L., WU, W., LIU, Y., MCBRIDGE, M.B., AND CHEN, Y., 2009. Reduction of nitrogen loss and Cu and Zn mobility during sludge composting with bamboo charcoal amendment. *Environmental Science and Pollution Research*, 16, 1-9.

74. HUE, N.V, IKAWA, H. AND SILVA, J.A., 1994. Increasing plant available phosphorus in Ultisol with a yard- waste compost. *Communications in Soil Science and Plant Analysis*, 25, 3291-3303.

75. INBAR, Y., HADAR, Y. AND CHEN, Y., 1993. Recycling of cattle manure: the composting process and characterization of maturity. *Journal of Environmental Quality,* 22, 857 – 863.

76. IWEGBUE, C.M.A., EGOBUEZE, F.E., AND OPUENE, K., 2006a. Preliminary assessment of heavy metals levels of soils of an oil field in the Niger Delta, Nigeria. *International Journal of Environmental Science and Technology*, 3(2), 167–172.

77. IWEGBUE, C.M.A., ISIRIMAH, N.O., IGWE, C., AND WILLIAMS, E.S., 2006b.Characteristic levels of heavy metals in soil profiles of automobile mechanic waste dumps in Nigeria. *Environmentalist,* 26, 123–128.

78. JAMEEL, M., QUASIM, M., UMAR., M. AND SUBHAN, A., 2004. Impact of Organic Wastes (Bagasse Ash) on the Yield of Wheat (Triticum aestivum L.) in a Calcareous soil. *International Journal of Agriculture and Biology*, 6 (3), 468 – 470.

79. JERIS, J.S. AND REGAN, R.W., 1973. Controlling Environmental Parameters for Optimum Composting II Moisture, Free Air, Space and Recycle. *Compost Science*, 14 (2), 8-15.

80. JIMENEZ, E.I. AND GARCIA, V.P., 1992. Determination of maturity indices for city refuse composts. *Agriculture Ecosystems & Environment,* 38, 333 – 343.

81. KALBASI, A., MUKHTAR, S., HAWKINS, S.E., AND AUVERMANN, B.W., 2005. Carcass composting for management of farm mortalities: a review. *Compost Science and Utilization,* 13, 180-193.

82. KEENER, H.M, ELWELL, D.L. AND MESCHER, T., 1997. Composting swine mortality. *Extension Factsheet AEX 711-97.*

83. KEENER, H.M., ELWELL, D. L. AND MONNIN, M. J., 2000. Procedures and equations for sizing of structures and windrows for composting animal mortalities. *Applied Engineering in Agriculture*, 16, 681–692.

84. KIM, B., PREZZI, M. AND SALGADO, R., 2005a. Geotechnical Properties of Fly and Bottom Ash Mixturesfor Use in Highway Embankments. J*ournal of Geotechnical and Geoenvironmental Engineering*, 131 (7), 914-924.

85. KIM, B., PREZZI, M., SALGADO, R. AND LEE, J., 2005b. Mechanical properties of class F fly and bottom ash mixtures for embankment application. *In: IGC-2005, 17-19 December 2005, Ahmedabad, India*. 239-242.

86. KOIVULA, N., RÄIKKONEN, T., URPILAINEN, S., RANTA, J. AND HÄNNINEN, K., 2004. Ash in composting of source-separated catering waste. *Bioresource Technology*, 93, 201- 299.

87. KUBA, T., TSCHOLL, A., PARTL, C., MEYER, K. AND INSAM, H. 2008. Wood admixture to organic wastes improves compost and its performance. *Agriculture, Ecosystems and Environment.*

88. LAKE, D.L., KIRK, P.W.W. AND LESTER, J.N., 1984. Fractionation, characterization, and speciation of Heavy metals in sewage and sludge amended soil: A review. *Journal of Environmental Quality*, 13, 175-183.

89. LAU, S.S.S., FANG, M., AND WONG, J.W.C., 2001. Effect of composting process and fly ash amendment on phytotoxicity of sewage sludge. *Archives of Environmental Contamination and Toxicology*, 40, 184-191.

90. LAUDYN D, PAWLIK M., AND STRZELCZYK F., 2000. Power plants. *Wydawnictwo Naukowo Technize.*

91. LOFGREN, I., 1979. Composting Plant in Laxa. *In: Elmia- Arfall 79 "Conferences in Connection with the International Tradefair On Recycling Refuge Collection and Waste Treatment", Sept. 17-21, 1979, Jonkoping, Sweden 37.* 181-201.

