STUDY OF THE EFFECTS OF BINDING AGENTS ON THE PROPERTIES OF COMPOST PELLETS

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Thesis submitted in partial fulfillment of the requirement for the degree
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Declaration

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Abstract

Composting of the organic Municipal Waste (MW) is one of the sustainable answers for the management of MW. The bulky nature of the loose compost is one of the main drawbacks in promoting the use of compost in agriculture governed by various practical and economic reasons.

Pelletization of compost seems to be the solution to offset the drawbacks caused by loose compost. The pelletizing process with a die and roller pelletizer is comparatively less complex compared to other common pelletizing methods. This research identified the optimum conditions to form a pellet with the desirable properties of high density, compressive strength, ideal pellet length and disintegration ability with three mesh sizes (2.5 mm, 3.5 mm, and 5 mm sieves), five moisture contents (25%, 30%, 35%, 40%, and 45%), three binding agents (Rice Flour (RF), Lime, Eppawala Rock Phosphate (ERP)) and three different binding agents' percentages (1%, 2%, and 3%) by weight basis. The pelletizing process increases the bulk density of compost by about 30%.

Pellets made with ≤ 5mm particles are longer and show higher strength (50% more) than those prepared with the other two particle sizes (≤ 2.5 mm & ≤ 3.5 mm). It was evidenced that 25% moisture content produces the highest strength pellets than higher moisture contents.

Pellets with binding agents at ≤ 5mm particle size and 25% moisture content were tested for bulk density, strength, percentage of long pellets and disintegration ability. It was observed that the tested properties have varied compare to pellets without binding agents. Lime and ERP showed promising results that enhancing pellets' bulk density and compressive strength and percentage of long pellets than RF. However, the disintegration ability nearly 100% in RF added pellets, which was less than 30% and 10% in ERP and Lime respectively and 0% in non-binding agent added pellets over one month of time in immersed water. With the increasing weight percentages of the binding agents, pellets strength increased in Lime and ERP and the same decreased with RF. Disintegration ability improved in RF and increased with the increased weight percentages. Same decreased in Lime and ERP and when increase the binding agents' weight percentages, longer the time to disintegration the pellets.

Key words: binding agents, co-compost, moisture content, particle size, pellets

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List of Abbreviations

cm	- centimeter
$Ca(OH)_2$	- Calcium Hydroxide
$CaCO_3$	- Calcium Carbonate
$Ca_3(PO_4)_2$	- Calcium Phosphate
CaO	- Calcium Oxide
Ca^{2+}	- Calcium ion
^0C	- Celcius
C	- Carbon
CO_2	- Carbon Dioxide
C-SDFS	- Composted Saw Dust Feacal Sludge
DFS	- Dried Feacal Sludge
EC-DFS	- Enriched Compost Dry Feacal Sludge
ERP	- Eppawala Rock Phosphate
FS	- Feacal Sludge
G	- gram
H	- Hour
HP	- Horse Power
I-DFS	- Irradiated Dry Feacal Sludge
K	- Potassium
Kg	- kilo gram
km^2	- Square kilo meter
L	- Liter
LAs	- Local Authorities
Mm	- millimeter
MSW	- Municipal Solid Waste
m^3	- Cubic meter
MPa	- Mega Pascal
MCK	-Municipal Council Kurunegala
mL	- milli Liter

m	- meter
N_2	- Nitrogen
N	- Newton
O_2	- Oxygen
OH^-	- Hydroxide ion
P	- Phosphate
PC	- Particle Category
PO_4^{3-}	- Phosphate ion
RF	- Rice Flour
SL	- Sri Lanka
SW	- Solid Waste
T	- Temperature
V	- Volt
W	- Watt
W_f	- Weight final
W_i	- Weight initial

CHAPTER 1
Introduction

1.1 Background

Total quantity of waste generated in Sri Lanka is estimated as 7,500 metric tons/day and the total waste collection is 3,500 metric tons/day, which is only 46% of the total waste generation (CEA, 2015). These estimated quantities are based on per capita waste production, which includes the waste from households, commercial institutes such as shops, markets, public places and street sweepings. Urbanization, unplanned urban development, industrialization and population growth at a high rate have created urban waste collection and management issues and therefore need for properly planned waste management systems to answer the problems caused by municipal solid waste (MSW). Most of the local authorities (LAs) in Sri Lanka spend a considerable portion of their budget on MSW management; this allocation is mostly spent on collection and transport of the waste material. Annually it costs US $ 27 million (Hikkaduwa *et al.,* 2015) for all MSW management processes. Under present management practice, considerable amount of collected waste including solid waste (SW) and septage are disposed into natural environmental sources or open dumps into natural water bodies without proper monitoring and treatment creating huge social and environmental issues (Liyanage *et al.,* 2015).

Generally, MSW generated in low and middle-income countries like Sri Lanka are high in organic matter and moisture. On average 62% of MSW collected in Sri Lanka is biodegradables such as vegetables, fruit waste, kitchen waste, garden waste, and animal waste as shown in Figure 1. MSW with high amounts of organic matter and moisture has a good potential for resource recovery and reuse. Composting is one such method for resource reuse and has been identified as a prioritized treatment method in MSW management in Sri Lanka.

Composting is a controlled bioconversion process of organic materials into a usable product. It is an environmental friendly, synergic effect of natural, microbial process that can easily be practiced as a sustainable management method for organic fraction of the municipal waste. In Sri Lanka, the prominent MSW composting method is turning windrow-composting method (where sorted biodegradable SW is piled up and turned frequently).

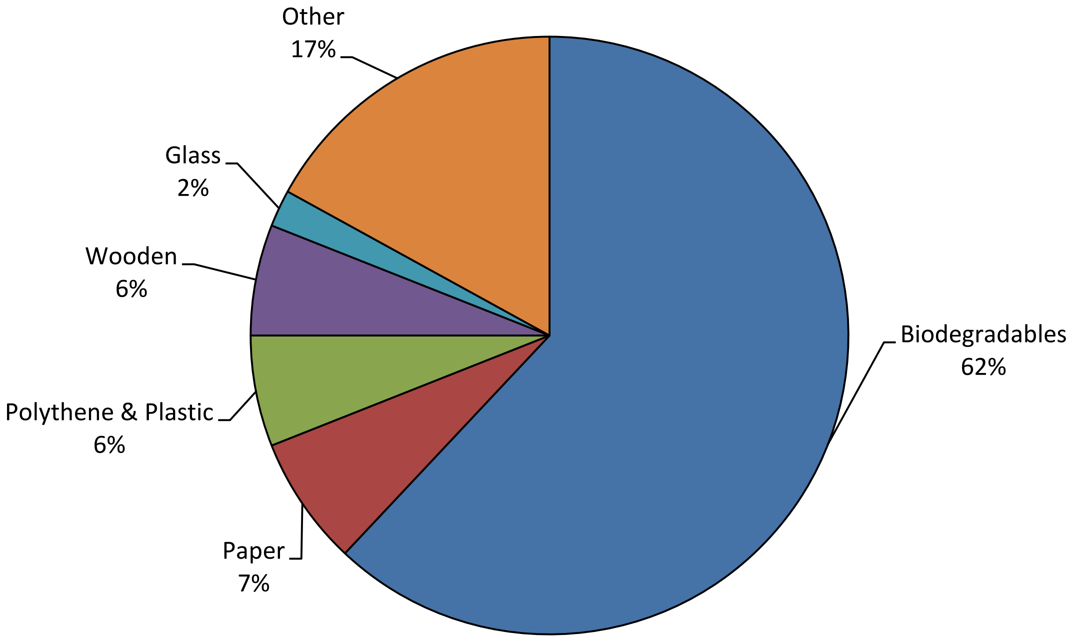


Figure 1 - Average waste composition in Sri Lanka

Source: CEA, 2015

Compost is an organic soil conditioner used all over the world. It is a stable, dark brown, soil-like material. It improves soil condition by enhancing soil organic content, soil moisture, water holding capacity, soil porosity, nutrient retention and buffering capacity. Improved soil condition, can increase yields in crops and improve water use efficiency in irrigated crops. Retention of more nutrients results in reduced leaching and less pollution of waterways. Other than that, compost contains important plant nutrients such as Nitrogen (N_2), Potassium (K) and Phosphorus (P), further compost contains micronutrients, which are not available in mineral fertilizers. The nutrient composition of compost made out of MSW is 45-60% Carbon, Nitrogen 0.9 - 1.35 %, Phosphorus 0.42-0.85%, and Potassium 1-1.8% (Jilani, 2007). Nevertheless, the nutrient composition of compost does not match with the requirements compared to other alternative chemical fertilizers. For example, the concentration of available N_2 in the final compost is generally low. Thus researches are being carried out to enrich MSW compost as co-compost by adding nutrient rich materials such as dried human feacal sludge (DFS), livestock manure or leguminous plant materials (Hara, 2001; Cofie, O., 2003; Rouse *et al.*, 2008).

There are challenges and limitations to overcome in order to make compost suitable for a range of applications. Most common limitations and challenges pertaining to usage of compost are high moisture content, irregular shape, low bulk density, dusty nature and low market demand which make compost uneconomical for long run as a business. Low bulk density of compost is responsible for most of the difficulties pertaining to packaging, storing (needs more space to store), transporting (high cost), handling and application of compost. Further, due to low bulk density compost can easily be leached out and washed away creating nutrient losses. Application of compost is labour intensive and generates dust at the point of application, thus creates health & sanitation impacts for farmers (Hara, 2001; Zafari and Kianmehr, 2012). In addition, due to irregular shape and size of the compost particles, it is difficult to mechanize the application of compost.

Densification of compost by “Pelletization” is a possible solution to address these challenges (Alemi *et al*., 2010). Pelletization is the use of mechanical pressure to increase the density of the material while converting it into pellets which is large and easy to handle that may not affect the content and availability of nutrients in pellets. Consequently, pellets require 20-50% less packaging volume than loose composts with a final bulk density over 1000 kg/m^3 (Nikiema *et al*., 2014; Javon Marcell Carter, 2010). Typically, pellets are cylindrical in shape, 5–10 mm in diameter, 25–30 mm in length. This uniform size, shape and other physical properties make most of the activities related to farm mechanization convenient (Hara, 2001). In addition to volume reduction, pelletization also contributes to facilitate broadcasting and application of compost, which makes it a dust-free process (Mavaddati *et al*., 2010;

Hara, 2001). Fertilizer pellets take a considerable time to disintegrate in the presence of water and hence slow and steady release of nutrients is possible reducing soil nutrient losses from agricultural fields (Siriwattananon and Mihara, 2008).

An effective pelletization process requires suitable moisture level with favorable particle sizes (of the powder compost), which imparts pellets' strength to be stable during packaging and transporting. A binding agent can be used to increase the pellet strength further. Moreover, these pellets should release nutrients upon application on the ground while disintegrating it and releasing nutrients into the soil.

1.2 Research objectives

To introduce compost commercially as pellets few key questions are to be addressed and therefore this study was carried out with the objective of addressing such issues.

- Identify impact of compost particle size (mesh size), and moisture content on pellet production process (pelletization efficiency) and pellet properties (strength, disintegration, bulk density, particle size distribution, pellets' length distribution).

- Identify appropriate local binding agents to strengthen compost pellets.

CHAPTER 2

Literature Review

2.1 Municipal Solid Waste

Municipal solid wastes (MSW) is often described as the waste that is produced from residential, industrial (non-process wastes), commercial and institutional sources (Tchobanoglous & Kreith, 2002). But in SWRMR, (1996) MSW is also defined as waste types including garbage, refuse, sludge, rubbish, tailings, debris, litter and other discarded materials resulting from residential, commercial, institutional and industrial activities which are commonly accepted at a municipal solid waste management facility.

In the municipal solid waste stream, waste is broadly classified into organic and inorganic. In general, waste composition is categorized as organic, paper, plastic, glass, metals, and 'other.' These categories can be further defined. Waste composition is influenced by many factors, such as level of economic development, cultural norms, geographical location, energy sources, and climate. As a country urbanizes and populations become wealthier, consumption of inorganic materials (such as plastics, paper, and aluminum) increases, while the relative organic fraction decreases. Generally, low and middle-income countries have a high percentage of organic matter in the urban waste stream, ranging from 40 to 85% of the total. Paper, plastic, glass, and metal fractions increase in the waste stream of middle- and high-income countries (AIT, 2004; CEA, 2012).

On average, MSW in Sri Lanka consists 62% of biodegradable waste (CEA, 2015). Composting is a cost-effective treatment option identified to manage the waste in developing countries, which consists over 50% of readily degradable organic material (Hoornweg *et al.,* 1999) (Figure 2).

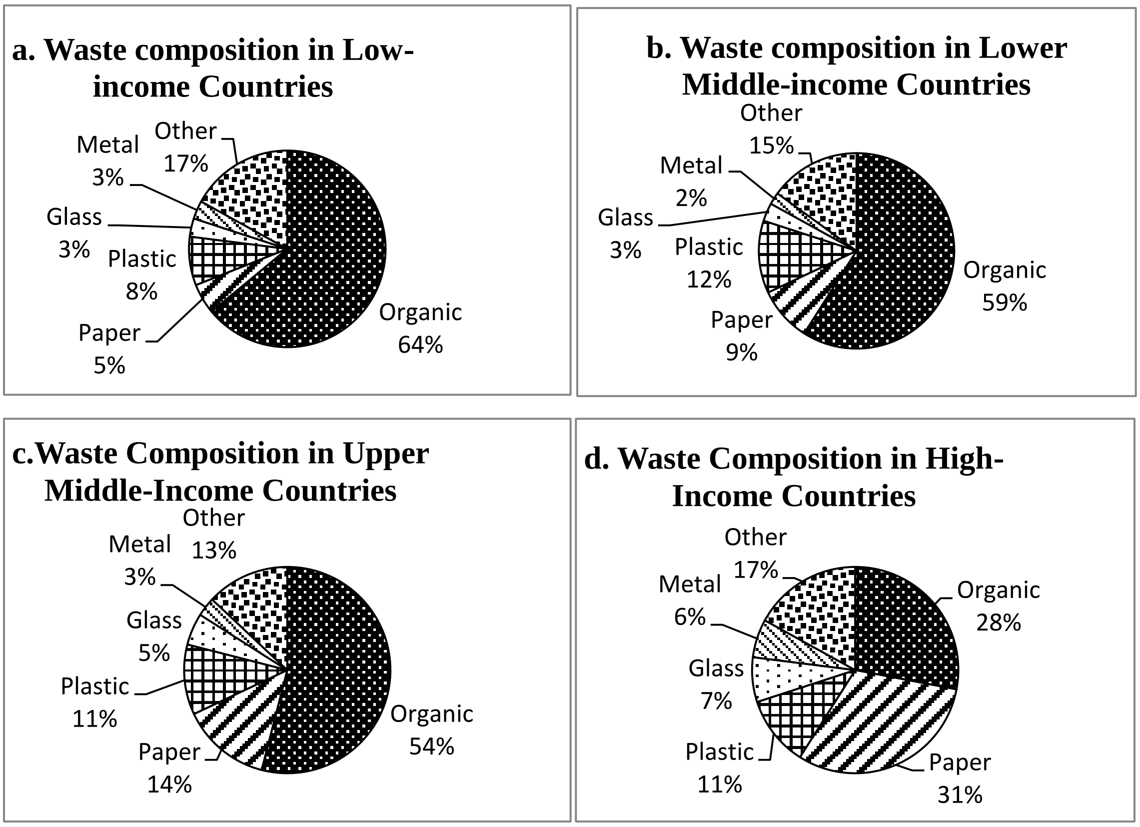


Figure 2 - Waste composition by income

Source: Hoornweg & Bhada-Tata, 2012

2.2 Composting Process

2.2.1 Composting of MSW

Composting may be divided into two categories, broadly by the nature of the decomposition process; anaerobic composting and aerobic composting. In anaerobic composting, decomposition occurs where oxygen (O_2) is absent or is in limited supply. Under this method, anaerobic microorganisms dominate the process as aerobic composting happens in the presence of oxygen (O_2). In this process, aerobic microorganisms break down organic matter and produce carbon dioxide (CO_2), ammonia, water, heat, and humus, the relatively stable organic end products. The generated heat accelerates breakdown of proteins, fats, and complex carbohydrates such as cellulose and hemi-cellulose. Hence, the processing time is short. Moreover, this process destroys many microorganisms that are human or plant pathogens as well as weed seeds, provided it experience sufficiently high temperature. Hence, this is considered more efficient and useful in urban waste composting for agricultural production (Polprasert and Koottatep, 2007).

