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Dewatering of sludge for small scale and decentralized production of biochar

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Declaration

We, RHODA BEMA BOATENG AND OPOKU FOSU SENIOR, authors of the thesis "Dewatering of sludge for small scale and decentralized production of biochar", hereby declare that this submission is our work towards the Master of Science (MSc.) Degree in Sustainable Water and Sanitation, Health and Development. To the best of our knowledge, except where due acknowledgement has been entirely made, it does not contain any material previously published by another person or material accepted for the award of any other degree by the University.

Dedication

We dedicate this thesis to the Almighty and Faithful God for helping us to come out with a successful dissertation.

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Abstract

Sewage sludge dewatering and drying is one of the major challenges in the current wastewater treatment systems. The current dewatering methods in centralized wastewater treatment plants whether using frame or belt filter press or centrifuges are energy intensive and requires up to 50% of the cost of wastewater treatment. The moisture content of the sludge cake after dewatering is also a key factor in determining the efficiency of sludge handling and utilization including energy efficiency and pollutant emission. This is even more challenging for decentralized sludge management aiming at resource recovery and local resource utilization from the perspective of circular economy. To overcome these challenges, an experiment was designed to develop an alternative sludge dewatering and drying method for decentralized wastewater treatment systems and local production of sludge-based biochar. Raw sludge was collected from Frogn Renseanlegg, a wastewater treatment plant in Drøbak, in Viken county of Norway. The sludge was filtered in the laboratory using a solid-liquid separation system containing a 200µm and 100µm mesh integrated with sand filtration to remove free water through gravity to produce a sludge cake. The effect of different percentages of Wood pellets (WP), Spent Coffee Grounds (SCG) and different mixture of the two as bulking agents for deep-dewatering (removal of tightly bound water) was investigated without energy input. The percentages of Wood Pellets (WP) and Spent Coffee Grounds (SCG), varied from 0% (control) to 20% by weight of the raw sludge. The moisture content of the mixture was determined at an average temperature of 17°C after 1, 24, 48, 72 and 96 hr. In the experiment, sludge with addition of 5% SCG, 10% SCG and 20% SCG had an average moisture content of 71.1%, 66.0% and 46.0%, respectively, after 96 hours. For 5% WP, 10% WP and 20% WP, the average moisture content after 96 hours were 70.3%, 55.9% and 45.6%. Adding a small amount of superabsorbent facilitated reduction of the amounts of SCG and WP and achieved a moisture content reduction down to 9.0% after 72 hours. The removal of tightly bound sludge water and fast drying in sludge conditioned with WP and SCG may be mainly explained by absorption by the amendment and subsequently a better porosity and larger surface area for evaporation.

List of Figures

List of Tables

Table of contents

Table of Contents

List of Abbreviations

MUG- 4-methylumbelliferyl-beta-D-glucuronide

ONPG- ortho-nitrophenyl-beta-D-galactopyranoside

SCG- Spent Coffee Grounds

WP- Wood Pellets

1 Background and Literature

Introduction

Water is required for all forms of life to exist and it is essential for long-term social and economic development. However, the world's water resources are under serious threat (Gutterer et al., 2009). The world has seen a remarkable rise in population and economic activity during the last 250 years. This growth process has resulted in considerable societal transformation and a fast-expanding demand for natural resources. Water quality and quantity are affected by urbanization, industrial development, and the expansion of agricultural production. Global trends include overexploitation of water bodies and deterioration of water quality.

One-third of the world's population now live in nations with moderate to severe water scarcity. Since the mid-1990s, 40% of the world's population have been suffering from severe water shortages in urban and rural areas due to recent socio-economic development (World Commission on Water, 1997). The contamination of ground and surface waters is closely related to the rising demand for freshwater supplies and quickly changing production and consumption patterns. More than half of the world's major rivers are severely depleted and polluted (Gutterer et al., 2009).

Urbanisation has increased mostly in developing countries due to an increase in the world's population. It is expected that 60% of the world's population (5 billion people) will be living in urban areas by 2030 (United Nations, 2012). As a result, billions of tons of waste, including wastewater, are produced annually. Empirical records obtained from AQUASTAT (2014) and Sato et al., (2013) indicate that more than 330 km3 per year of municipal wastewater are generated on a global scale. Countries like China, India, United States, Indonesia, Brazil, Japan and Russia produce more than 167 km3 of wastewater, representing half of the world's municipal wastewater. In addition, Europe produces about 10 million tons (dry matter) of sewage sludge annually (Milieu Ltd et al., 2008).

Various stakeholders, including politicians, scientists, engineers and households are much concerned about the management of sludge since it makes up to 40% to 45% of operational cost in a Wastewater Treatment Plant (WWTP) (Spinosa et al., 2011; Liu et al., 2016). In addition, it has a significant impact on the environment (Edwards et al., 2009). Due to the voluminous nature of the sludge, it is of great importance to decrease the volume of the sludge for easy transport and disposal (Raynaud et al., 2012; Vigneswaran 2009).

To reduce sludge volume, biological wastewater treatment uses the solid-liquid separation, where the treated water is separated from the activated sludge (Christensen et al., 2015). The end products of this operation are effluent, return sludge, and residual sludge. Wastewater sludge is transported to digesters for sludge reduction and bioenergy processing in some instances (Christensen et al., 2015).

In Sweden, a tax was introduced on the deposition of organic waste on landfills making landfill disposal quite expensive. If the sludge is disposed off in a landfill, a fee of 250 SEK per tonne of wet sludge must be paid. There is also a debate on whether a new tax should be introduced for incineration (Hultman et al., 2000; Lundin et al., 2004). However, in compliance with the EU Directive 99/31, depositing organic waste into landfills will not be allowed.

The desire to achieve sustainability in the management of water resources has become relevant due to high levels of pollution. The environment is frequently subjected to highly stressful conditions caused by inadequate or non-existent wastewater treatment plants, depriving people of access to water and sanitation (Libralato et al., 2011). Decentralization can be a potential solution to lowering the world's population without access to safe drinking water (Bieker et al., 2010).