92. LIN, JX., ZHAN, SL., FANG, MH., QIAN, XQ. AND YANG, H. 2008. Adsorption of basic dye from aqueous solution onto fly ash. *Journal of Environmental Management*, 187 (1), 193-200.

93. LUTHER, L., 2010. Managing Coal Combustion Wastes (CCW): Issues with Disposal and Use. *Congressional Research Service.*

94. MAO, I.F., TSAI, C.J., SHEN, S.H., LIN, T.F., CHEN, W.K. AND CHEN, M.L., 2006. Critical components of odors in evaluating the performance of food waste composting plants. *Science of The Total Environment*, 370, 323–329.

95. MARTINS, O. AND DEWES, T., 1992. Loss of nitrogenous compounds during composting animal wastes. *Bioresource Technology*, 42, 103-11.

96. MARTO, A., AWANG, A.R. AND MAKHTAR, A.M., 2011. Compaction Characteristics and Permeability of Tanjung Bin Coal Ash Mixtures. *In: 2011 International Conference on Environment Science and Engineering, 2011 Singapore*. IACSIT press.

97. MENON, M.P., GHUMAN, G.S., JAMES, J. AND CHANDRA, K., 1992. Effects of coal fly ash- amended compost on the yield and elemental uptake of plants. *Journal of Environmental Science and Health*, 27 (4), 1127-1139.

98. METHA, P.K., 1984. *Testing and correlation of fly ash properties with respect to pozzolanic behaviour.*

99. MILLER, F.C., 1993. Composting as a process based on the control of ecologically selective factors. *In*: F.B. METTING, ed. S*oil Microbial Ecology: Applications in Agricultural and Environmental Management*. New York: M. Dekker, 517-544.

100. MICHEL, F.C., KEENER, H.M., RIGOT, J., WILKINSON, T., AND PECCHIA, J., 2004. Effect of straw, sawdust and sand bedding on dairy manure composting. *In: Proceedings ASAE/CSAE, Annual International Meeting, 2004.*

101. MOHEE, R. AND BHURTUN, C., 2002. Assessing the potential of solid waste energy production for household purposes. *In: Domestic use of Energy Conference, 2002.*

102. MOHEE, R., DRIVER, M.B. AND SOBRATEE, N., 2008. Transformation of spent broiler litter from exogenous matter to compost in a sub-tropical context. *Bioresource Technology*, 99(1), 128-136.

103. MOHEE, R., RUNGASAMY, S. AND BUNDHOO, M.A.Z., 2012. Solid Waste Management in Mauritius, with emphasis on the National Composting Plant. *Journal of Institution of Engineers Mauritius*, 67-73.

104. MOREL, J.L., GUCKERT, A., NICOLARDOT, B., BENISTANT, D., CATROUX, C. AND GERMON, J.C., 1986. Etude de l'evolution des caractéristiques physico - chimiques et de la stabilité biologique des ordures ménagères au cours du compostage. *Agronomie*, **6 (8),** 693 – 701.

105. MORISAKI, N., PHAE, C.G., NAKASAKI, K. AND SHODA, M., 1989. Nitrogen transformation during thermophilic composting. *Journal of Fermentation and Bioengineering*, 67, 57–61.

106. MORSE, D. E., 2001. *Composting animal mortalities* [online]. Available at: www.mda.state.mn.us [Accessed 17 November 2012]

107. NAKASAKI, K., YAGUCHI, H., SASAKI, Y. AND KUBOTA, H., 1993. Effects of pH control on composting of garbage. *Waste Management and Research*, 11, 117–125.

108. NAKASAKI, K., AKAKURA, N. AND ATSUMI, K., 1998. Degradation patterns of organic material in batch and fed-batch composting operations. *Waste Management and Research*, 15, 484–489

109. NAKASAKI, K. AND AKIYAMA, T., 1988. Effects of seeding on thermophilic composting of household organic waste. *Journal of Fermentation Technology*, 66, 37–42.

110. NORBU, T., 2002. *Pretreatment of Municipal Solid Wastes by windrow composting and vermicomposting. Thesis* (Master). Asian Institute of Technology.

111. NURMESNIEMI, H., KOIKANNEN, T. AND POYKIO, R. Liming effect and leachability of heavy metals in fly ash originated from a fluidized bed combustion process at a pulp and paper mill complex. *In*: E. PONGRACZ, ed. *Proceedings of the RESOPT closing seminar 'Waste minimization and utilization in Oulu region: Drivers and constraints'*. 153-156.