Aerobic composting process mainly consists of two phases. Each phase has its own process characteristics and is important in the view of product safety and product quality. These two phases are *decomposition (or composting) phase* and *curing (maturing) phase* (Shilev *et al.*, 2007).

During the first phase of the aerobic composting process, the temperature rises rapidly as high as 70 °C within the first few days. The mesophilic organisms (optimum growth temperature range = 20 - 45 °C) multiply rapidly on the readily available sugars and amino acids and generate heat by their own metabolism, and raise temperature to a point where their own activities become suppressed. Then a few thermophilic fungi and several thermophilic bacteria (optimum growth temperature range = 50 - 70 °C) continue the process, raising the temperature of the material to 65 °C or higher. This peak heating phase is important for the compost quality as the heat kills pathogens and weed seeds (Sundberg, C., 2005). Temperature and duration needed to destroy pathogens can be found in Figure 3.

The active composting stage is followed by a curing stage, and the pile temperature decreases gradually. Start of this phase is identified when turning no longer reheats the pile substantially. At this stage, another group of thermophilic fungi starts to grow. These fungi bring about a major phase of decomposition of plant cell-wall materials such as cellulose and hemi-cellulose. Curing the compost provides a safety net against the risks of using immature compost such as Nitrogen (N_2) hunger, O_2 deficiency, and toxic effects of organic acids on plants (Misra *et al*., 2003).

Eventually, the temperature declines to ambient temperature or closer. By the time composting is completed, the pile becomes uniform and biologically less active. The material becomes dark brown to black in colour and emits a pleasant earthy odor.

The particles reduce in size and become consistent as soil-like in texture. In the process, the amount of humus increases, the ratio of carbon to nitrogen (C:N) decreases, pH neutralizes, and the exchange capacity of the material increases (Misra *et al*., 2003).

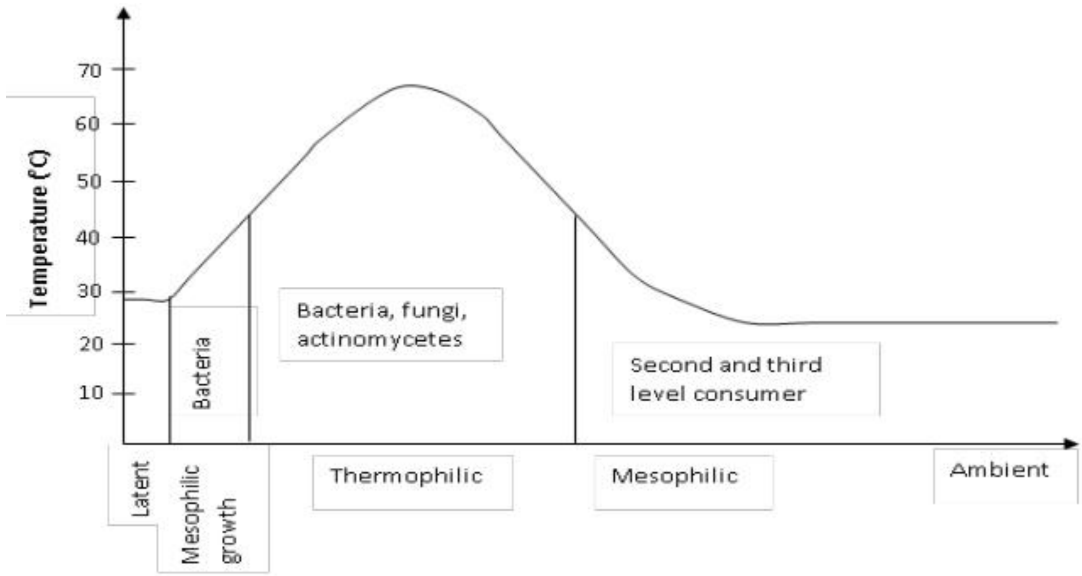


Figure 3 - Patterns of temperature and microbial growth during composting

Source : IWMI, unpublished

2.2.2 Production Process

At the simplest level, the composting process simply requires selection of input waste, windrow construction, and turning and watering to allow break down into humus. Controlled and methodical composting is a multi-step and closely monitored process with measured inputs material (nutrients), water, and many process controls. The decomposition process is aided by optimum conditions (such as moisture content, particle size, C:N ratio) to confirm access to water, air, and food for microorganisms. The main activities along the production process are shown in Figure 4.

2.2.3 Quality of the input waste

If the proper process is maintained, the final product quality mainly depends on the input material quality. As illustrated in Figure 5, high carbon wastes such as tree cuttings have low composting potential compared to manures, food waste and kitchen wastes. in the technical point of view. As per Figure 5, high potential waste for composting has the highest environmental impact and the highest impact on the health, if linked by a pathway. Additionally, high potential waste has the highest nutrient densities, which makes the high valued final product attractive to farmers. In such case, use of short-term biodegradable waste in composting should be promoted, as it could holistically fulfill the technical, health, environmental, and economic aspects (Department of Environment Affairs, 2013).

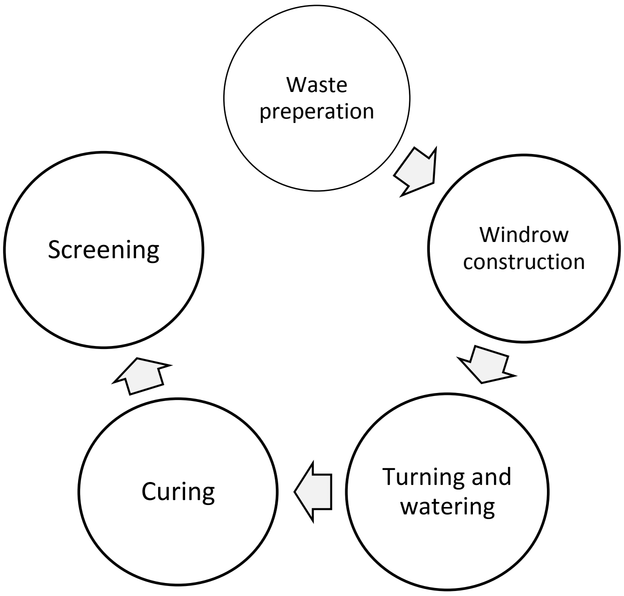


Figure 4 - Key process activities considered in Process Analysis

2.3 History of Pelletizing

Biomass densification, which is also known as briquetting or pelletizing of various agro and industrial bio-mass has been practiced for many years in several countries (Suppadit and Panomsri, 2010). Thomas and Poel, (1996**)** reviewed that the making up of bulky mash in the form of pellets, originated nearly 80 years ago. They reviewed a literature of 1937 which defined the nutrient enhancement of pelleted poultry feeds against bulky mashes. Tumuluru *et al.*, (2010a) mentioned that William Smith was the first to receive a United States patent (1880) for biomass densification. According to Suppadit and Panomsri, (2010) screw extrusion briquetting technology was invented and developed in Japan in 1945. As of April 1969, there were 638 pelletizing plants in Japan. He further expresses that this technology is known in Japan as “Ogalite”, in USA as the “Prest-o-log”, In Switzerland the “Glomera” and the “Compress” in West Germany. Present day, densification process is moreover utilized in different fields and applications like, coal pelleting in thermal engineering, extrusion cooking in food processing, production of agglomerates and granules in chemical industries and production of compact tablets in pharmaceutical industries (Mani *et al*., 2003).

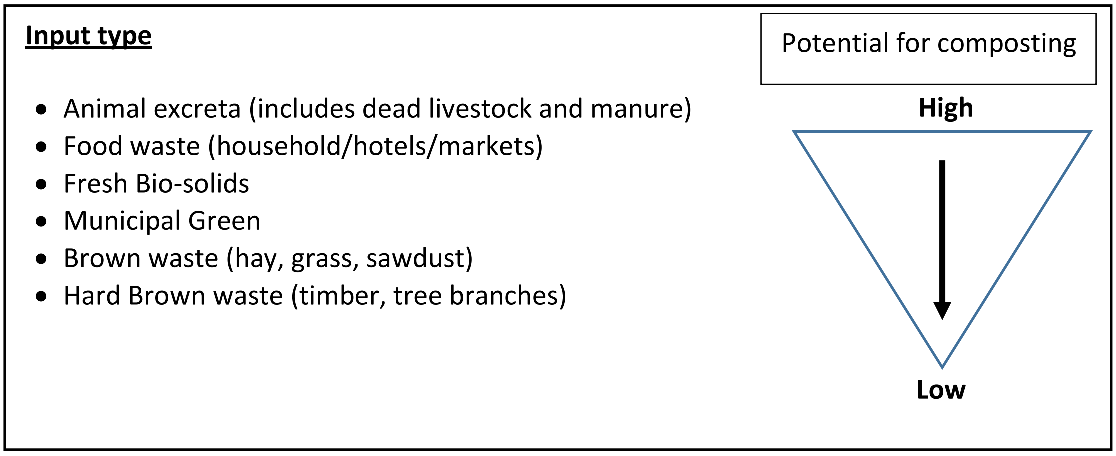


Figure 5 - Quality guideline for different types of input for composting

Source: Department of Environment Affairs, (2013)

2.3.1 Pelletization Mechanism

Pelletizing is a compaction or a densification process of biomass where a complex interaction occurs among the fine particles, their constituents, and forces. Using some form of mechanical pressure, pelletizing converts fine particles into pellets by bringing small particles closer and together. So that the forces acting among them are large enough to yield a product which can withstand harsh handling and transportation (Tabil and Sokhasanj, 1996); (Tabil, 1996). The primary purpose of this densification is to remove air from low bulk density material and to convert of these bulk materials into a solid form than the original material. Compost made out of livestock manure, biomass like sawdust, plant residues, and MSW easily can be converted into pellets as a compressed form (Hara, 2001); (Mani *et al*., 2003); (Zafari and Kianmehr, 2012); (Tumuluru *et al.*, 2010b); (Kaliyan and Morey, 2009).

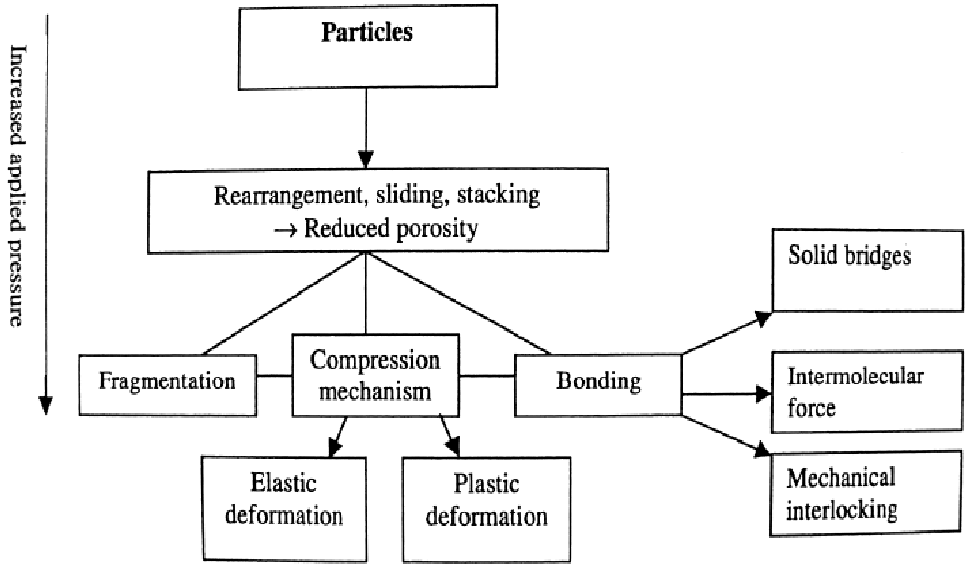


Figure 6 - The deformation mechanisms of powder particles under compression

Source: (Bakis, 2007)

According to Tabil, (1996); Tumuluru *et al.*, (2010c); Bakis (2007) volume reduction and compaction of particles take place in as following 3 main stages (Figure 6).

1. Rearrangement of the particles at low pressures resulting in a closer packing structure and reduced the porosity
2. Elastic and plastic deformation occur at higher pressures and increases the contact area among particles resulting mechanical interlocking through Van der Waal's and electrostatic force bonding (Figure 7).
3. Continuation of stage 1 and 2 until the compact density approaches the specific density, while materials melt at the melting point of the ingredients.

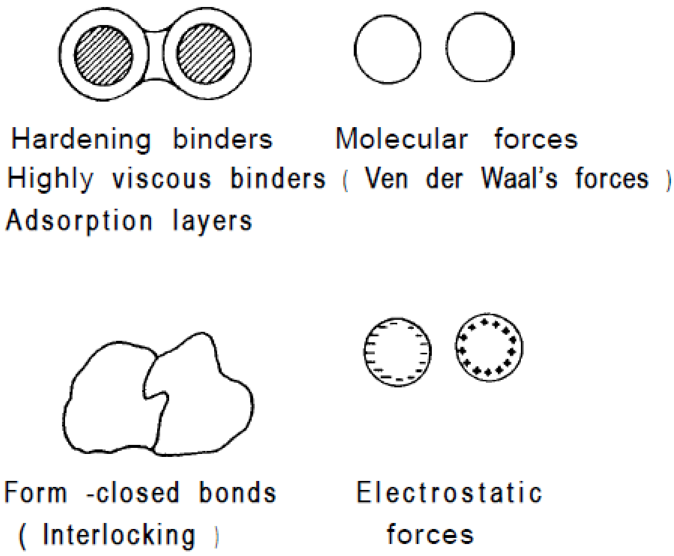


Figure 7 - Mechanical Interlocking of the particles

Source: (Grover and Mishra, 1996)

2.4 Types of biomass densified products

Kaliyan and Morey, (2009); Mani *et al*., (2003) cited that conventional biomass densification processes can be classified into few categories as bailing, pelletizing, extrusion, and briquetting. Pelleting and briquetting have been applied for many years in several countries as a popular biomass densification process. When biomass densification utilized for energy production is called briquetting. Densification of biomass for animal feed production is called pelletizing and cubing.