1.1 Current sludge management practices

For more than a century, wastewater systems in Europe and the United States have relied on a sewage network to collect wastewater, typically handled by a central treatment unit. This concept is increasingly being questioned, primarily because of its long-term sustainability and the difficulty of transferring these ideas to countries which experience drought (Larsen and Gujer, 1997).

Sludge is a by-product of treating municipal wastewater to withdraw impure organic and inorganic impurities from dilute solutions (Singh and Agrawal, 2008; Feng et al., 2014). Sludge is defined by Markis et al., (2014) as the solid residue obtained from the municipal wastewater treatment process. The composition of sludge is defined according to Rulkens et al., (2003) as:

- Organic carbon molecules that are not harmful to the environment
- Organic micropollutants that are harmful to the environment
- Heavy metals (Zn, Pb, Cu, Cr, Ni, Cd, Ag, As), PCBs, PAHs, dioxins, insecticides, nonylphenols
- Microbiological contaminants such as pathogens and other microbes
- Inorganic compounds such as aluminates, magnesium, silicates, and calcium-containing compounds
- Water, with concentrations ranging from a few percent to over 95%

A peculiar nature of sludge is its high amount of water, its compressible and colloidal nature (Mahmoud et al., 2013). Sewage sludge contains as little as 1-5% (wt%) of dry solids on a wet basis and about 95-99% of the remaining part is made up of water (Saveyn et al., 2005). The high water content of sludge produces low energy content. It is prudent to decrease the water content as this improves the possibility of using sludge as organic matter for composting or as fuel.

In centralized systems, mechanized dewatering systems are used in dewatering the sludge. Mechanical dewatering reduces the total volume of the sludge and improves the caloric value of the sludge (Tuan and Sillanpää, 2010). The current dewatering methods in conventional wastewater treatment include plate and frame filter presses, centrifuges and belt presses. These methods are used in wastewater treatment plants, power plants, refineries and drinking water facilities to reduce the level of sludge and the cost of transport. The plate and filter press is widely used because of their flexibility, large capacities, ability to withstand high pressures and fast filtration process. The primary advantage of the centrifuge is the process's speed.

Issues sometimes found in these dewatering processes in sludge handling facilities include the formation of sludge cake with high moisture content, sticky sludge formation, improper release of cake from dewatering equipment, lengthy dewatering time, and inefficiency of equipment (To et al., 2016). These methods also require huge capital investment, high maintenance and operational cost. The cost involved in operating these dewatering techniques in centralized wastewater treatment plants makes it difficult to be operated in developing countries and decentralized treatment systems (Rocky Mountain Institute, 2004; Chen et al., 2002; Massoud et al., 2009).

Much advancement has been made in wastewater treatment in urban centers than rural areas. Rural areas lack sophisticated equipment, expertise and funding to operate wastewater treatment plants (Paraskevas et al., 2002). However, decentralized systems can be introduced to small and isolated rural settlements with fewer inhabitants due to their simplicity and cost-effectiveness (USEPA, 2005). Decentralized wastewater treatment systems are suited for small-scale operations (USEPA, 2004). In as much as decentralized systems help in the reduction in environmental and public health impacts, they also allow for a more significant amount of wastewater to be recycled, depending on the community type, technological choices, and local conditions. When appropriately utilised, decentralized systems encourage the return of treated wastewater to the watershed from which it was initially collected and treated.

There are a variety of onsite wastewater treatment systems. However, the most familiar treatment system is the septic tank. The septic tank system is the most often used primary treatment technique for onsite wastewater treatment because of its benefits. Septic tanks remove most settleable particles and operate as an anaerobic bioreactor, allowing organic waste to be partially digested (Dawes and Goonetilleke, 2003). Decentralized systems may now be designed based on a given location, overcoming issues like high groundwater tables, impermeable soils, shallow bedrock, and limestone formations, among others. Decentralized systems also provide management flexibility since a succession of procedures may be integrated to fulfil treatment goals while addressing environmental and public health concerns (Massoud et al., 2009).

Even though decentralized treatment systems are more suitable than centralized, they are not without flaws. Septic tanks, for example, if not properly maintained, can cause effluent to overflow into nearby communities, posing a health risk (Carroll et al., 2006). The septic tank may have a challenge with odor if the sludge is stored for a long time before it is treated. Another challenge with the onsite decentralized systems is that many current systems have low possibility to remove and recycle phosphorus and nitrogen compounds effectively (Massoud et al., 2009).

1.1.1 Treatment and disposal routes of sludge

In wastewater treatment, sludge treatment takes about 50% of the cost (Campbell, 2000). Due to the high cost of treating sludge, sludge management has become a priority today, and it is of prime concern to the increasing human population. Sewage sludge disposal routes should be designed under the Waste Framework Directive (EU Directive, 2008), which establishes a hierarchy of waste reduction and management actions, including prevention, minimization, reuse, recycling, energy recovery (Bianchini et al., 2016).

Figure 1 :Waste Hierarchy

https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en

Figure 1 indicates the waste hierarchy. The hierarchy of waste management alternatives ranks them with the waste reduction being the most desirable and waste disposal being the least. In this case, minimization encompasses more than just waste creation; it also includes recycling and reuse.

Landfill and agriculture reuse are mainly the alternatives for the final disposal of sludge for various WWTP (Nowak et al., 2004). Sludge disposal in a landfill is one of the easiest and cheapest methods of managing sludge. In the 1970s and 1980s, issues of situating new landfills became a political nightmare for various governments as this strategy started to be seriously challenged. Several studies have suggested that landfilling is one of the least attractive alternatives since nutrient recovery is not considered (Campbell, 2000). Landfills as a final disposal route for sewage sludge has many challenges including demand for sizable lands, negative aesthetic value to the environment, contamination of surface water and groundwater (Tsybina & Wuensch, 2018).

Composting is another way of managing municipal sludge and environmental activists have accepted it as green technology. However, the challenge in composting is odor control in the processing and the maturation stage, which is usually a nuisance to the surrounding community. Moreover, depending on the maturation period, and the type of composting, it may require quite a large area for compost production (Campbell, 2000).