112. OOGATHOO, S., 2012. *Coal ash management in Mauritius: Coal ash generation* [online]. Available from: http://coalmgt.blogspot.com/ [Accessed on 18 November 2012]

113. PACE, M.G., MILLER, B.E. AND FARRELL-POE, K.L., 1995. *The composting process*. Utah State University.

114. PAGE, A.L., ELSEEWI, A.A. AND STRAUGHAN, I.R., 1979. Physical and chemical properties of fly ash from coal fired power plants with reference to environmental impacts. *Residue Reviews*, 71, 83 -120.

115. PARE, T., DINEL, H., SCHNITZER, M., AND DUMONTET, S., 1998. Transformations of carbon and nitrogen during composting of animal manure and shredded paper. *Biology and Fertility of soils*, 26, 173–178.

116. PARÉ, T., DINEL, H. AND SCHNITZER, M., 1999. Extractability of trace metals during co-composting of biosolids and municipal solid wastes. *Biology and Fertility of Soils*, 29, 31–37.

117. PELS, J.R., DE NIE, D.S. AND KIEL J.H.A., 2005. Utilisation of ashes from biomass combustion and gasification. *In: 14th European Biomass Conference and Exhibition, Paris, France, 17-12 October 2005.*

118. PETRUZZELI, G., 1989. Recycling wastes in Agriculture- Heavy metal bioavailability. *Agriculture, Ecosystems and Environment*, 27, 493-503.

119. PUNJWANI, J., KRISHNA, R., KALPANA, S. AND GUPTA, K.K., 2011. Application impact of coal fly ash, and water hyacinth on cultivation of tomato. *International Journal of Research in Chemistry and Environment*, 1(1), 71-76.

120. QIAO, L., AND HO, G., 1997. The effects of clay amendment and composting on metal speciation in digested sludge. *Water Research*, 31 (5), 951-964.

121. RAO BHARNIDIMARRI, S.M. AND PANDEY, S.P., 1996. Aerobic thermophilic composting of pigerry solid wastes. *Water Science and Technology*, 33, 89-94.

122. RAVIKUMAR, T.N., YELEDHALLI, N.A., RAVI, M.V. AND NARAYANA RAO, K.., 2008. Physical, physico-chemical and enzyme activities of vermiash compost. *Karnataka Journal of Agricultural Sciences*, 21 (12), 222-226.

123. REBOLLIDO, R., MARTINEZ, J., AGUILERA, Y., MELCHOR, K., KOERNER, Y. AND STEGMANN, R., 2008. Microbial populations during composting process of organic fraction of Municipal Solid Wastes. *Applied Ecology and Environmental Research*, 6 (3), 61-67.

124. REPUBLIC OF MAURITIUS, 2010. *Mauritius Strategy for Implementation National Assessment Report, 2010* [online]. Available from: www.sidsnet.org/msi_5/docs/nars/AIMS/Mauritius-MSINAR2010.pdf (Accessed 27 October 2012)

125. RICHARD, D., ZIMMERMAN, R.A., JOCHIM, B. AND MCLAUGHLIN, M., 1993. Respiration rate: the true measure of compost stability. *In: Proceedings 16th International Madison Waste Conference, Municipal and Industrial Waste, Sept 1993, Madison, WI, USA.* 285-293.

126. ROUHIER, S., 2009. Environmental Impacts of Rising Energy Use in China: Solutions for a Sustainable Development. *In: Proceedings of the 32nd IAEE International Conference on Energy, Economy, and Environment: The Global View, 21-24 June 2009, San Francisco CA.* 33-36.

127. SATHYANATHAN, V.T., 2011. *Predicting Combustibles in Pulverized Coal Fired Boilers - Fly Ash and Bottom Ash* [online]. Available from: http://www.brighthubengineering.com/power-plants/37958-predicting-combustibles-in-pulverized-coal-fired-boilers-fly-ash-and-bottom-ash/ [Accessed 25 October 2012]

128. SCHWARZ-HERION, O., OMRAN, A., AND RAPP, H.P., 2008. A case study on successful municipal solid waste management in industrialized countries by the example of Karlsruhe City, Germany. *Annals of the faculty of Engineering Hunedoara- Journal of Engineering,* 6, 266 – 273.