2.5 Types of pelletization machines (Pelletizer)

According to Zafari and Kianmehr (2012), there are two kinds of molding machines, which shape composted livestock manure into pellets. One kind is the pelletizer and the other is the extruder (Figure 8). Pelletizing machines that is the extruder type have a horizontal barrel, where the raw material is forced, into the barrel by a screw. The material is then compressed into the die installed at the end of the horizontal barrel, producing the pellet. During screw extrusion, the biomass material moves from the feed point through the barrel and compacts against a die with the help of a pressure building by rotating screw. This screw causes an increase in temperature of the biomass. Then the heated biomass is forced through the extrusion die, forms briquettes or pellets with the required shape. Pelletizing is similar to briquetting except that it uses smaller dies to produce smaller densified products called pellets.

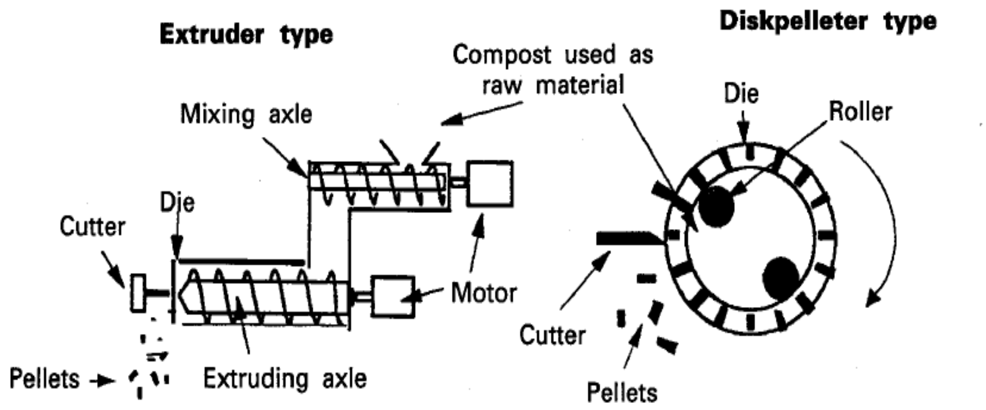
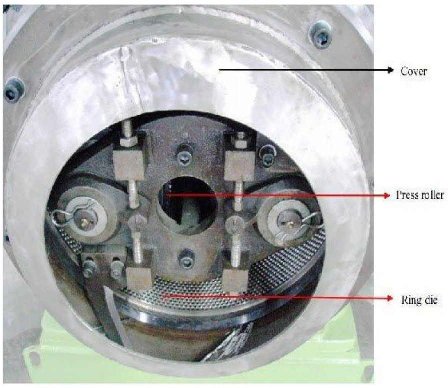


Figure 8 - Characteristics of the two kinds of moulding machines

Source: (Hara, 2001)

The main parts of a pelletizer are die and roller and there are two main types of die and roller pelletizers. Those are Ring die and Flat die (Figure 9), normally die remains stationary and the rollers rotate. According to Hara, (2001) die and roller pelletizers were categorized into three kinds: the roller disk die type, the roller ring die type, and the double die type. Each type has a basic structure of a disk or two with many holes and rollers. The compost is fed between the disks and/or roller, and as the disk and/or roller turns, the compost is forced into the holes, producing the pellets. A comparative description regarding two main pelletizers is described in Table 01.



Flat die pelletizer　　　　　Ring die pelletizer

Figure 9 - Ring die pelletizer & Flat die pelletizer

Source: Anon, 2016a

2.6 Pelletization Process & Pellets

In an extruder, the raw material is compressed by a screw or a piston through a die to form compacted particles, normally the shape is cylindrical. In pelleting equipment, the feed material is pressed through open-ended cylindrical holes (dies). One to three small rotating rolls push the feed material into the die holes from inside towards the outside. The skin friction between the feed particles and the wall of the die resists the free flow of feed and thus the particles are compressed against each other inside the die to form pellets. One or two adjustable knives placed outside the ring cut the pellets into desired lengths. The diameter of the pellets may range from 4.8 to 9.0-mm, and the length of the pellets may range from 12.7 to 25.4 mm. Cubing equipment is similar to that of pelleting equipment. The cubes usually have one row of holes in the die ring, and the holes are made as square cross section. Cube sizes are from 12.7 × 12.7 mm to 38.1 × 38.1 mm in cross section, and from 25.4 to 101.6 mm in length. In a roll press briquette compactor, material is densified by compression between two counter-rotating rolls. Initial densification of the material may occur through compressing the material with a tapered auger in the feed mechanism. The densified products are mostly of pillow-shape with a size of 10 to 40-mm or larger (Kaliyan and Morey, 2009).

Table 1 - Comparison of the Types of pelletizers

	Disk Pelletizer			**Extruder Pelletizer**
Sub Types	Roller Disk die type	Roller Ring die type	Double die type	Extruder type
Design	• Dies with many holes and a roller or two disks			• Have a barrel and a screw
Input method	• Compost is fed between disks and roller			• Fed into the barrel and forced by a screw
How Pellet Form	• Disk or roller turns and compost is forced into the holes to form pellets			• Material compressed into the die installed at the end of the machine by the screw to form pellets
Advantages	• Does not become block easily			• Die Temperature can be controlled
	• Suitable for substances with low moisture content (20-30%)			• Can adjust the pressure applied
	• Does grinding simultaneously			• Die replacement is easy and produce pellets with various shapes
Disadvantages	• Damages to the dies and roller is severe due to foreign bodies			• Machine easily block by foreign bodies such as long fibers and small stones
	• Demand for frequent replacement of the machine components			
Key Operating Parameters	• Feeding Rate			• Speed of the screw • Moisture of the feeding material

Source: Hara, (2001)

2.7 Literature on Pelletization

2.7.1 Biomass pelletization

Youn *et al*., (2014) studied the pelletizing of *Miscanthus sacchariflorus* is an agricultural residues as per an energy source. In this regard, *Miscanthus* pellets were investigated for further use as a renewable resource and investigated moisture content, density of raw materials and die ratio to identify how those factors affect on pelletization. Tumuluru *et al.,* (2010a) studied pelletizing of dried wheat grain, to investigate effect of die temperature and feed moisture content on pellets' moisture content, durability and pellets density. Serrano *et al.,* (2011) conducted investigation on barley straw pellets evaluating die temperature and straw moisture on pellet durability, density, length and moisture. Mani *et al.,* (2006) studied on grass pelletizing and Tabil and Sokhasanj, (1996) studied on Alfalfa, an agricultural crop residue pelletizing to optimize the quality of pellets by conditioning the manufacturing process as controlling of pellet temperature, die geometry, hammer mill screen size, and die speed.

Though, animal feed and energy pellets production have been practiced for long and has extensively been studied by Thomas and Poel, (1996) on animal feed to identify the effect of binding agents on pellets durability. Samson and Duxbury, (2000) identified Switchgrass as a promising pelleting feedstock for economical biofuel production. Roeper *et al.,* (2005) studied chicken waste pelletization by adjusting the parameters of moisture content, rotation speed, aeration and temperature. Suppadit and Panomsri (2010) developed a model machine to convert broiler litter in to pellets compressing the voulume up to 60-90% and Babatope *et al.,* (2012) did pelleting of poulty waste fertilizers. How ever literature regarding pelletization of compost or co-compost are very much rare.

2.7.2 Compost and Co-compost Pelletization

Nikiema *et al.,* (2013a) experienced the pelletizing of co-compost made incorporating of MSW compost and dried human faecal sludge together. Zafari and Kianmehr, (2012) did pelletizing on MSW compost into pellets. Thomas and Poel, (1996); Roeper *et al.,* (2005); Hara, (2001) experienced the process of pelletization using composted livestock manure. LaDePa is a latest method, which involved to form feacal sludge pellets within a short period of time in South Africa as described by Nikiema *et al.,* (2013a).

2.8 Factors affecting on pelletization

Hara, (2001) suggested that compost pellets should be a high-grade product with several desirable qualities, such as durable enough to maintain their shape when being transported to distant areas, easily spread by machine, constant nutrient content and not deteriorate during prolonged storage. Most of the studies revealed, the densification increases the bulk density of biomass from an initial bulk density of 40-200 kgm^{-3} to a final bulk density of 600-800 kgm^{-3}. Kaliyan and Morey, (2009); Tabil and Sokhasanj, (1996) and Nikiema *et al*., (2013a) mentioned that pelletization increased the bulk density by 20-50%, compared to the powder product. Samson and Duxbury, (2000) described moisture content, density, particle size, and natural binders of the material are commonly known to affect the success of pelletizing. Zafari and Kianmehr, (2012) suggests the process of forming biomass into pellets depends upon the physical properties of the material particles and the process variables during pelletizing. Tabil and Sokhasanj, (1996) cited that pellet quality can be optimized by 1) Control of the manufacturing process 2) Change of the formulation and 3) Use of the additives.

Youn *et al.,* (2014) investigated moisture content, density of raw materials and die ratio on pelletizing agro waste and identified ideal moisture content was 20-25%, ideal density of raw material was 240 to $300kg/m^3$ and die ratio was 4.5:1 to 5.0:1. Tabil and Sokhasanj, (1996) studied the physical quality parameters of pellets, such as pellet temperature, die geometry (length –to-diameter ratio), hammer mill screen size (Particle size) and die speed. The conclusions of this study were increasing of the conditioning, increases the temperature of the material and increased temperature increases the durability of the pellets. Further to that, high length to diameter ratio produced more durable pellets. Die speed and hammer mill screen size were not significant on pellet durability. Nikiema *et al.,* (2013a) studied the effect of temperature, pressure, and moisture content on cattle manure pelletization and concluded that there was an effect of the mentioned factors on pellet durability and Tumuluru *et al*., (2010a) studied and confirmed the effect of die temperature and moisture of the feedstock on pellets durability. Hara, (2001) experienced the moisture content and feeding rate of the feed stock have a significant effect on pellet production efficiency in composted livestock manure.

Nikiema *et al.,* (2013a) investigated on the moisture content in human faecal sludge based material. They have found that the moisture level is a dependent on binder type and concentration. Lowest moisture amount is required for Enriched Compost with Dry Feacal Sludge (EC-DFS) and Irradiated Dry Feacal Sludge (I-DFS) while the highest is required for co-compost of dewatered feacal sludge and saw dust (C-SDFS). Samson and Duxbury, (2000) engaged to find out the effect of moisture content, particle size of the materials and density of the material to the success in pelleting. Importance of the parameters like moisture content, rotation speed, aeration, and temperature were studied by Roeper *et al.,* (2005). Tabil and Sokhasanj, (1996), Mani *et al.,* (2003), Ghadernejad and Kianmehr, (2012) reviewed the biomass pelletizing process and the effect of particle size, moisture content and compressive force on pellet density and durability. They suggested particle size and moisture content significantly affect the pellet density and durability.

2.8.1 Moisture Content

Moisture content is one of a significant factors affect the durability and strength of the compost pellets. The durability of the densified product is initially increased with the increasing of moisture content until an optimum level and then started to decrease until a unit density (Kaliyan and Morey, 2009; Zafari and Kianmehr, 2012). Kaliyan and Morey, (2009) cited that at high moisture content (≥ 25 %), the durability is low probably due to the incompressibility of water. Trapped moisture within the particles may prevent complete flattening and the release of natural binders from the particles. The optimum moisture content for the densification process is varied based on the type of biomass and process condition. Much higher moisture content causes a biphasic mixture (liquid phase and solid phase) and disappear intermolecular force entirely (Zafari and Kianmehr, 2012). The dies of both extruder and disk-pelletizer types of molding machine tend to block if the moisture content is too low (Suppadit and Panomsri, 2010; Hara, 2001). However, according to Adeoye, (2012) those with 40% water content gave very strong pellets but less than 20-30% or above 40% moisture content make the pellets brittle, i.e. weak and friable. Nikiema *et al*., (2013a) suggested the applicable moisture contents for co-composting pellets are 27-31% for C-DFS (Composted Dry Feacal Sludge), 21-25% for EC-DFS and 38-46% for C-SDFS. Zafari and Kianmehr, (2012) investigated different moisture contents for compost pelletization and identified the moisture content was laid between 35% to 45% and concluded that the best moisture content achieved for higher density is 40%. According to Hara, (2001) the moisture content is about 40% for an extruder, and about 20-25% for a disk- pelletizer. Roeper *et al.*, (2005) mentioned that, the best results for chicken manure pelletizing were obtained at moisture content of 38% - 44% and above 45% of moisture level makes it stickier. According to Suppadit and Panomsri, (2010) the suitable moisture content for cattle manure pelletization is 20%-30% and the processing performance falls 30-50% if the moisture content of the compost is only 5% higher or lower than its optimal level. Zafari and Kianmehr, (2012) says using cattle manure with 50% moisture content, medium temperature about 40 °C and pressure at 6 MPa resulted maximum pellet durability.

2.8.2 Particle Size

In general, the density and durability of pellets is inversely proportionate to the particle size. This is due to the fact that, during the process, the smallest particles have higher surface areas, obtaining higher density values. (Tumuluru *et al.,* 2010c; Zafari and Kianmehr, 2012; Youn *et al.,* 2014; Mani *et al.,* 2003; Mani *et al.,* 2006; Kaliyan and Morey, 2009; Serrano *et al.*, 2011; Adapa *et al.,* 2005; Tabil and Sokhasanj, 1996; Mirenda *et al.*, 2015; Grover and Mishra, 1996; Wilson, 2010). Finer particle sizes generally correspond with greater pellet strength and durability as larger particles serve as fracture points (Wilson, 2010). When particle size increases, the effect of 'Van der Waals' forces diminishes and other binding mechanisms (capillary forces and binder materials) become more pronounced (Thomas and Poel, 1996). Several researchers observed that optimal pellet quality is achieved with a mixture of particle sizes due to increased inter-particle bonding (mechanical interlocking) and the elimination of inter-particle spaces (attractive through adhesive and cohesive forces) (Wilson, 2010; Kaliyan and Morey, 2009). The presences of different sized particles improve the packing dynamics and contribute to high static strength. It is generally agreed that biomass material of 6-8 mm size with 10-20% powdery component gives the best results. Only fine and powdered particles of size less than 1 mm are not suitable for screw extruder because they are less dense, more cohesive, non-free flowing entities (Grover and Mishra, 1996; Kaliyan and Morey, 2009).