In the agricultural sector, the use of sludge on arable lands from wastewater treatment plants is accepted only when it will improve the quality of the soil (biosolids used as fertilizers) and when it has no limitations on heavy metal concentration (Nowak et al., 2004). Sludge is known to contain valuable plant nutrients such as nitrogen, phosphorus and organic matter. About 60% of sludge is applied on farmlands while 15% is disposed off during incineration in Denmark. However, major problems which have been identified when using sludge for agriculture include the presence of heavy metals, xenobiotic compounds and pathogens (Ucisik and Henze, 2008).

Incineration has become a local concern and has grown into one of the hottest environmental debates of the century in many communities. A challenge in the burning of municipal waste is the production of dioxins and furans. Emissions from the burning of sludge is a nuisance to the public (Rulkens, 2004).

1.1.2 Challenges in the treatment of sludge in centralized and decentralized systems

One of the main challenges in the treatment of sludge is sludge dewatering (Glendinning et al., 2010). A combination of a conventional mechanical dewatering and polymer flocculant method could only remove about 20% of water in wastewater (Liu et al., 2016).

In general, to achieve better dewatering efficiency, the disruption of the EPS structure to release bound water and/or agglomerates of sludge colloids into larger particles has to be applied. The efficient removal of interstitial bound water, however, still presents a major challenge. The use of many conditioning procedures, including chemical, physical, biological and hybrid conditioning methods has improved sludge dewatering efficiency (Guan et al., 2017; Skinner et al., 2015).

1.1.3 Socio, economic and environmental challenges on sludge use

Over the past twenty years, there has been a conscious effort to improve the effluent quality by upgrading existing treatment plants, designing and constructing improved treatment plants. Effort is being made by industries and households to minimize or eliminate the discharge of toxic pollutants into the sewer (Rulkens, 2003). Another aspect is an increasing awareness of the challenges associated with the production of sewage sludge during wastewater treatment processes.

During the treatment process, some of the contaminants are degraded (chemical and biological treatment). However, not all heavy metals are eliminated during the treatment process (Jelic et al., 2011). There is a high risk of these heavy metals in the environment due to its persistence in the environment, bioaccumulation and low degradability. Farmers especially, are aware of the presence of toxic pollutants and pathogens concentrated in the sludge. Due to this awareness, sludge recovery as a fertilizer has come under serious scrutiny as the awareness has given farmers more insight into the adverse effects of the pollutants in the environment (Campbell, 2000).

1.2 Legislation on sludge management in Europe

Nutrient recovery from wastewater has gained much attention over the past few years (Shaddel et al., 2019). Important measures and approaches for sustainable nutrient recycling are being taken into consideration. Though countries in Europe are doing their very best to manage wastewater sludge, there are several constraints they face which include stringent measures on heavy metals, micropollutants, pharmaceuticals, local stakeholders opposing the use of sludge in agriculture, high cost for off-site treatment and disposal and non-availability of land for landfilling. The introduction of the European Council Directive 97/271/EC on Urban Wastewater Treatment resulted in significant adjustments in the treatment of wastewater (Shaddel et al., 2019). More efficient treatment methods are required for sludge dumping in the sea which includes phosphorus and nitrogen discharge limits. However, an increase in population has resulted in higher demand for food placing greater pressure on the availability of nutrients such as nitrogen and phosphorus.

Table 1: Limits of Cd, Cu, Hg, Ni, Pb and Zn for sludge use in agriculture (mg/kg DM of sewage sludge) (Mininni et al., 2015).

State/lander	Cd	Cu	Hg	Ni	Pb	Zn
Directive 86/278/EEC	20–40	1,000–1,750	16–25	300–400	750–1,200	2,500–4,000
Lower Austria	2	300	2	25	100	1,500
Upper Austria	10	500	10	100	400	2,000
Burgenland	10	500	10	100	500	2,000
Voralberg	4	500	4	100	150	1,800
Steiermark	10	500	10	100	500	2,000
Carinthia	2.5	300	2.5	80	150	1,800
Belgium (Flanders)	6	375	5	50	300	900
Belgium (Walloon)	10	600	10	100	500	2,000
Bulgaria	30	1,600	16	350	800	3,000
Cyprus	20–40	1,000–1,750	16–25	300–400	750–1,200	2,500–4,000
Czech republic	5	500	4	100	200	2,500
Denmark	0.8	1,000	0.8	30	120	4,000
Estonia	20	1,200	20	400	900	3,500
Finland	3	600	2	100	150	1,500
France	20	1,000	10	200	800	3,000
Germany (ordinance BMU, 2002)	10	800	8	200	900	2,500
Germany (proposed new limits)	2	600	1.4	60	100	1,500
Greece	40	1,750	25	400	1,200	4,000
Hungary	10	1,000	10	200	750	2,500
Ireland	20	1,000	16	300	750	2,500
Italy	20	1,000	10	300	750	2,500
Latvia	10	800	10	200	500	2,500
Lithuania	PTE regulated through limits in soil					
Luxembourg	20–40	1,000–1,750	16–25	300–400	750–1,200	2,500–4,000
Malta	5	800	5	200	500	2,000
Netherlands	1.25	75	0.75	30	100	300
Poland	10	800	5	100	500	2,500
Portugal	20	1,000	16	300	750	2,500
Romania	10	500	5	100	300	2,000
Slovakia	10	1,000	10	300	750	2,500
Slovenia	2	300	2	70	100	1,200
Spain	40	1,750	25	400	1,200	4,000
Sweden	2	600	2.5	50	100	800
UK	PTE regulated through limits in soil					
Range in Europe	0.5–40	75–1,750	0.2–25	30–400	40–1,200	100–4,000

Table 1 shows the European limits of Directive 86/278 that has been incorporated by all EU memberstates into their country's regulations for the use of sludge in agriculture (European Commission, 2010). Countries like Belgium, Czech Republic, Germany, Netherlands, Slovenia, Sweden, Denmark have imposed stricter measures than that of the sludge directive. However, Cyprus, Estonia, France, Luxembourg are countries that have set limits close to the EU Directives. The Landfill Directive (EC Directive, 1999) requires member states to reduce the quantity of biodegradable waste dumped into landfill to about 35% of the 1995 levels by 2016. The volume of sewage sludge disposed of in landfills is expected to drastically decline in the coming years. This means that by 2020, no large amounts of sewage sludge are projected to be dumped by the European Countries (Milieu Ltd et al., 2008).The reuse of sewage sludge on land, which is governed by the Sewage Sludge Directive, is the most preferred method of sludge management in Europe.