129.   SCHULZE, K. L., 1961. Relationship between Moisture Content and Activity of Finished Compost. *Compost Science*, 2 (2), 32-34.

130. SESAY, A.A., LASARIDI, K.E. AND STENTIFORD, E.I., 1998. Aerated static pile composting of municipal solid waste (MSW): a comparison of positive pressure aeration with hybrid positive and negative aeration. *Waste Management Research*, 16(3), 264-272.

131. SINGH, J. AND KALAMDHAD, A.S., 2012. Reduction of Heavy Metals during Composting- A review. *International Journal of Environmental Protection*, 2(9), 36-43.

132. SUN, X.L., 2006. *Nitrogen Transformation in Food Waste Composting*. Thesis (Master). University of Regina.

133. SUNDBERG, C. AND JÖNSSON, H., 2005. Process inhibition due to organic acids in fed-batch composting of food waste–influence of starting culture. *Biodegradation,* 16, 205–213.

134. SUSAN, E.M., 1994. *Packing and the environment*. Pennsylvania, USA: Technomic Publishing Company Inc.

135. SUVIMOL, S. AND DAUNGRUEDEE, C. 2008. Bagasse ash: effect of pozzolanic activity And application in cement use aspect. *In: The 3rd ACF International Conference-ACF/VCA, 2008.*

136. TEDESCO, M.J., TEIXEIRA, E.C., MEDINA, C. AND BUGIN, A., 2009. Reclamation of spoil and refuse material produced by coal mining using bottom ash and lime. *Environmental Technology*, 20, 523 – 529.

137. TEIXEIRA, S.R., DE SOUZA, A.E., PENA, A.F.V., DE LIMA, R.G. AND MIGUEL, A.V., 2011. Use of Charcoal and Partially Pirolysed Biomaterial in Fly Ash to Produce Briquettes: Sugarcane Bagasse. *Environmental Sciences*.

138. TENESSE VALLEY AUTHORITY, 2009. *Regulatory submittal for Kingston Fossil Plant: Offsite ash disposals options plan* [online]. Available from: http://www.epa.gov/region4/kingston/Approved%20Offsite%20Ash%20Disposal%20Options%20Plan.pdf [Accessed 22 October 2012]

139. TEZUKA, R., HIJIKATA, N., KAZAMA, S., SOSSOU, S.K., FUNAMIZU, N., 2012. *Inactivation mechanism of pathogenic bacteria using lime and ash in composting toilet*

[online]. Available from: http://www.drytoilet.org/dt2012/full_papers/5/Rui_Tezuka.pdf [Accessed on 27 October 2012]

140. THE OUTLOOK FOR ENERGY, 2012. *A view to 2040*. Available from: http://www.exxonmobil.com/Corporate/files/news_pub_eo.pdf [Accessed on 12 November 2012]

141. THE US COMPOSTING COUNCIL, 2001. *Field guide to compost use* [online]. Available from:http://compostingcouncil.org/admin/wp-content/plugins/wppdfupload/pdf/1330/Field_Guide_to_Compost_Use.pdf [Accessed on 20 November 2012]

142. TIQUIA, S.M., TAM, N.F.Y. AND HODGKISS, I.J., 1997. Composting of spent pig litter at different seasonal temperatures in subtropical climate. *Environmental Pollution*, 98(1), 97 – 104.

143. TIQUIA, S.M., 2002. Microbial Transformation of Nitrogen during Composting. *Microbiology of Composting*, 237 – 245.

144. TIQUIA, S.M. AND TAM, N.F.Y., 2000. Fate of nitrogen during composting of chicken litter. *Environmental Pollution*, 110, 535-54.

145. TIQUIA, S. M., RICHARD, T.L. AND HONEYMAN, M.S., 2002. Carbon, nutrient, and mass loss during composting. *Nutrient Cycling in Agroecosystem*, 62, 15–24.

146. TWEIB, S.A., RAHMAN, R.A., AND KALIL, M.S., 2011. A literature review on composting. *In: International Conference on Environment and Industrial Innovation, Singapore, 2011*. IACSIT Press, 124-127.

147. US DEPARTMENT OF AGRICULTURE. *National Resource Conservation Service: Soil Quality Kit- Guides for educators* [online]. Available from: http://soils.usda.gov/sqi/assessment/files/bulk_density_guide.pdf [Accessed on 27 December 2012]

148. US EPA, 1994. *Composting yard trimmings and municipal solid waste* [online]. Available from: http://www.epa.gov/ttnatw01/burn/burnalt1.pdf [Accessed on 23 November 2012].