2.8.3 Binding Agents

The strength and durability of the densified products depend on the physical forces that bond the particles together. According to Kaliyan and Morey, (2009) the binding forces that act between the individual particles in densified products have been categorized into five major groups. They are: (i) solid bridges, (ii) attraction forces between solid particles, (iii) mechanical interlocking bonds, (iv) adhesion and cohesion forces, and (v) interfacial forces and capillary pressure. Due to the application of high pressures and temperatures, the bonds like hydrogen bond, Van de Waals' bridge, electrostatic, and magnetic forces can cause solid particles to adhere to each other, if the particles are brought close enough together. Binders are the agents who adhere to the surfaces of solid particles to generate strong bonds that are very similar to those of solid bridges. In some operations, binders or stabilizing agents are used to reduce the pellet springiness and to increase the pellet density and durability (Javon Marcell Carter, 2010; Mani *et al.*, 2003).

A binder (or additive) can be a liquid or solid that forms a bridge, film, matrix, or causes a chemical reaction to make strong inter-particle bonding. Binders can be classified for pelletizing into three general group according to Tabil, (1996). Those are (a) matrix type which includes paraffin, clay, dry starch and dry sugars: (b) film type which includes starch, bentonite, gums, lignosulfonates, alginates: (c) chemical binders which includes calcium hydroxide with carbon dioxide and sodium silicate with calcium chloride. Kaliyan and Morey, (2009) in their review described that steam conditioning or preheating is essential to provide heat and moisture to activate the inherent or added binders. The selection of binders mainly depends on cost and environmental friendliness of the binders and desired quality of the pellets Tabil, (1996).

When strength and durability values of pellets do not match with the quality standards or marketing requirements, additives in the range of 0.5 to 5% (by weight) are added to the feed to increase the pellet quality or to minimize the pellet quality variations (Tabil, 1996). More than 50 organic and inorganic binders have been employed for densification (Tabil,1996; Kaliyan and Morey, 2009). Chemical binders such as lignosulfonate and lime would positively affect the quality of the densified products. Biological binders such as molasses, starch, waste paper, and sawdust can also help to improve the quality of the densified products (Kaliyan and Morey, 2009)

Water is also a suitable binding aid in briquetting mixtures containing water-soluble constituents such as starches, sugars, soda ash, phosphate salts, and Calcium Chloride (Mani *et al.,* 2003). According to many authors, certain types of waste in the densified mixture can play the role of a natural binder and make the produced pellets more durable, and have a positive effect on the power demand of the process of forming pellets (Niedziółka *et al.*, 2015) Biomass have a limited degree of elasticity. So any physical form that the biomass may be forced into may have a tendency to spring back or even fall apart when compressive force is released. Normally binding agents should be added externally to get the proper binding (Shyamalee *et al.,* 2015).

Shyamalee *et al.*, (2015) used dry cow dung; wheat flour and paper pulp as possible binders and says dry cow dung was not suitable while paper pulp binder exhibited comparatively high compressive strength compared to wheat flour binder on sawdust densification at the binder concentration at 30% (w/w). According to Serrano *et al.*, (2011) the mechanical durability of pellets was enhanced over one point when the barley straw was blended with pine sawdust (2, 7 and 12 wt.%), adjusting the moisture content to 12% in the mixture. Mani *et al.*, (2003) reported the binders used for most biomass briquettes are molasses and starch. Increasing amount of binder in the briquetting process increases the relaxed density, durability and shear strength of briquettes. Nikiema *et al.*, (2013a) did an experiment on co-compost using cassava starch and clay as binders (concentration: 0-10% in mass) for pelletization. They pre-treated the materials before use, either through gamma irradiation or pre-gelatinization, in order to improve the binding ability. Based on the results of this study, the addition of 3% of pre-gelatinized starch is recommended during pelletization. Tabil, (1996) reported the performance of different binders during alfalfa pelleting. He concluded that addition of binders to low quality alfalfa grind significantly improved the pellet durability and hardness to levels comparable to that of pellets from high quality chop. He recommended the use of hydrated lime (calcium hydroxide) and pea starch as binders for the production of the most durable and hard pellets.

2.9 Pelletization Process

According to (Anon, 2016b) biomass pelletizing process consisted of few steps as: 1) Initial size reduction 2) Drying 3) Initial Sieving 4) Grinding 5) Pelletizing 6) Cooling 7) Final Sieving 8) Storage. Hara, (2001) described the pelletizing process made out of livestock manure compost. Figure 10 shows the conventional flow chart of pellet production.

Nikiema *et al.*, (2013b) described the co-composting pellet production process. It consisted of preparing DFS based co-compost with biologically accepted way, then grind the compost to make it into small particles. After that, enriching with nutrients and treated binding agents, and were mixed with favourable water content. Next the mixture was sent to the pelletizer and pellets were taken out. Pellets were dried under the sun and sieved again before packaging as per Figure 11. There are few energy consuming steps: grinding and mixing of co-compost and drying co-compost pellets.

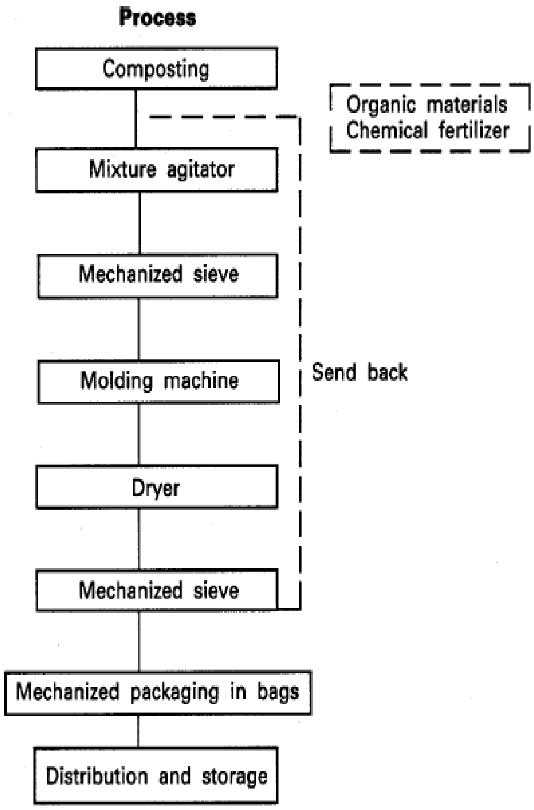


Figure 10 - Conventional flow Chart of Pellet Production

Source: Hara, (2001)

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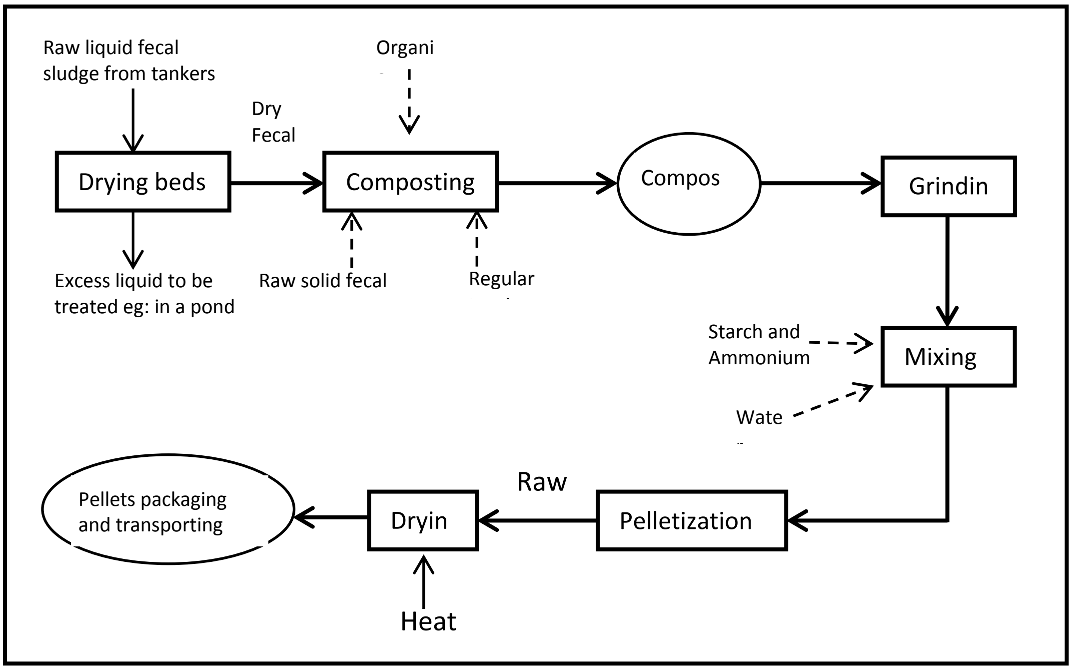

Figure 11 - Fortifier Pellet Production Process

Source *:* Nikiema *et al.*, (2013b)

CHAPTER 3

Materials and Methods

3.1 Introductions to the composting site

The research was conducted at the composting site situated in Kurunegala Municipal Council (MCK) area which has 36,500 resident population and 200,000 floating population. Total area of the MCK is 13.5 km^2 and land use is dominated by commercial and residential units. Total land area of the compost plant is about 13.5 acres and it is divided into two sections; compost plant and the dumpsite (Figure 12).

Compost yard

Dump Site

Figure 12 - Compost plant and dumpsite

3.1.1 Collection of MSW

Total MSW collection at the MCK is 40 T per day on average and all the collected waste is transported to the composting site. Composition of the waste collected from MCK is shown in Figure 13. Non-biodegradable waste is disposed into the dump after sorting and the remaining biodegradable waste which is nearly 16 T and out of that only 5 T a day is used for the production of compost.

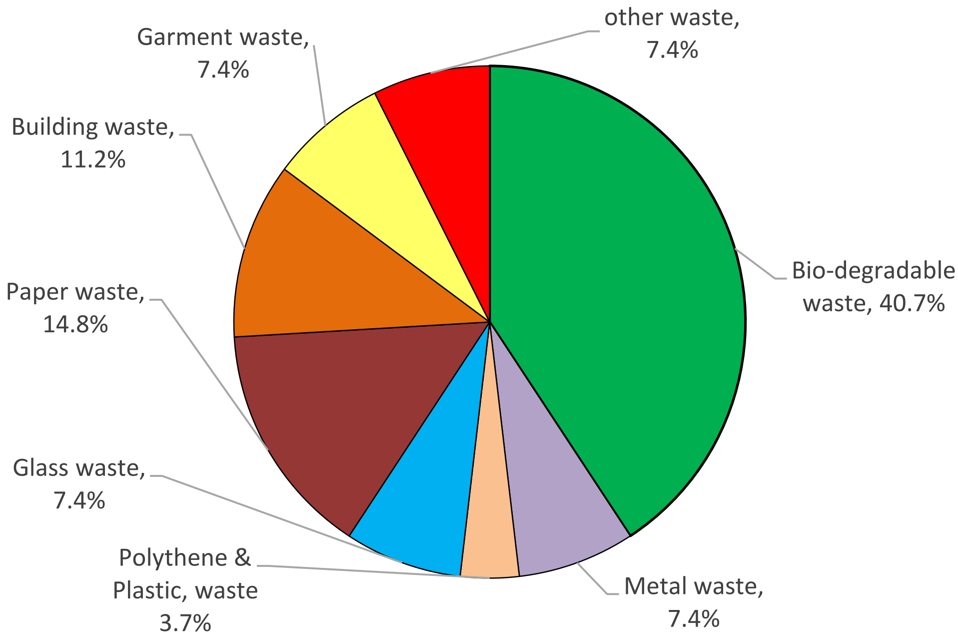

Figure 13 - Waste composition in Kurunegala Municipal Council area

3.1.2 Preparation of Dried Faecal Sludge

Faecal Sludge (FS) is collected daily from households, commercials, and army bases by the bowsers belonging to the MCK and transported to the composting site where a sand bed for de-watering of FS has been installed. Transported FS is discharged onto the sand beds (Figure 14) and allowed to dry (Figure 15). This takes up to 20-30 days and depends on the weather conditions, wind speed, sun light and humidity. After de-watering and drying DFS is manually collected and piled up (Figure 16).

Figure 14 - FS discharge in to the sand beds

Figure 15 - Drying stages of FS in the sand bed

Figure 16 - Manual collection of DFS & DFS pile

3.2 Preparation of compost and co-compost

1 T of sorted short-term biodegradables comprised of vegetable and fruit wastes from markets, households and garden waste were put into piles for the preparation of

compost by windrow method as in Figure 17. In the preparation of co-compost, DFS 10% by weight was used (Jayawardena *et al.*, 2017). Both compost and co-compost were produces according to the method reported by Jayawardena *et al.*, (2017).

In the co-compost pile, the organic portion of the sorted waste (900 kg) and DFS (100 kg) were arranged in alternate layers (Figure 18).

Figure 17 - 1T of Compost pile made out of sorted short-term biodegradable waste

Figure 18 - Preparation of co-compost pile incorporating MSW:FS at 9:1 ratio

3.3 Pelletization

3.3.1 Equipment

A motor operated disk type pelletization machine installed at the composting site (Figure 19) was used for the preparation of compost pellets. Pelletizer has the capacity to process up to 300 kg/h compost (Machine specification are: 415 V, 30 HP, 22W motor, outside dimension: 1.85 m height, 2.18 m length and 1m width). As the two rollers circularly run on the die, it compresses compost into the holes (Figure 9). The holes of the die plate are 6 mm in diameter. The pellets are cut using a rotating cutter when formed pellets come out from the die and finally collected on to the tray. Compost that has not been pelletized (loose compost) are screened (the bottom of the outlet channel is made out of a mesh) before pellets are discharged to the collecting tray.

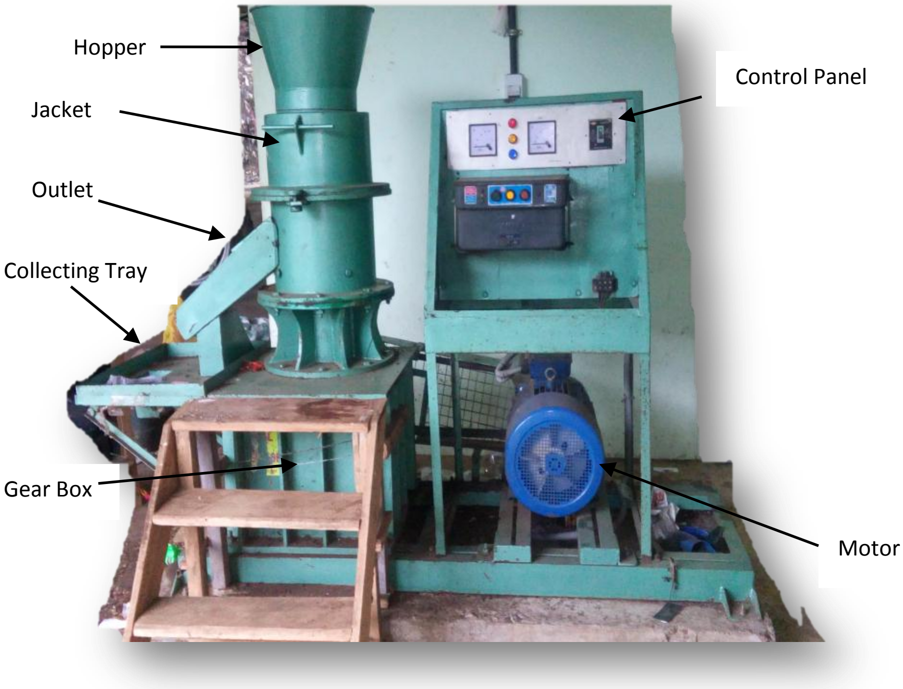

Figure 19 - Pelletization Machine installed at the compost site

3.4 Material Preparation

3.4.1 Compost Sieving

Matured compost and co-compost were sieved manually and mechanically as shown in Figure 20 with selected meshes.