1.3 Circular economy and sewage sludge as a resource

The world's attention is geared towards reducing emissions that will exacerbate climate change and therefore circular economy (CE) has become an important strategy in creating a sustainable environment in recent years (Ferronato et al., 2019). The concept of CE was introduced in 2002 by the People's Republic of China (PRC) as a key plan for national development (Geng et al., 2009). It was however adopted by the European economy in 2014 (Imbert et al., 2019).

In circular economy, there is less production of waste while the value of materials, resources and products are maintained. The EU Commission developed a 10- year roadmap known as "Europe 2020' to improve EU competitiveness and employment after the economic meltdown in 2010 (European Commission, 2010). The focus of circular economy as stated by Tsybina & Wuensch, (2018) are:

- Nutrient recovery from wastewater sludge (Phosphorus and Nitrogen are the main nutrients)
- Reduced usage of natural primary resources such as fossil fuels which pollutes the environment.
- Discouraging the use of landfills which leaches pollutants into groundwater.
- Reduce the rate of atmospheric pollution
- Implementation of systems thinking which brings all stakeholders together to solve wastewater issues.

Many economic models over the last century do not consider the depletion of resources and the contaminants disposed off into the environment. To improve productivity, increase competitiveness and to reduce cost, “a resource-efficient Europe” was identified as the main proponent for sustainable growth. The main aim of circular economy is to “close the loop” and to minimize the impact of the final disposal in the environment. "Closing the loop" is anticipated to contribute to the reduction of environmental pollution and the minimization of the use of natural resources (Mesjasz-Lech, 2011).

Sewage sludge may be one of the options available for sustainable development, as the global demand for renewable energy and organic matter grows. According to Gherghel et al., (2019), scientists have recognised sludge as a resource and have considered the recovery of nutrients including phosphorus and nitrogen from sludge. In traditional and emerging technologies, the sludge can be used as an energy resource for electric and heat energy (Kacprzak et al., 2017).

In addition, sewage sludge may be used as a base for the fertilization and remediation of soil if the equipment used makes it possible to produce a quality product. Compared to waste handling and landfilling, these re-uses of sewage sludge are economically feasible and environmentally friendly. Considering the regulatory standards, using wastewater sludge as an energy source and nutrient recycling is a suitable solution for its management as it is in line with the circular economy guidelines. Energy and nutrients recycled from sewage sludge will be a safe alternative to satisfy existing and future energy needs (Gherghel et al., 2019).

Biochar, a solid product made from biomass pyrolysis, which is a potential concept for climate change mitigation and adaptation whilst enhancing the soil quality (Mašek et al., 2013) can also be a potential end use of sludge. Biochar not only minimizes carbon emissions into the atmosphere, but it also serves as an environmentally acceptable substitute for activated carbon and other carbon compounds. Several studies have been done to explore new applications of biomass since biochar is affordable, environmentally beneficial, and may be utilized for a variety of purposes, including soil remediation, waste management, greenhouse gas reduction, and energy production.

1.3.1 Market development and consumers’ interest

Sludge management is of much concern to a wide range of people which include politicians, environmentalists, engineering consultants and the general public (Campbell, 2000). With increasing population, urbanization and climate change, sludge handling becomes a huge cost factor not only for medium and large water and wastewater treatment plants but also for small plants (Nowak et al., 2004). The potential disposal of sludge can also turn out to be the main cost factor in the decision between a centralized and a decentralized solution.

From the circular economy perspective, sludge is viewed simply as a resource that can provide an additional revenue. Many benefits can be obtained from sludge as a resource (Pott et al., 2018). These benefits can be related to the market in technological development of sludge treatment and sludge recovery systems and from the resources recovered in the form of nutrients, energy, and other resources of industrial applications. Sludge treatment systems include the following sub-segments; sludge thickening and dewatering, sludge digestion and sludge drying. On the other hand, sludge recovery systems consist of nutrient recovery and energy recovery. Recent advances in research and development showed great potential to close the nutrient recycling loop, support the circular bioeconomy and to create viable businesses through the conversion of waste to organic fertilizers and waste to energy (Tsybina & Wuensch, 2018).

The idea of closing the nutrient and energy cycle by using municipal organic waste and faecal sludge for urban and peri-urban agriculture increases the consumers' interest. This, however, requires cost and energy saving sludge management and processing systems. The current sludge management and processing systems are criticized as energy intensive with less resource recovery. The emerging view is that sludge may be viewed as a renewable resource with a potential value chain, and that effective sludge management can save money (Kumar et al., 2017).

Sludge disposal legislation associated with environmental protection, and implementation of stricter disposal restrictions promote recycling of the waste streams and improve the market value of sludge (Sengupta et al., 2015). Increased demand in nutrient and energy issues drive the sludge market. Additionally, reducing operating costs through energy efficiency is an attractive prospect, as this energy recovery through biogas production, biochar and bio oil is a growing interest (Ok et al., 2015).

The key opportunity in energy recovery is capturing and using the biogas generated by anaerobic digestion. This is particularly true, now that improved anaerobic digestion (AD) technology has been developed, which increases the amount of biogas produced. The introduction of renewable energy incentives is making the energy opportunity more compelling (Zhang et al., 2016).

The use of sludge for biochar production is an alternative and economically and environmentally feasible option for improved sludge market development and to increase consumers' interest. Nitrogen and Phosphorus can be recovered and used as compost, liquid fertilizers or organic pellets in agriculture. Sewage sludge is difficult to recycle and has led to a constant review of strategies to solve this problem (Tomczyk et al., 2020).

Biochar may be a solution to existing issues with the reuse of waste sludge. Although it is not a new approach, its use in farming is new. The revived interest in biochar started to grow in the 1980s

(Zielińska et al., 2015). One of the best ways suggested to combat climate change by soil carbon sequestration is the conversion of biomass to biochar and its application for soil change. Moreover, the alkaline nature of biochar produces a liming effect that can be used in soil acidification (Zielińska et al., 2015). This, therefore, improves crop yield. However, in terms of properties, biochar varies from one another.