149. US EPA, 1995. *Decision Maker's guide to solid waste management, Volume II: Composting* [online]. Available from: http://www.epa.gov/osw/nonhaz/municipal/dmg2/chapter7.pdf [Accessed on 18 October 2012].

150. US EPA, 2007. *Coal Combustion Waste Damage Case Assessments*.

151. US EPA, 2009a. *Potable Water Sampling Results Kingston Fossil Fly Ash Response*.

152. US EPA, 2009b. TVA Kingston Fly Ash Release, Lab Analytical Results for Surface Water Samples.

153. VAN GINKEL, J.T., RAATS, P.A.C. AND VAN HANEGHEM, I.A., 1999. Bulk density and porosity distributions in a compost pile. *Netherlands Journal of Agricultural Science*, 47, 105-121.

154. VAN LIER, J.J.C., VAN GINKEL, J.T., STRAATSMA, G., GERRITS, J.P.G. AND VAN GRIENSVEN, L.J.L.D., 1994. Composting of mushroom substrate in a fermentation tunnel: compost parameters and a mathematical model. *Netherlands Journal of Agricultural Science,* 42, 271–292.

155. VOLESKY, B., 2001. Detoxification of metal-bearing effluents: biosorption for the next century. *Hydrometallurgy*, 59, 203-216.

156. VINING, M.A., 2002. *Bench scale compost reactors systems and the self- heating capabilities*. Thesis (Master). B.S, Texas A&M University

157. WANG, Q., LI, Y. AND KLASSEN, W., 2006. Summer Cover Crops and Soil Amendments to improve growth and nutrient uptake in Okra. *HortTechnology*, 16 (2), 328 – 338.

158. WILEY, J.S. AND PEARCE, G.W., 1955. A Preliminary Study of High Rate Composting. *Journal of Sanitary Engineering*, ASCE, 81, 846, 1-29.

159. WITTER R., LOPEZ-REAL, J.M., 1987. The potential for sewage sludge composting and composting in a nitrogen recycling strategy for agriculture. *Biological Agriculture and Horticulture*, 5, 1-23.

160. WITTER, E. AND LOPEZ-REAL, M.J., 1988. Nitrogen losses during the composting of sewage sludge and the effectiveness of clay soil, zeolite and compost in adsorbing the volatilized ammonia. *Biological Wastes*, 23, 279–294.

161. WONG, J.W.C., FUNG, S.O. AND SELVAM, A., 2009. Coal fly ash and lime addition enhances the rate and efficiency of decomposition of food waste during composting. *Bioresource Technology*, 100, 3324 - 3321.

162. WONG, J.W.C., LI, S.W.Y. AND WONG, M.H., 1995. Coal fly ash as composting materials for sewage sludge: effect of microbial activities. *Environmental Technology*, 16 (6), 527-537.

163. WONG, J.W.C., AND FANG, M., 2000. Effects of lime addition on sewage sludge composting process. *Water Research*, 34 (15), 3691-3698.

164. YEON, KS. AND KIM YS. 2011. The engineering characteristics of fly-ash and bottom-ash soil mixtures. *Scientific Research and Essays*, 6(24), 5224 – 5234.

165. ZACH, A., BINNER, E. AND LATIF, M., 2000. Improvement if municipal solid waste quality for landfiling by means of mechanical-biological pretreatment. *Waste Management Research*, 18(1), 25-32.

166. ZENG, G., YUON, X., LI, C., HUANG G., LI, J., SHANG, Q. AND CHEN, Y., 2003. Research on municipal solid waste composting with coal ash. *The Transactions of Nonferrous Metals Society of China*, 13(2), 457-461.

167. ZENG, J., 2011. *Evaluation of an Aerobic Composting Process for the Management of Specified Risk Materials (SRM)*. Thesis (Master). Dalhousie University.

168. ZIMMERMAN, R.A., 1991. *Evaluation of oxygen utilization as an indicator of municipal solid waste compost stability*. Thesis (PhD). North Dacota State University of Agriculture and Applied Science, US.

169. ZORPAS, A.A., CONSTANTINIDES, T., VLYSSIDES, A.G., HARALAMBOUS, I., AND LOIZIDOU, M., 2000. Heavy metal uptake by natural zeolite and metals partitioning in sewage sludge compost. *Bioresource Technology*, 72, 113-119.