Figure 20 - Compost sieving of manual and mechanical method

The recommended mesh size for compost screening is 5 mm according to the SL standards. To test the effect of compost particle size on pelletization, three sizes of sieves; 2.5 mm, 3.5 mm and 5 mm were used to sieve compost and the oversized particles remained on the sieve were discarded. Sample having ≤ 2.5mm (Particle Category (PC)1), ≤ 3.5mm (PC 2) and ≤ 5mm (PC 3) were used in subsequent experimental works.

3.4.2 Moisture adjustment in compost

Initial moisture of the compost at the production site was within the range of 20-25% wet basis. A series of compost and co-compost mixtures with different moisture contents from 25% to 45% with 5% increment were prepared (Figure 21) to test the effect of moisture on pelletization.

Figure 21 - Moisture content adjustment by addition of water

Moisture content of the sample was adjusted by adding water or drying the sample and the measurement was done with a portable moisture meter (Vktech-54433). Moisture adjusted compost mixture was kept in an air-tight polythene bag for 24 hours for homogenization and stabilization. Moisture content was measured after 24 hrs and the same procedure was repeated until the required moisture level was achieved.

3.5 Pellet Preparation

3.5.1 Preparation of co-compost pellets with different particle sizes

Co-compost with 3 particle size ranges; PC1, PC2 and PC3, after adjusting the moisture content to 25% were fed to the pelletization machine.

3.5.2 Preparation of co-compost pellets with different moisture contents

Co-compost having < 5 mm (PC3) particles and the moisture adjusted to 25 to 45% in 5% increments were used in preparation of pellets.

3.5.3 Preparation of compost pellets with different binding agents

Moisture content of the compost used in this study was 25% and the compost was from PC3. Three types of materials; rice flour (RF), lime and Eppawala Rock Phosphate (ERP) were used as external binding agents and each of these materials were mixed manually with compost at 1, 2 and 3% weight basis (Figure 22).

Figure 22 - Adding binding agents and mixing

Prepared compost or co-compost mixture (moisture adjusted and/or fortified with binding agents) was fed to the pelletization machine.

A representative sample of compost and co-compost mixture and pellets from each lot were stored in air tight containers for laboratory analysis and the remaining pellets were sun dried (Figure 23).

Figure 23 - (a) Compost pellets produced and (b) Drying of Pellets

The block diagram in Figure 24 shows the compost/co-compost pellet production process and the Table 2 summarizes the materials used and the specific objectives of the experiment carried out.

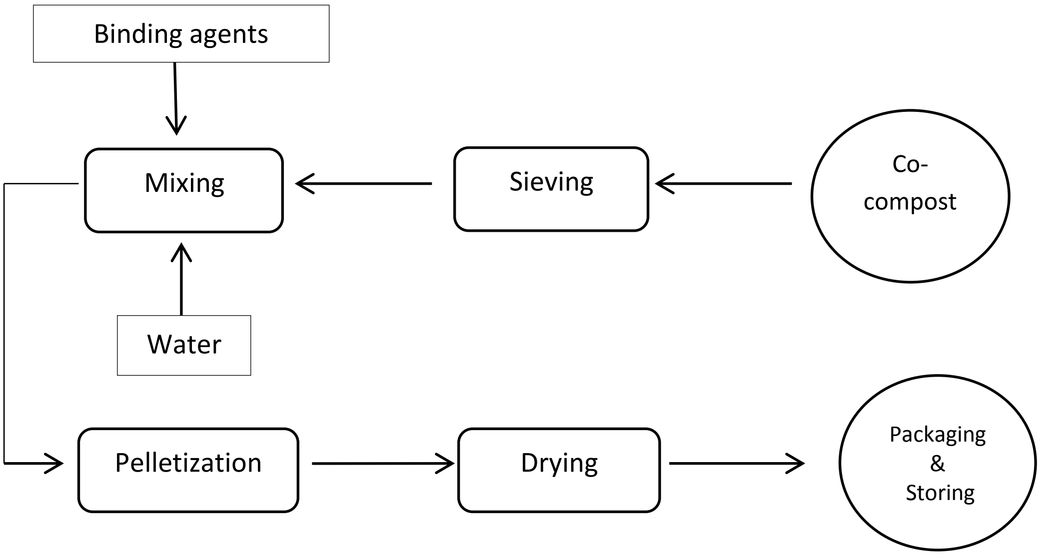

Figure 24 - Proposed pellet production process without grinding step

3.6 Evaluation of physical parameters of compost/co-compost pellets

3.6.1 Determination of Particle Size Distribution in compost pellets

Representative sample of compost, co-compost from each PC and pellets prepared from each PC were subjected to wet sieve analysis (Anon, 2005) to determine the particle size distribution in each sample. The analysis was conducted at the laboratory in Industrial Technology Institute (ITI).

3.6.2 Pellet Length Distribution

A representative sample of 200g were taken from each treatment and pellets in each sample was categorized according to their length; (<5mm, 5-10mm, 10-15mm, 15-20mm and 20mm<). Then weight of pellets in each length category was recorded and calculated as percentage of the whole sample. The method repeated thrice for each sample.

3.6.3 Bulk Density

Bulk density (packing density) refers to the mass of pellets per unit volume and was determined by following method given in ASAE Standards S269.5 (equation 1) (This experiment was also conducted at ITI)

$$\text{Dry bulk density} = \text{Wet bulk density} * \frac{\text{moisture content}}{100} \qquad (1)$$

3.6.4 Compressive Strength

The diametrical compression test proposed by Tabil, (1996) was done to determine the compressive strength of densified products (equation 2).

$$\text{Compressive force} = \frac{\text{force at fracture of the pellet (N)} * 10}{\text{length of the pellet (cm)}} \qquad (2)$$

3.6.5 Disintegration of pellets

A representative pellet sample of 50g from each test with different particle sizes, moisture contents and binding agents were tested for disintegration in the presence of water. This experiment was also done at the ITI. The pellets were placed into a transparent cup filled with 200 mL distilled water. After that, the cups with distilled water and pellets were kept undisturbed for one month to disintegrate the pellets.

In addition pellets prepared with PC 3 with 25% moisture and RF as the binding agent were transported 50 km distance to study the effect of pellet breakage during transportation.

3.6.6 Machine Efficiency

To calculate the Machine Efficiency, weight (dry) of pellets produced (W_f) in the pelletization process within a given time (T) was obtained. Three sets of weight and time data were obtained and the mean value was applied to the equation (3) to calculate the machine efficiency.

$$\text{Machine Efficiency (kg/h)} = \frac{\mathrm{Wf}}{\mathrm{T}} \times 60 \qquad (3)$$

3.6.7 Production Efficiency

All the compost fed to the pelletizing machine do not involve in pellet forming and all the compost particles that have not pelletized are removed through a vent. To assess the production efficiency final weight of dried pellets (W_f) and initial bulk weight (Wi) were recorded and the production efficiency was calculated as given in equation 4.

$$\text{Production Efficiency (\%)} = \frac{\mathrm{Wf}}{\mathrm{Wi}} \times 100 \qquad (4)$$

Table 2 - Summary of the specific objectives of experiments carried out

Section	Specific Objective of the experiment	Material used
3.5.1	Identify variations in co-compost particle sizes on pellet properties and production process	Co-compost (Particle size - 2.5, 3.5 & 5 mm) (Moisture content 25%)
3.5.2	Identify variations in co-compost moisture content on pellet properties and production process	Co-compost (Particle size 5mm) (Moisture Content - 25, 30, 35, 40 & 45%)
3.5.3	Identify impacts of local binding agents on pellet properties and production process	Compost (Particle size 5mm) (Moisture content 25%) (Binding agents - Lime, RF & ERP) (Binding weight percentage – 1-3%)

CHAPTER 4

Results and Discussion

Results of the experiments conducted to determine the effect of compost and co-compost particle size, moisture content and binding agent on the pellet length, bulk density, compressive strength and the ability to disintegrate are presented and discussed in this chapter.

4.1 Physical parameters of co-compost pellets with different compost particle sizes

4.1.1 Determination of Particle Size Distribution in compost pellets

Figure 25 shows particle size distribution in loose compost after wet sieve analysis. Compost of PC1 and PC2 has higher percentage of small (<2 mm) particles (99 & 94% respectively) while PC3 sample had only 63% of small size (<2mm) particles. PC3 compost sample shows a good distribution of particles of different sizes. In PC3 about 10% particles by weight is above 3.5 mm in size.

Particle size distribution of loose compost of PC3 by sieve analysis and that of compost pellet (prepared by same particle category compost) by wet sieve analysis are shown in Figure 26. 73% (by weight) particles are smaller than 2.5 mm in PC3 loose compost while pellets from the same category has 92% (by weight) particles under 2.5 mm sieve size. Further, all the particles in pellets made out of PC3 are below 4 mm in size.

In this work compost pellets were made after sieving and moisture adjustment to compost but without grinding. As can be seen from Figure 26 wet sieve analysis of pellets shows an upward shift in particle size distribution indicating that the percentage of smaller particles has increased during pelletization, it was 26% increase for 2.5 mm size particles and all the particles present in compost pellets made with PC 3 are smaller than 4mm in size. This is a clear indication that even though grinding was not done prior to pelletizing, grinding of compost happened in the pelletizing machine during the process.

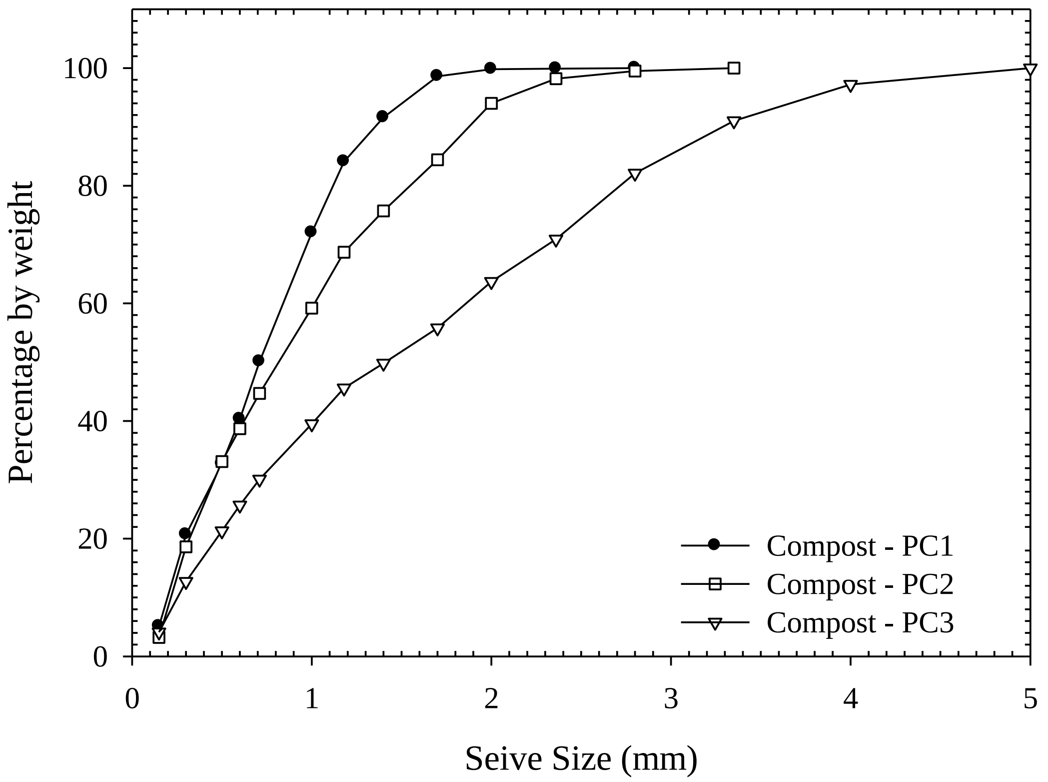

Figure 25 - Particle size distribution of loose compost of all 3 particles size categories

In all the reported work on compost pellets compost grinding has been done prior to pelletizing (Nikiema *et al.,* 2013a; Kaliyan and Morey, 2009). Grinding of compost adds an additional processing step in the production of pellets which is energy and cost intensive. This work demonstrates that grinding step can be eliminated in compost pellet production cutting down the production cost and increasing the efficiency.

4.1.2 Pellet Length Distribution

Length distribution (by weight) of compost pellets made with all three particle categories at 25% moisture resulted higher percentage of 5-10 mm long pellets (Figure 27) and that was 35, 36 and 34% for pellets made with PC1, PC2 and PC3 respectively. Pellets made with PC1 has 32% (by weight) pellets shorter than 5 mm while pellets made out of PC2 and PC3 particles resulted 22 and 21% pellets that are shorter than 5mm.