1.4 Problem statement

Sludge management and disposal is a great challenge to all treatment plants, whether decentralized or centralized. This is mainly because of sludge dewatering and drying. Many current sludge dewatering techniques used in wastewater treatment plants are costly and energy intensive. Due to the large volume of sludge, it makes it difficult to transport. Current sludge treatment technologies require sophisticated machines and high energy to reduce sludge volume. Most sludge is conditioned before dewatering to accelerate the process. However, it is still difficult to attain low water content (Mahmoud et al., 2013). There is the need to improve the conventional mechanical dewatering to achieve a low water content to reuse the sludge for beneficial purposes. There are natural and biodegradable absorbents which can be recycled and can be used in the dewatering of sludge. These waste products are cheap and easily accessible. This research seeks to propose alternate solutions that can improve the dewaterability of wastewater sludge for beneficial use, less moisture from sludge cakes, lower energy requirements, low production cost and less environmental impact. In the aspect of biochar production, the use of some of these natural absorbents also tends to improve sewage sludge-based biochar yield.

1.5 Objectives

The main objective of this study is to investigate alternative methods of sludge dewatering and drying on small scale and decentralized wastewater treatment systems mainly for biochar production for local use.

Specific objectives

- To investigate the removal of bound water using Spent Coffee Grounds and Wood Pellets
- To investigate the removal of bound water using various proportions of Spent Coffee Grounds and Wood Pellets

2 Materials and Methods

This chapter aims at presenting all materials and procedures used during the study period. It is organized in the order in which the whole experiment was conducted. The following is a list of routine tasks that were carried out to achieve the major goal of this thesis:

- Obtaining all the various materials needed
- Characterization of raw sludge
- Filtration of raw sludge
- Characterization of filtrate and residual sludge
- Addition of absorbents to residual sludge
- Daily sample taking for moisture content analysis
- Sludge drying
- Odor assessment

The experiment was conducted at the main laboratory at Fløy IV and Fløy V (RealTek) which is located at the Norwegian University of Life sciences (NMBU), Ås, Norway. The materials used in this experiment were obtained from different sources. The main materials used included raw sludge, Wood Pellets (WP), Spent Coffee Grounds (SCG) and super absorbent extract from diapers mixed with wood pellets (SA).

2.1 Sludge collection

Primary raw sludge was obtained from Frogn renseanlegg, a wastewater treatment plant in Drøbak, in Viken county in Norway. This treatment plant is mainly a domestic wastewater treatment plant receiving wastewater from human settlements.

Figure 2: Raw Sludge obtained from the Wastewater Treatment Plant

2.2 Spent Coffee Grounds: Source, composition, and availability

Coffee is part of our everyday life as it is one of the highest consumed beverages in the world. Coffee is cultivated in about eighty (80) countries worldwide (Murthy & Naidu, 2012a). Coffee was introduced in Europe in 1615, and it quickly became popular. Germans, Frenchmen, and Italians were searching for a way to expand their coffee plantations in their various territories. However, it was the Dutch who obtained the first seedlings and planted them in Amsterdam's botanical garden (Mussatto et al., 2011). Globally, coffee production has risen by about 17% due to an increased yield from the period of 2000 to 2012. Spent Coffee Grounds (SCG) is the waste material obtained after the consumption of coffee (Cruz et al., 2014).

In 2018, a total of about 9.5 million metric tonnes of coffee was produced while the quantity of SCG generated was 6 million globally (Wu et al., 2019). The amount of waste generated from producing coffee is about 50% of the fruit mass. The huge waste produced yearly in the production of soluble coffee requires a waste management plan. In present times, there is social and political pressure on the industries to reduce its pollution into the environment. Most companies do not view their residue as waste but have modified their processes to recycle their waste to mitigate their effects on the environment (Mussatto et al., 2006). The matrix of coffee beans is highly hygroscopic. The moisture content of raw coffee has been known to be approximately 7% (Pittia et al., 2007). The constituents of SCG are 12.4% cellulose, 39.1% hemicellulose (3.60 % arabinose, 19.07 % mannose, 16.43 % galactose), 23.90 % lignin, 2.29 % fat, 17.44 % protein, and 60.46 % total dietary fibre. This makes

SCG an interesting resource for a variety of uses (Blinová and Sirotiak, 2019).

The presence of caffeine, polyphenols and tannins makes it dangerous to discharge SCG into the environment without any form of treatment. Polyphenols, caffeine, and tannins inhibit SCG to be used as feed for domestic animals although it contains many nutrients (Rojas et al., 2003). SCG can be used to improve soils as composts, acts as heavy metals adsorbent, and also in the production of biochar, biodiesel, pellets and many others (Liu and Price, 2011).

The SCG used in this study was readily obtained from Espresso Coffee shop (Flytoget) in Oslo central station in Norway. The residue collected was wet and had to be air- dried before it was used for the experiment. The moisture content of the air-dried SCG was 7% and the ash content was 1.8%.

Figure 3: Wet SCG obtained from coffee shop (left) and the SCG after air drying (right)

2.3 Wood pellets: Source, composition, and availability

In recent years, the global wood pellet business has risen dramatically, presenting an exciting new opportunity for the solid fuels market. In 2012, global production reached 22.4 million tonnes, which represents about a 55% rise compared to 2010 production (Craven et al., 2015). The European Union (EU) is currently the world's wood pellets industry leader, producing almost half of all wood pellets. Sawdust, planer shavings, and dry chips are the most common raw materials used in the production of wood pellets. However, due to the vast volumes available, other types of biomass, such as tree barks and logging residues are also used (Lehtikangas, 2001).

A characteristic of wood pellets is that they are hygroscopic. These hydrophilic properties are primarily due to their low moisture content, high density and the hydroxyl groups in their structures. Commercially produced pellets have an average moisture content of about 10–12% (Lehtikangas, 2001). The bulk density of wood pellets is about 650 kg/m3 after reaching stable conditions in terms of pressure and temperature (Schweitzer et al., 2018). The same study found out that the ability of wood pellets to absorb moisture is more dependent on the raw materials used. It was further inferred by Lehtikangas, (2000) that increasing the number of pellets also increases the moisture uptake. In an experiment conducted by Craven et al., (2015), the main parameters relating to wood pellets are enlisted in the table below:

Table 2: Characteristics of Wood Pellet

Parameter	Value	Unit	Relevant standard
Diameter	6	mm	–
Length	$3.15 \leq L \leq 40$	mm	–
Bulk density	651	Kg m^{-3}	EN 15103
Net calorific value	18.4	MJ kg^{-1}	EN 14918
Moisture content	≤10	wt%	EN 14774-1
Ash content	≤0.7	wt%	EN 14775

Wood pellets used in this study were obtained from Felleskjøpet in Ås, Norway. The wood pellets used in the experiment had an energy content of 4.8 kWh/kg, a moisture content of 7-9% and an ash content of 0.5%. The WP had an average height of 6mm.

Figure 4: Wood Pellets used as absorbents

2.4 Experimental design

The experiment was conducted in two folds; Experiment 1 and Experiment 2. The difference is the amount of residual sludge, the amount and type of absorbents used and the duration of the experiment.

The sludge was characterized to know the composition of the sludge. Filtration was done afterwards to remove mainly free water from the sludge. The composition of the residual sludge and the filtrate were also determined. Spent coffee grounds (SCG), Wood Pellets (WP) and Super absorbent of extract from diapers mixed with wood pellets (SA) were used as absorbents at different amounts to test their abilities in the removal of bound water from the sludge in the first experiment whilst SCG and WP were used in the second experiment. The samples were left to air dry. All samples for analysis were taken in three replicates unless otherwise indicated.

2.4.1 Sludge Characterization

Sludge characterization plays an important role in the management of sludge, not only to establish parameters for transport, storage and landfill, but in many treatment processes such as stabilization and dewatering (Lotito et al., 1997). In this study, the raw sludge, residual sludge and the filtrate were characterized based on the following parameters: pH, Electrical conductivity, Total solids, Volatile Solids, Total Suspended Solids, Volatile Suspended solids, Total Nitrogen, Total Phosphorus and Pathogen (Total Coliform Count and E. coli).

2.4.1.1 pH

According to Mesner and Geiger (2010), pH is a measurement of a solution's acidity or basicity, expressed as the negative common logarithm of hydrogen ion concentration. pH is mathematically expressed as: pH = - log [H+].

On the pH scale, the values start at 0 and ends at 14, with 0 and 14 denoting extreme acidity and basicity, respectively. Basic water contains more hydroxyl (OH^-) ions and is basic between 7 and 14. Acidic water contains extra hydrogen ions (H^+) and is acidic between 0 and 7. WTW Electrode pH meter was used to measure pH in this study. 50ml of the sample was pipetted into a glass beaker. The pH probe was placed in the sample and the steady pH value was recorded.

2.4.1.2 Electrical conductivity

Inorganic compounds such as nitrate, sulphate, chloride, phosphate anions and magnesium (Mg), Sodium (Na), aluminium (Al) cations affect the conductivity of water. Organic compounds such as alcohol, phenol and sugar have a low conductivity in water because they do not conduct electricity.

Conductivity is influenced by temperature. Higher temperatures indicate higher conductivity and vice versa. As a result, conductivity is measured at a temperature of 25 °C (Baird et al., 2020). According to Baird et al., (2020), the closer the temperature for measuring conductivity is to 25 °C, the higher the accuracy.

In this study, electrical conductivity was measured using Cond 3210. 50ml of the sample was pipetted into a glass beaker. The probe was placed into the sample and the steady reading was recorded.

2.4.1.3 Total solids

A true measure of water quality is related to the amount of solids in a sample. It is essential to know the amount of solids in order to be able to regulate treatment processes (Baird et al., 2020). The residue left of a sample after heating or oven drying at a certain temperature (usually between 103 and 105 °C) for some number of hours, mostly twenty-four (24) hours is referred to as total solids of that sample (Baird et al., 2020). Total solids (TS) can be calculated as;

$$\%TS=\frac{Dry\ Weight\ (g)}{Wet\ weight\ (g)}x100 \qquad \text{.................. (Equation 1)}$$

A thoroughly mixed sample was evaporated in an already weighed dish and dried to a constant weight in a heat chamber at 105 °C. The residue left in the pre-weighed dish after drying was taken as total solids. This procedure was done according to standard methods (Baird et al., 2020).

This approach used in determining the total solids in this study is effective. However, there are other instruments which can be used to determine total solids which include METTLER TOLEDO HC103 Moisture Analyzer which is a fast way of determining Total Solids.

(https://www.mt.com/au/en/home/library/applications/laboratory-weighing/total-solids-in-wastewater-treatment-process.html)

Figure 5: Weighing of Sludge Samples

Figure 6: Drying at 105°C

2.4.1.4 Volatile and fixed solids

The portion of total solids that remain after a sample has been ignited at a specific temperature at a specific time is called fixed solids. The portion of total solids that evaporates after a sample has been ignited at a specific time is called volatile solids (Baird et al., 2020).

The dried residue obtained as the total solids of the sample was ignited at 550 °C in a furnace to a constant weight. The solids that remained were taken as fixed solids. The portion of the total solids that was lost through ignition was recorded as volatile solids. This was done according to standard methods (Baird et al., 2020).

$$\% \text{ Volatile solids} = \frac{Dry\ weight - Ash}{Dry\ Weight} \text{x } 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 2)}$$

2.4.1.5 Total suspended solids

Total suspended solids, the portion of total solids retained by a filter, and total dissolved solids, the amount that goes through a filter, are both included in total solids (Baird et al., 2020). The organic particles released into the water when certain water sources are contaminated with decaying plants or animals are usually suspended solids. While some sediment settles to the bottom of a water source, other TSS float to the surface or remain suspended in the sample. TSS influences water clarity, so the higher the TSS content of a water source, the more turbid it will be.

In rural areas, low TSS concentration effluents for agricultural reuse are preferred because they reduce the risks of clogging irrigation equipment. The risk of clogging is decreased when the final TSS concentration is less than 50 mg/L (Capra and Scicolone, 1998).