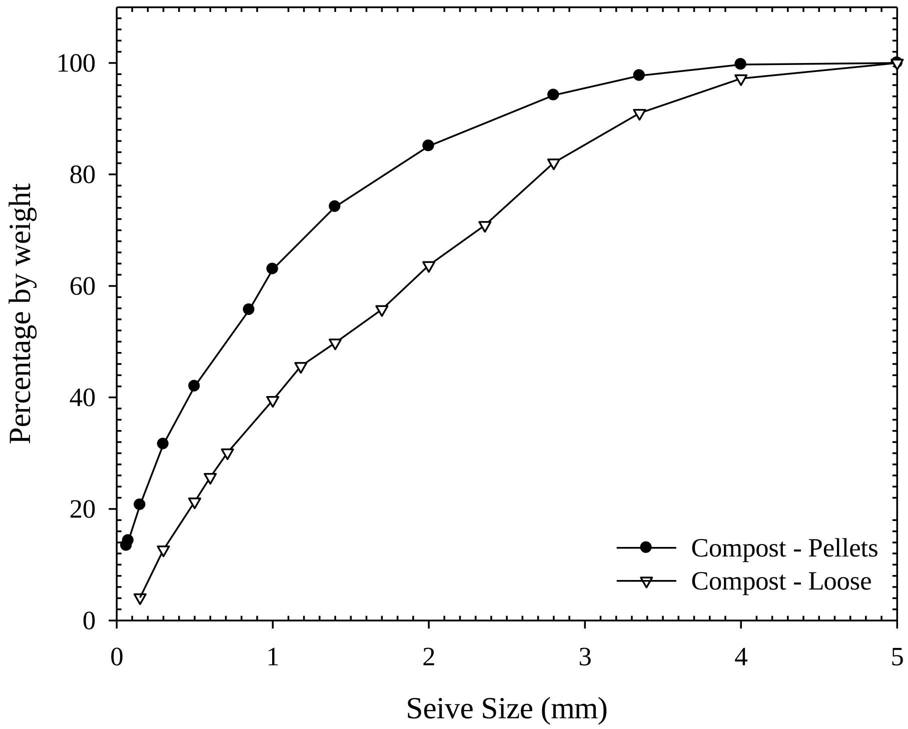

Figure 26 - Particle size distribution of loose compost and pellets of PC 3 (≤-5 mm) moisture content 25%

Pellets made with PC1 and PC2 particles have high percentage (> 85%) of pellets that are less than 15 mm in length. Pellets of PC3 resulted higher percentage (25%) of long pellets (15mm <) while pellets made with PC1 particles resulted the lowest percentage (13 %) of longer pellets (15mm<).

According to results obtained, the best particle size to achieve long pellets with the selected die (6mm in diameter) in this work is PC3 which has particles similar size to the die diameter. When the die diameter is close in size to the particles, good compaction happens in the die in pelletizing. Further, presence of particles with wide range of particle sizes (in PC3) allows good compaction giving a good strength invariably resulting long pellets. Compost pellets with small particles; PC1 and PC2 resulted more pellets that are shorter than 10mm in length and this is due to the easy movement of particles through the die without proper compaction giving rise to weaker pellets which are susceptible to break easily.

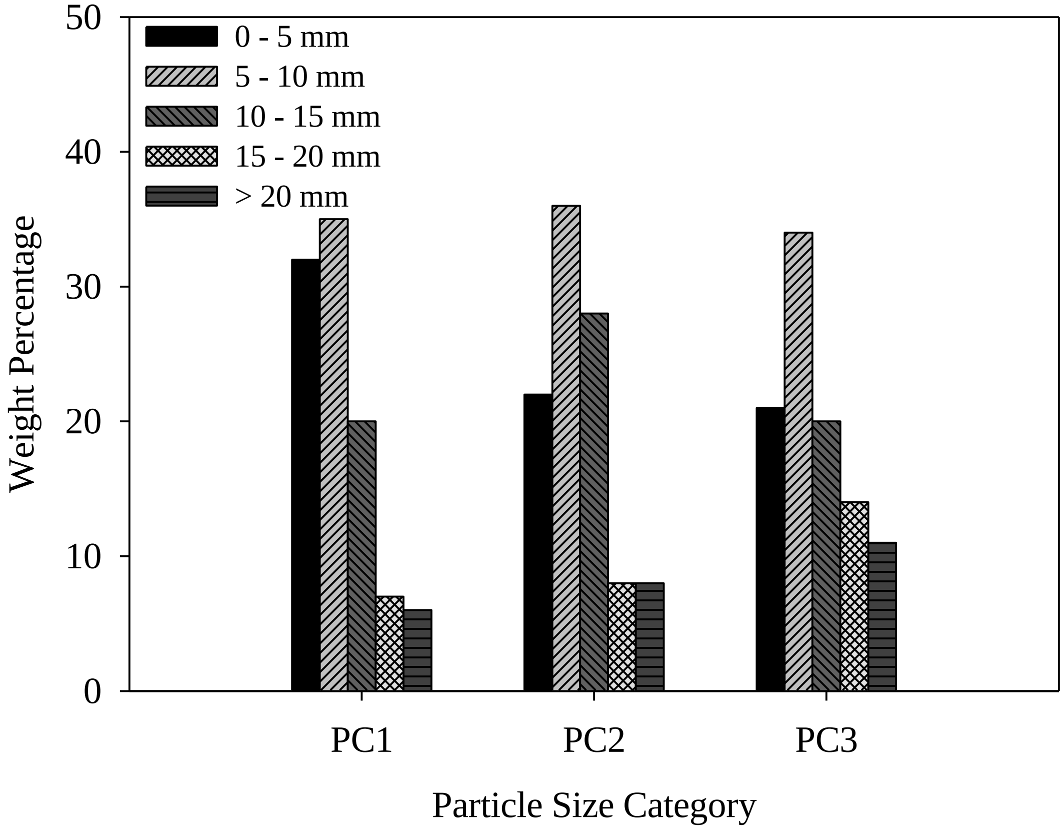

Figure 27 - Weight percentage of pellets lengths of compost pellets prepared with PC 1, PC 2 and PC 3 at 25%

4.1.3 Bulk Density

It can be seen from Figure 28 that the bulk density of loose compost does not appreciably change when composed of different particle sizes. The density of bulk compost was 557.0 kg/m^3, 551.0 kg/m^3 and 567.0 kg/m^3 for the 3 different particle categories; PC1, PC2 and PC3. Moreover, there is no distinct difference in bulk density of compost pellets made from PC1 & PC2 particles (730.3 kg/m^3 and 730.7 kg/m^3) however, there is a noticeable drop in the bulk density of pellets made from PC3 (687.5 kg/m^3).

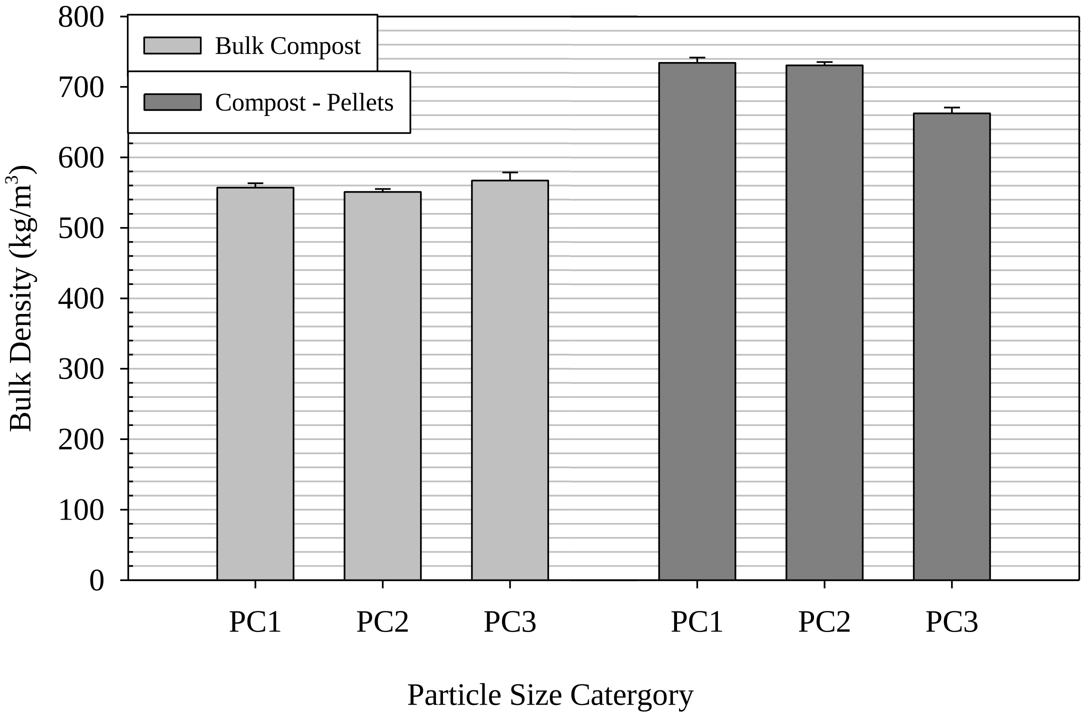

Figure 28 - Bulk Density of loose compost and compost pellets made with PC 1, PC 2 and PC 3 at 25% moisture

Bulk density gives an indication of the level to which compost (both loose and pellets) can be packed in a given volume which is highly important in transportation. As can be seen from Figure 28, there is no much difference in the bulk density of loose compost, composed of different particles sizes. However, bulk density of compost pellets made with all 3 particle sizes has increased by 33-45% due to compaction of compost in pellets increasing the total mass in a unit volume. The bulk density of pellets made with PC1 and PC2 does not show a noticeable difference and that may be due to similar distribution of pellet lengths in both categories. In both these categories, the presence of high percentage of short pellets allows better packing, filling the voids in the container. Packing was not good with long pellets giving a lower bulk density compared to other types as can be seen when pellets were prepared from PC3 particles. This study demonstrates that the length distribution of pellets has an influence on the bulk density of compost pellets.

Therefore, in order to increase the bulk density, a mixture with appropriate amounts of both long and short length pellets are required.

4.1.4 Compressive Strength

Figure 29 shows the variation of pellet strength (given as the load required to rupture 1 cm long pellet) with compost particle sizes (3 particle categories considered). According to results obtained, pellet strength increased when the particle size was increased. Pellets made with PC1 could withstand only 43.0 N/1cm but pellets made with PC3 could withstand 64.3 N/1cm.

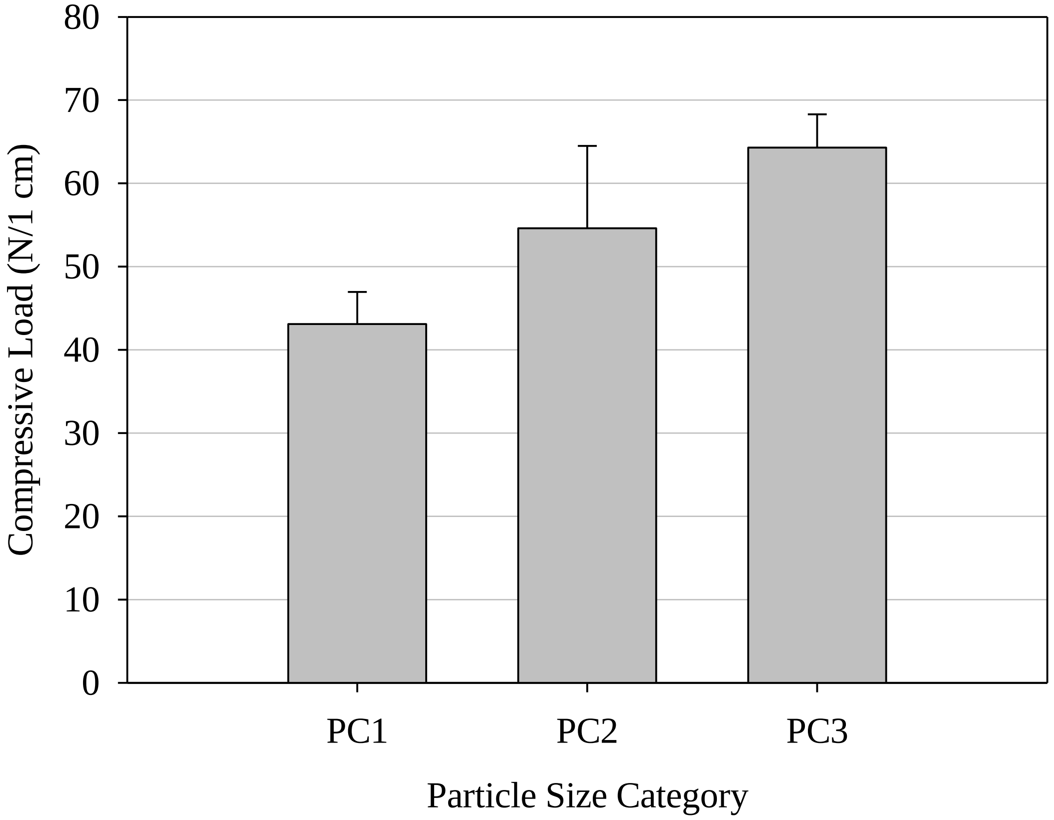

Figure 29 - Variation of compressive strength of pellets prepared with PC1, PC 2, and PC 3 at 25% moisture with compost particle size

A mixture of different particle sizes and a wide particle size distribution support compaction of material. Smaller particles fill gaps facilitating interlocking of particles and minimizing the voids present. In addition short range forces such as hydrogen bonds and Van der Waals forces are present in closely packed particles and these too contribute to the increase of strength of pellets. These forces are strong when the particles are close to each other and the forces decrease when the particles are loosely packed. As seen from Figure 25, PC3 has a wide distribution of particles compared to PC1 & PC2. Therefore, pellets made with PC3 shows high compressive strength (Figure 29) due to better compaction that has resulted because of presence of well distributed particles of different sizes. Further, these closely packed particles with high inter-particle bonding make pellets strong. So that they can withstand high compressive forces. Similar findings for extrude briquettes of agro biomass (Grover and Mishra, 1999) and for corn waste, rice husk and livestock diet briquettes (Kaliyan and Morey, 2009) have been reported.

4.2 Physical parameter of co-compost pellets with moisture content

4.2.1 Pellet Length Distribution

Distribution of pellet length with moisture for PC3 is shown in Figure 30. For all moisture contents considered, the highest weight was recorded for 5-10 mm length class and pellets longer than 20 mm showed the lowest percentage.

It can be seen that when the moisture content was increased, the percentage weight of long pellets decreased and that of short pellets increased.

According previously published work moisture in the feedstock acts as an important factor in the pelletizing process. Moisture has an ability to serve as a binding as well as lubricating agent. The right amount of moisture develops self-bonding properties in densification (Kaliyan and Morey, 2009). Interfacial forces between solid compost and moisture create strong bonds adding strength to pellets (Mani *et al.,* 2003). However, with the increase of moisture, the distance between particles increases trapping water in voids creating a biphasic mixture (liquid phase and solid phase). In such a situation intermolecular forces such as Hydrogen bonds and Van der Waals forces disappear weakening the forces between particles (Zafari and Kianmahr,

2012) and hence strength of pellets decreases, result in short pellets as clearly seen in Figure 30. Therefore, higher the moisture level in compost, lower the strength of pellets and consequently are short in length. Moreover, moisture may help to increase the lubricity and the fluidity of compost and therefore easily pass through the die without proper compaction resulting short pellets. No previous studies have been carried out to determine the effect of moisture level on the strength and length of compost pellets and therefore this works provides valuable information on physical properties of compost pellets with different moisture content.

4.2.2 Bulk Density

Bulk densities of pelleted compost at various moisture contents are shown in Figure 31.