Total Suspended Solids was calculated as:

$$\text{TSS mg/l} = \frac{(Weight\ of\ filter + dry\ residue) - (weight\ of\ filter)}{Sample\ Volume} \text{x } 1000 \text{ ....(Equation 3)}$$

A thoroughly mixed sample was filtered through a pre-weighed glass microfiber filter (Whatman®, grade GF/A). The diameter of the glass filter was 47 mm and 0.45 µm porosity. The sample was filtered through the glass microfiber with the aid of suction. The residue that remained on the filter was dried at a constant weight of 105°C. The extra weight on the pre-weighed filter was taken as total suspended solids after drying. This procedure was done following the standard methods (Baird et al., 2020).

2.4.1.6 Total Phosphorus

Total phosphorus was determined using Easychem plus systea. A calibration curve was obtained using five standards and a blank solution. A dilution factor of 4x was used for raw sludge. 5ml of the sample was pipetted into a screw cap reagent bottle. 0.5ml of saturated potassium peroxodisulphate was added to the sample. 100μl of concentrated sulphuric acid was then added. The sample was swirled well to obtain a uniform solution. The sample was then put in a heating chamber with a temperature of 120°C for one hour to digest. The hot sample was left to cool down after a short period of time. 1ml of the sample was then pipetted into a test tube and then inserted into the holes in the systea machine to run the process. The final result was adjusted by a factor of 1.12 to get the final concentration. This was done according to standard methods (Baird et al., 2020).

2.4.1.7 Total Nitrogen

Total Nitrogen was determined using Easychem plus systea. A calibration curve was obtained using five standards and a blank solution. 5ml of sample was pipetted into a screw cap reagent bottle. 0.5ml of saturated potassium peroxodisulphate was added to the sample. 100μl of sodium hydroxide was then added. The sample was mixed well to obtain a uniform solution. The sample was then put in a heating chamber with a temperature of 120°C for one hour to digest. The sample was left to cool down after the digestion. 1 ml of mixture was then pipetted into a cylindrical bottle and then inserted into the Systea machine to run the process. The final result was adjusted by a factor of 1.12 to get the final concentration. This was done according to standard methods (Baird et al., 2020).

2.4.1.8 Pathogen analysis

The transmission of pathogens from sludge to humans is a serious health issue which must be considered with prime importance by various wastewater stakeholders. The organisms classified as pathogens in wastewater are bacteria, viruses, fungi, protozoa and helminths (Andreoli et al., 2007).

Bacteria can multiply when there are suitable conditions. They are mostly inactivated at temperatures above 70° C and at lower temperatures over long periods of time. In spite of this, there are some that are spore-forming, for example, Clostridium species and their inactivation require high temperatures. The optimum temperature for the growth of bacteria of mammals is always around that of the human body temperature, 35°C to 40°C. Below 25° C, it is rare for their multiplication to occur. Nutrients and moisture are very essential for their growth (Carrington, 2001).

People can be exposed to pathogens from sludge either directly or indirectly (Minnini et al., 2015). Individuals can be exposed directly to pathogens due to poor hygienic conditions and lack of protective gears. This usually happens to personnel who normally work with sludge. According to Tanner et al., (2008), people living close to agricultural fields which have been treated with sludge can be exposed indirectly to pathogens through aerosols.

Various ways can be used to reduce pathogens, which is dependent on the method used to stabilise the sludge. Sludge stabilisation include; sedimentation, anaerobic digestion (mesophilic or thermophilic), composting and many more (Sahlström et al., 2004). It is necessary to reduce the pathogens of the sludge in the wastewater treatment plant in order to minimize health concerns for the public and for employees who handle it, as well as to prevent negative environmental effects. Pathogen elimination mechanism is therefore dependent on the ultimate disposal method selected. Application of sludge in public parks and gardens or its recycling in agriculture is subject to more stringent hygienic regulations than other disposal options, such as landfills (Andreoli et al., 2007).

The samples in this study were analysed for the presence of pathogens. 10ml of raw sludge was added to 990 ml of deionised water. The sample was swirled gently until it was evenly mixed. The dilution factor was 1:100. This was used to obtain a series of dilutions, 1:10,000 and 1:1,000,000. For the filtrate sample, 1ml of filtrate was added to 999 ml of deionised water.

Colilert-18 was used to analyse total coliforms and E.coli. 100ml of the solution was poured into a labelled bottle and one capsule of Colilert-18 was poured into it. The sample was swirled to get a uniform mixture. After that, the sample was poured into a quanti-tray and was passed through a quanti-tray sealer to seal it in order to prevent spillage.

The Colilert sample was incubated at a temperature of 35°C for 18 hours. Enterolet was used to analyse the presence of enterococci. 100ml of the solution was poured into a labelled bottle and one capsule of Enterolet was poured into it. The sample was swirled to get a uniform mixture. After that, the sample was poured into a quanti-tray and was passed through a quanti-tray sealer to seal it in order to prevent spillage. The Enterolet sample was incubated at a temperature of 44 °C for 24 hours. The quanti-tray used had 96 wells; 48 big wells and 48 small wells. At the end of the incubation period, the yellow wells from the colilert-18 samples were represented as total coliforms whilst the yellow wells which showed fluorescence were counted as E-coli. All the colourless wells were negative. For the enterolet samples, the wells that showed fluorescence were counted as positive for the presence of enterococci. All the positive wells were counted and referred to the Most Probable Number (MPN) table (Baird et al., 2020).

2.5 Dewatering process

The dewatering process consisted of column-sand filtration of the raw sludge, addition of different absorbents to the residual sludge and further sludge drying.