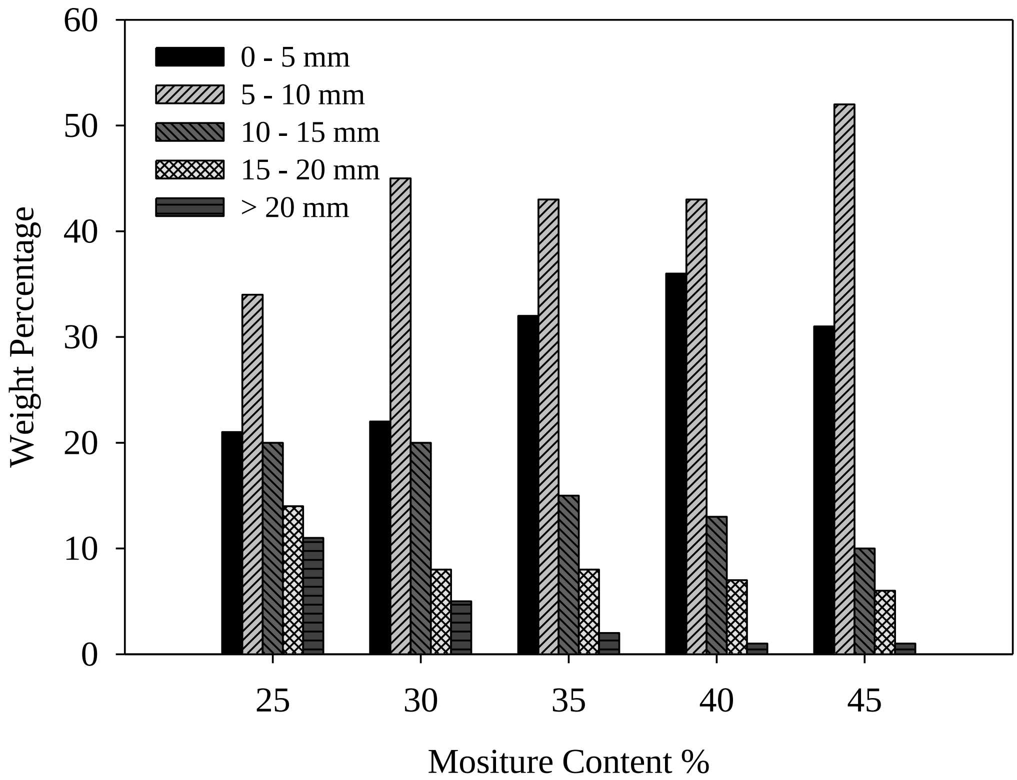

Figure 30 - Weight percentage of compost pellets of different lengths at different moisture levels (pellets made out of PC3)

Bulk density of compost pellets increases when pellets were made with compost having increased moisture. This could be due to two reasons. One could be with the increase of moisture, pellets produced were short as per Figure 30 and hence those easily filled the container minimizing voids that have high bulk density. The other reason could be due to increase in the mass of compost mixture with the addition of extra water and during pelletizing the extra moisture could be retain in the pellets.

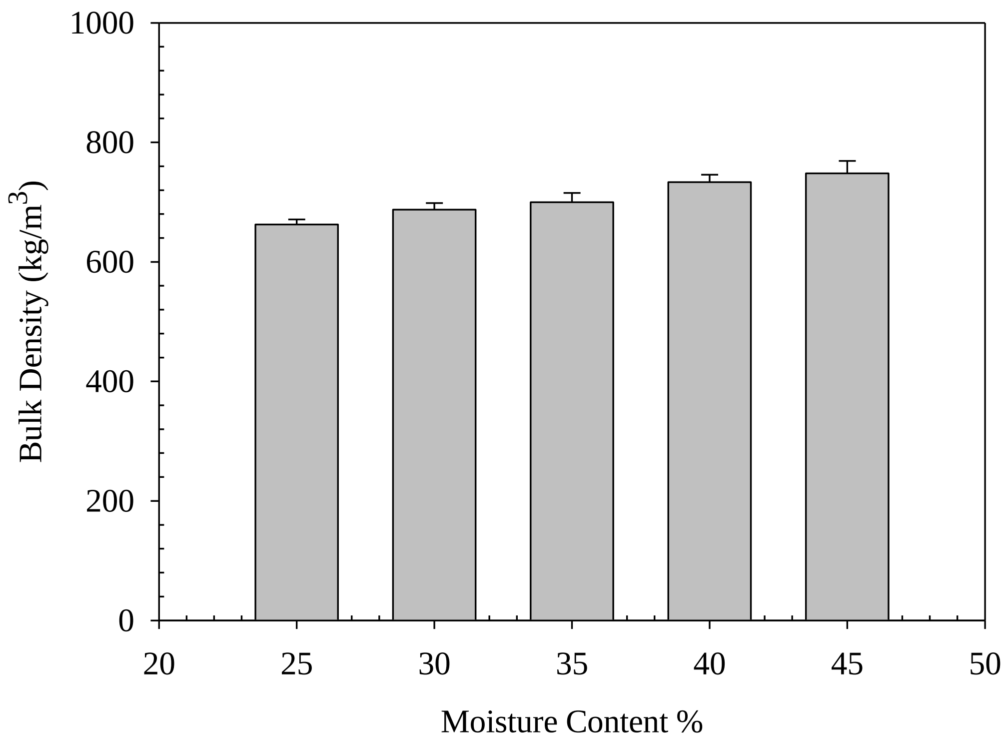

Figure 31 – Variation of Bulk Density of compost pellets with moisture

4.2.3 Compressive Strength

Pellet strength with increased moisture for five different moisture contents (25-45% in 5% increments) is shown in Figure 32. In all the samples tested, the highest strength was observed in pellets made with 25% moisture compost where the compressive strength was 64.3 N/1 cm. The lowest strength was shown in pellets made with compost having the highest moisture content of 45% and the load required to break the pellets was 18 N/1 cm.

As explained in 4.2.1 moisture in the compost mixture tends to produce weak pellets that rupture easily at low compressive strength as can be seen from Figure 32. Similar observations have been observed by Mani *et al.,* (2003), Zafari and Kianmahr, (2012) and Romano *et al.,* (2014). It can been seen that the best moisture content is about 25% for the Die and Roller disk pelletizer used in this work. This is because the fluidity of compost falls with reducing moisture increasing the frictional resistance as the compost passes through the holes of the die and increases the strength of the compost pellets as described by Hara, (2001).

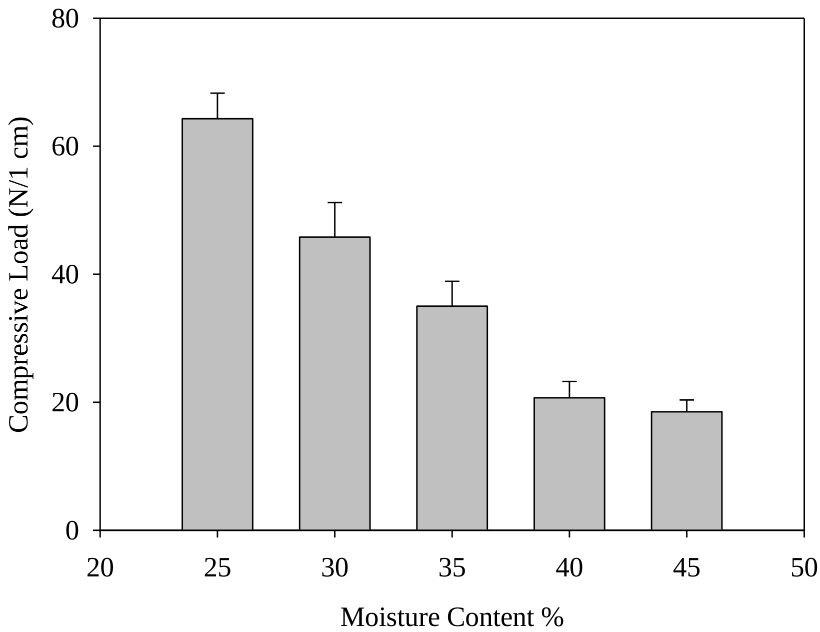

Figure 32 – Variation of the Compressive Strength of compost pellets with moisture

4.2.4 Production and Machine Efficiency

As can be seen from Table 3, machine efficiency and the production efficiency increased with compost particle size. When the particle size of compost (with 25% moisture) was increased from PC1 to PC3, the production and machine efficiencies increased. Further, both production and machine efficiencies decreased with increasing moisture content for when compost of PC3 was used.

Table 3 - Production and machine efficiency with varying particle size and moisture content for compost pelletizing

Particle Size and Moisture Content			
Particle Size (mm)	**Moisture Content (%)**	**Production Efficiency (%)**	**Machine Efficiency (Pellet kg/h)**
2.5	25	55	30
3.5	25	75	41
5	25	85	64
5	30	83	54
5	35	78	50
5	40	70	40
5	45	64	25

The efficiency of production of marketable compost pellets from a given machine is an important factor that determines the commerciality of compost pellets. In this work the effect of compost particle size and the moisture level was evaluated on the production efficiency. Machine efficiency is the amount of marketable pellets produced in an hour and this is a property specific to the machine and the die used for a given compost sample.

Production efficiency increased with the increase of particle sizes considered in this work and it decreased with moisture. This can be explained with Figures 30 and 32; the pellet strength decreases with the moisture resulting weaker pellets which break easily giving short pellets and reduced amounts of sellable pellets. In addition it was encountered that handling of moist compost was difficult in the pelletizer; clogging of the die reduced both production and machine efficiencies. These results are in agreement with Hara, (2011) for livestock manure compost, Zafari and Kianmahr, (2012) for cattle manure, Romano *et al.*, (2014) for swine manure.

4.2.5 Disintegration of Pellets

Table 4 - Disintegration of pellets

Particle Size (mm)	Moisture Content (%)	Disintegration after 4 weeks
2.5	25	Not observed
3.5	25	Not observed
5	25	Not observed
5	30	Not observed
5	35	Not observed
5	40	Not observed
5	45	Not observed

Table 4 shows the percentage disintegration of pellets in the presence of water after one-month period. Both pellets with different particle sizes and moisture content show no disintegration even after one month in water. However, it can be assumed that pellets disintegration can happen once these pellets are applied to the farmer fields under different physical and chemical effects like wind, chemicals in the soil and disturbance by machinery or humans

4.3 Physical parameters of compost pellets with binding agents

4.3.1 Pellet Length Distribution

Length distribution (Percentage by weight) of compost pellets with 3 different binding agents, 3 different weight percentages and pellets with no binding agents is shown in Figure 33. It is very clearly seen that the percentage of short pellets have decreased and that of long pellets have increased when binding agents (all 3 types) were used compared with pellets with no binding agents. Therefore, it can be considered that all three binding agents were able to enhance the binding ability resulting long pellets

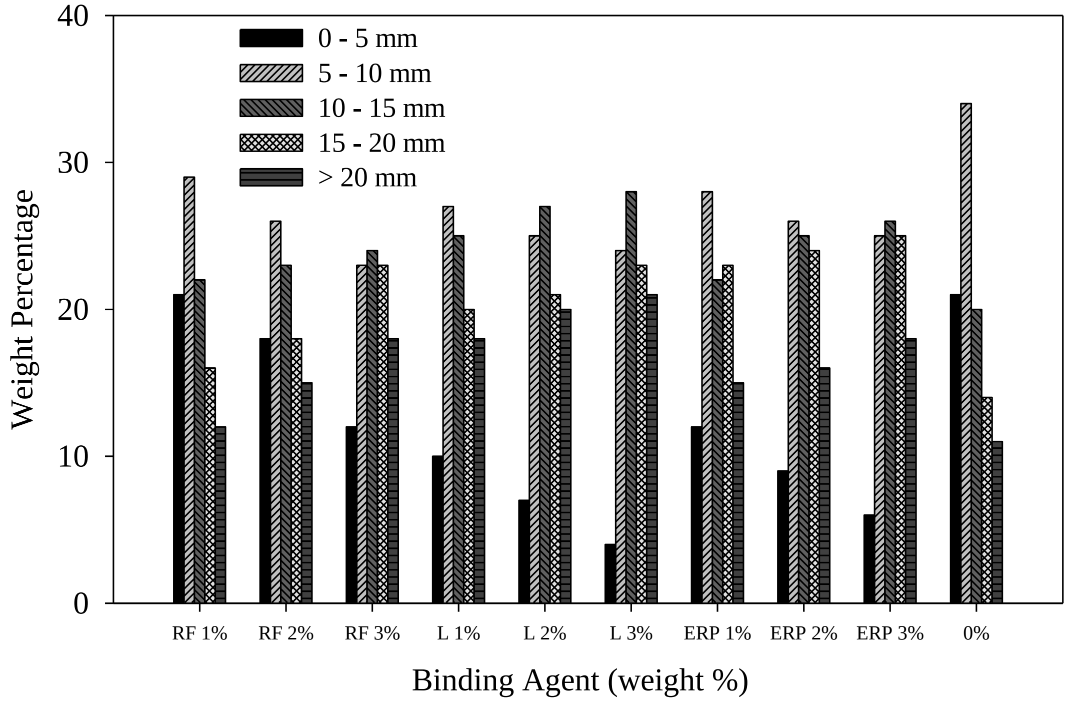

Figure 33 – Pellet length distribution of compost of PC 3 at 25% moisture enriched with different types [RF- Rice Flour, L- Lime, ERP-Eppawala Rock Phosphate] and weights of binding agents

Out of the three binding agents, the highest percentage of long pellets (20mm<) was obtained when lime was used and the lowest percentage of long pellets was obtained when RF was used as the binding agents. Length distribution of ERP added pellets showed a pattern in between the length distribution of lime and RF added pellets. The highest percentage of short (< 5mm) pellets resulted from RF added compost and the lowest percentage resulted from lime added compost. ERP resulted long pellets than RF and less percentage than lime.

According to Figure 33, lime (CaO) is the most effective binding agent among all binding agents that results long pellets.

at 25 % moisture and PC 3 particles with the selected die (6mm in diameter) was used in this work. In the presence of moisture, CaO forms Calcium Hydroxide ($Ca(OH)_2$) where Ca^{2+} and OH^- ions are produced. Ca^{2+} is a strong ion and it tends to attract molecules presented in the mixture to form ion dipole interaction, a type of Van der Walls force where interaction occurs between an ion and a neutral molecule that helps to bind particles together. The interaction can be strong; either charge of the ion increases or magnitude of the dipole of the polar molecule increases (Jordan and Tim, 2017). When the weight percentage of lime is increased, eventually Ca^{2+} ions increases and produces more interactions binding particles together to produce long pellets.

ERP is a less soluble binding material used in this experiment. The major element in ERP is Ca which was present in the range of 21.5-24.5% and the main constituent is apatite ($Ca_5(PO_4)_3$ (OH,F,Cl)) (Rathnayake and Navarathne, 2014). Although, Ca^{2+} ions are present in ERP, their interactions with compost are weaker than that of Ca^{2+} in lime because of the presence of OH^-, F^- and Cl^-. These weak interactions give low strength to pellets and in turn produce short pellets than lime.

RF has no effective ions and free ions identified to produce strong pellet and hence RF added pellets gave the lowest percentage of pellets of length >15mm. However RF is a potential binder at adequate moisture and heat (Tabil, 1996). Although RF in dry form has limited binding ability, gelatinized RF shows good binding ability due to stickiness and can make stronger pellets; (Tabil, 1996; Nikiema *et al*., 2014). Even if heat is generated during pelletization by friction, the moisture level is not sufficient for gelatinization and it is reported that moisture in the range of 30-50% is required for geletinization (Tabil, 1996). Due to dry nature of RF compost even at 25% moisture, material move easily through the dies of the pelletizer to form short pellets. However, when RF percentage was increased there is a possibility of enhancing the interlocking and adhesion of particles with pressure, which may results in sufficient strength in pellets as explained for biomass densification (Tabil,1996; Grover and Mishra,1996).

4.3.2 Compressive Strength

Figure 34 shows the change of compressive strength of compost pellets made with different types and weight percentages of binding agents. Pellets with no binding agents (25% moisture and PC 3) have compressive strength of 64 N/cm. Pellets with 1% RF gave the highest compressive strength of 107 N/cm. However, when the percentage of RF was increased to 2% and 3%, the strength gradually decreased to 70 N/cm and 63 N/cm respectively. Pellets with 1% (by weight) lime showed a decrease in compressive strength than that of pellets with no binding agents and then increased from 43N/cm to 80N/cm when the amount of lime increased from 1-3%. ERP added compost pellets also showed a compressive strength increase similar to lime added compost pellets from 30N/cm to 80N/cm when the binder percentage increased from 1-3%.

When the percentage of RF is increased up to 3%, compost remains in dry form with reducing binding ability, which in turn results in weak pellets compared to other two binding agents. Nikiema *et al.,* (2013a) has incorporated cassava starch up to 5% by weight to fecal sludge-based compost pellets and reported an increase in strength and Tabil, (1996) reported that RF at 30-50% moisture is needed to produce strong Alfalfa pellets.

The reason for the decrease in strength of 1% Lime and 1% ERP added pellets compared to pellets with no binding agent may be due to the moisture level. Water (moisture) in the compost with no binding agent acts as a self –bonding agent and support higher densification by promoting Van der Walls forces, capillary pressure and interfacial forces for binding of particles (Tabil, 1996; Grover and Mishra, 1996). With the addition of external binding agents, the ability of water to bind with compost gets limited resulting pellets with low strength. However, with the increase of lime to 2 and 3 %, compressive strength increased and this could be due to ion dipole interaction available in the compost mixture with strong Ca^{2+} ions in lime to form strong pellets as explained in 4.3.1.

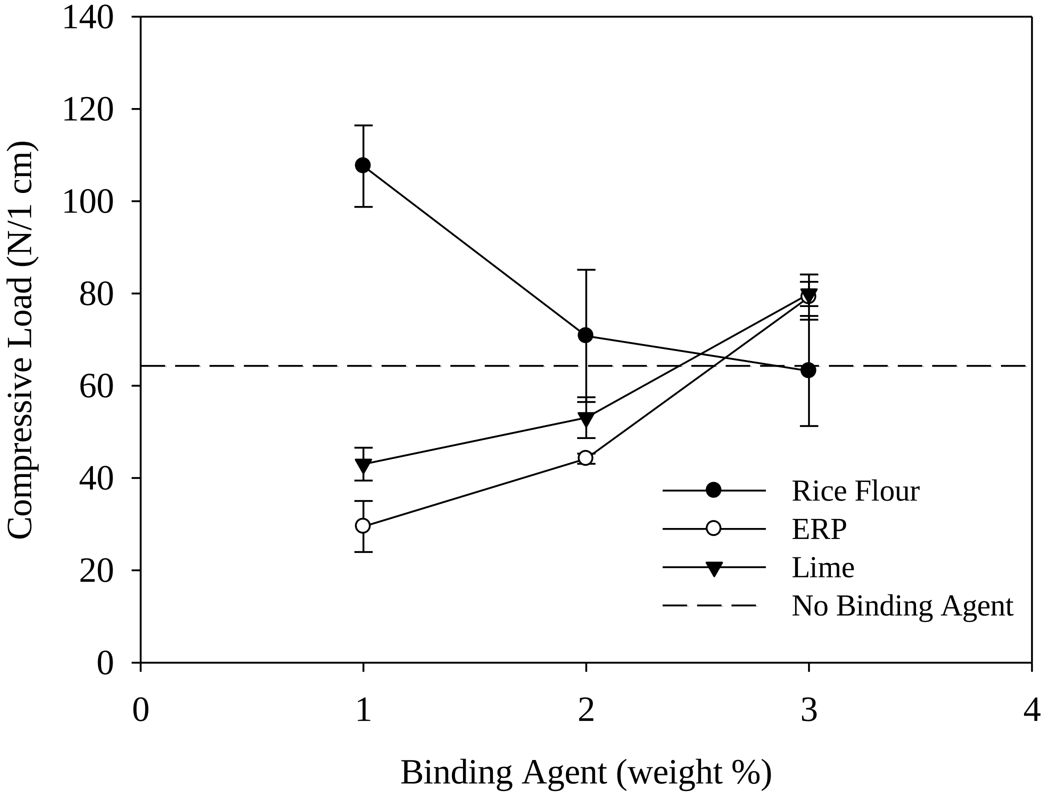

Figure 34 - Variation of compressive strength with different binding agents and their weight percentage

The reason to produce weak pellets with 1% ERP (compared to lime) could be due to weak interactions by the Ca^{2+} ions in ERP with compost particles as explained. However, gradual increase of ERP, increased the strength similar to that obtain with lime due to formation of solid bridges and Van der Walls forces at high temperature and pressure during densification. (Tabil, 1996; Grover and Mishra, 1996).

4.3.3 Bulk Density

Bulk densities of compost with RF, compost pellets with RF and lime as binding agents at different weight percentages are shown in Figure 35. The bulk density of RF added compost was in the range between 300-400 kg/m^3. After pelletization; same binding agent added compost pellets showed bulk density between 586-640 kg/m^3 and while the bulk density of lime added compost pellets was 825-870 kg/m^3.

Nevertheless, in all cases, with the increase binding agents weight percentage from 1 to 3%, there was a noticeable decrease in the bulk density.

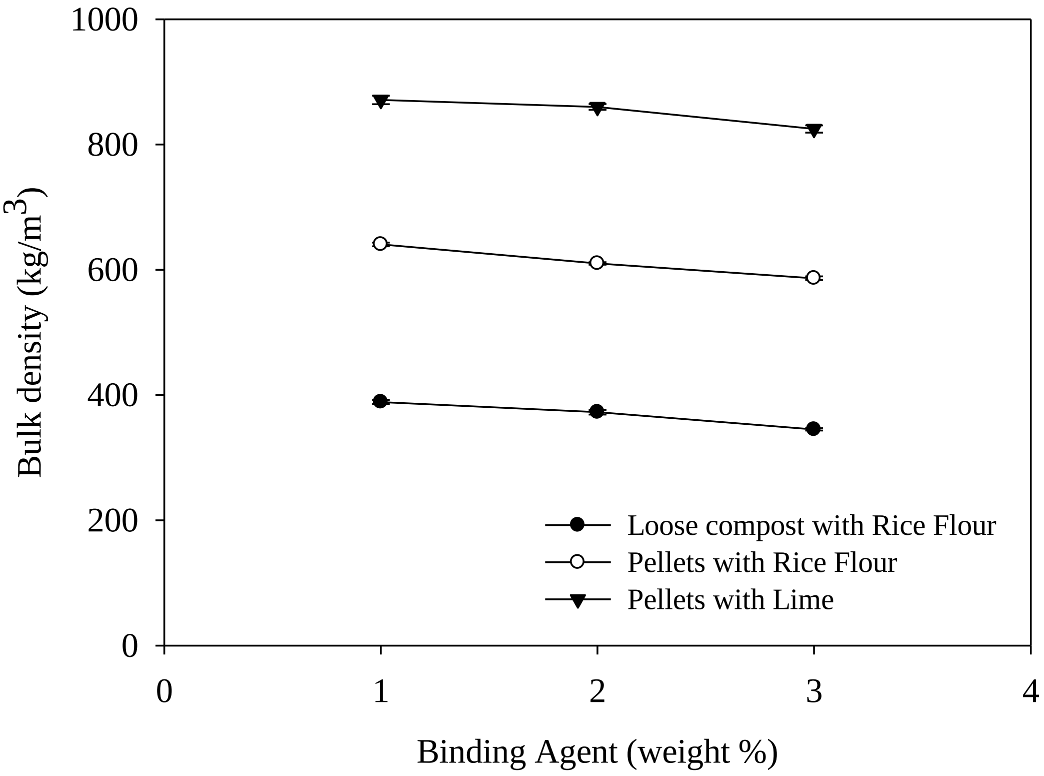

Figure 35 - Variation of bulk density of compost with RF, compost pellets with RF and pellets with lime as binding agents

RF added compost pellets resulted more short pellets and hence it is expected to increase the bulk density by minimizing the voids in the container used in the test. However, bulk density of pellets, made with lime added compost showed a noticeable increase than that of pellets made with RF added compost. Lime has ions that binds compost particles very strongly and results highly-densified product as previously mentioned in 4.3.1 and 4.3.2. Therefore, the weight of compost present in a unit length of a pellet is more in highly densified lime added pellets compared to RF pellets, which are not densified as the former. Hence, that could be the reason for high bulk density in lime added pellets compared to RF added pellets.

4.3.4 Disintegration of Pellets

Percentage disintegration of pellets made with different weight percentages of three binding agents in the presence of water is shown in Figure 36.

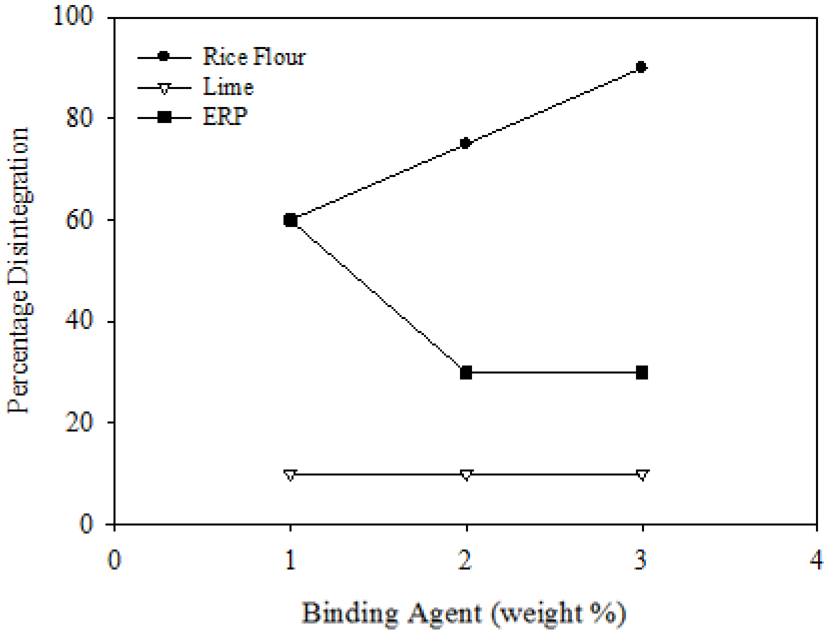

Figure 36 - Percentage Disintegration of compost pellets made with 1-3% RF, lime and ERP as the binding agent

Pellets made with RF as the binding agent showed the highest disintegration ability than pellets made with other two binding agents. With increased percentage of RF in compost was increased, disintegration also increased from 60% to 90%. With the increase of the amount of ERP, pellet disintegration decreased while lime added compost pellets did not show a change in percentage of disintegration with increased amounts of lime and remained around 10% during the one month period considered for the experiment.

Changes that happen in pellets can be due to interaction of pH, temperature, movement of ions and diffusion of molecules (Nikiema *et al.*, 2013a). As a result, molecules induce, swell, and start to disintegrate. In addition, growth of microorganisms helps disintegration, especially in RF added compost where moisture and nutrients for microbial growth are available. RF added compost pellets are weaker due to absence of intermolecular forces and these pellets disintegrate readily in the presence of water. Reason for low disintegration of pellets with ERP is the low solubility of ERP and hence it does not release ions and diffuse molecules for easy disintegration. In the case of lime, CaO reacts with water and form calcium hydroxide ($Ca(OH)_2$). Long period (one month) of $Ca(OH)_2$ in water, in the presence of atmospheric CO_2 may form Calcium Carbonate ($CaCO_3$) and it strongly bind compost particles producing strong pellets. The solubility of $CaCO_3$ is poor in water and therefore remains without disintegrating the pellet.

Pellets produced from PC 3 compost particles with 25% moisture content were transported a 50 km distance to observe the resistance against shocks and impacts. It was assumed that the compost would be marketed within maximum 50 km in urban context in Sri Lanka. Transport trial confirmed the pellets were in good condition even after 50 km transportation and pellets can endure shocks and impacts especially in packaging and transportation.

CHAPTER 5

Conclusion

- This research on co-compost pelletization was conducted using Die and Roller method which was proved to be less complex and economical compared to extruder method.
- Die and Roller disk pelletizer has a grinding effect and hence additional step of grinding is not required giving advantages in commercialization.
- Pelletization increased the bulk density of compost pellets by 30% due to compaction that occurs in the process along with good pellet length distribution.
- Compressive strength of pellets increased when compost particles have a good size distribution (PC 3). However, compressive strength of pellets decreased with the increase of moisture because high moisture tends to block the dies of the pelletizer. Mixing of proper binding agent at correct weight percentage, increase compressive strength compared to pellets with no binding. With the increase of the binder, RF compressive strength gradually decreased but ERP and lime gave promising increase of compressive strength with increasing of binder weight percentages.
- Lime and ERP as the binding agents in compost pelletizing significantly increased the percentage of long pellets compared to RF added pellets and compost with no binding agents.
- Pellets made out of three different particle sizes (PC1, PC2 and PC3) and five different moisture content (25-45%) and with no binding agents showed 0% disintegration in water.

- However, pellets with ERP and Lime (PC3 and 25% moisture) showed 10% disintegration when pellets with RF and same particles sizes and moisture showed 90% disintegration during the observation period of one month.
- Among the three binding agents used in this experiment, lime and ERP were found to be the most promising in terms of achieving strong and long pellets. However, disintegration of lime and ERP added pellets is very much low and can be used for perennial agriculture. RF was very promising in disintegration, and is more fitted for annual crops.
- Both production efficiency and machine efficiency decreased with moisture and increased with the particle size.

Recommendation and Future Works

Recommendation

- Appropriate particle size to produce co-compost pellets is 5 mm.
- Appropriate moisture content to produce co-compost pellets is 25%.
- Recommended compost pellets for perennial crops are Lime or ERP added pellets.
- Recommended compost pellets for short-term crops are Rice Flour added pellets.

Future Works

- Identification of different other binding agents in compost pelletizing
- Identification of the combined effect of different binding agents in compost pelletizing
- Effect of binding agents when fortified at different stages of composting
- Study the disintegration ability of the pellets with different binding agents in the farmer field.

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