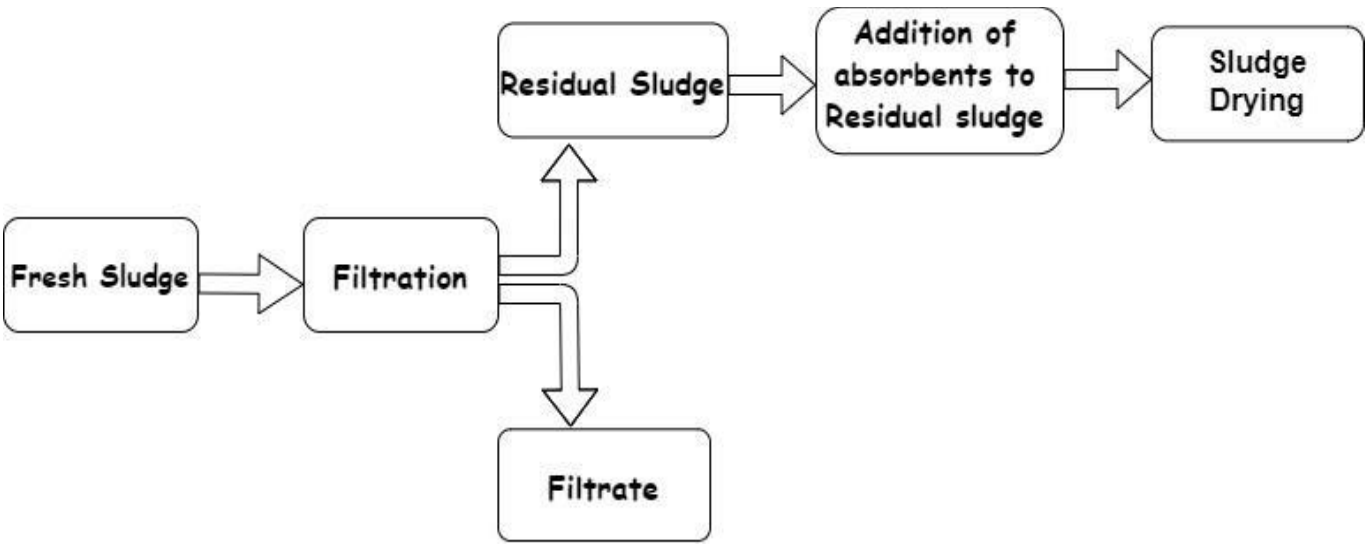

Figure 7: Flow sheet of the dewatering and drying process

2.5.1 The filtration process

The main goal of filtration is removing suspended particles from water by passing it through a porous layer. Straining and sedimentation are used to maintain larger particles, while adsorption and coagulation retains colloidal matter (Chen et al., 2005). The primary goal of sludge processing technologies is to reduce volume. Sludge typically has a dry solids concentration of 2-4 wt% before dewatering treatment, however following mechanical dewatering, dry solids values of 17-25 wt% are usually common (La et al., 1996). Dry solids values of 30 wt % have been recorded in a few cases. Sludge particles interact closely with one another to prevent settling and provide high filtering and compression resistance. Therefore, there is the need for dewatering forces to be more compressive in order to improve dewatering. Shear forces may also be used to facilitate dewatering. Sludge dewatering filtration technology has evolved to address the intrinsic properties of sludge, the most notable of which are their compressibility and tiny particle sizes (Wakeman, 2007). Vacuum filtration, pressure filtration, and gravity filtration are the three primary terminologies used to define the manner of applying the motive force in filtering systems (Chen et al., 2005). Water travels through the filter media under the force of gravity in gravity filtration.

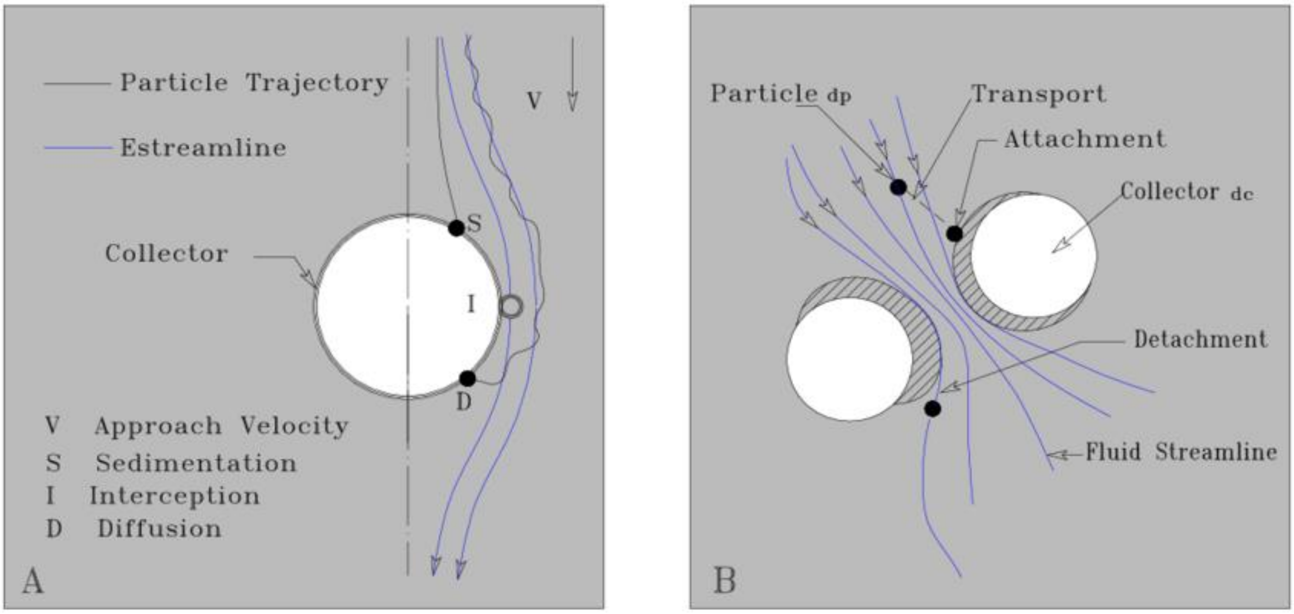

Figure 8: Basic transport mechanisms in water filtration (A: Yao et al, 1971; B: Amirtharajah, 1988)

2.5.1.1 Mechanisms aiding the filtration process

Within a filter, the removal of suspended particles is thought to include at least two discrete steps; transport and attachment. The porous media removes suspended particles mostly by transport and adhesion (attachment). Attachment mechanisms serve to keep a suspended particle in contact with the media surface or previously deposited solids by moving it into and through a filter pore such that, it comes very close to the surface of the filter media (Horner et al., 1965; Yao et al., 1971; Chen et al., 2005).

Considering the collector from Figure 8 (A), the suspended particles are aimed at being collected in that. Gravitational force is the main force directing the flow of particles. A particle may intercept with the collector depending on its size. Based on the density of the suspended particle, the gravitational force field can affect its path, that is when its density exceeds that of water. Owing to this, the sedimentation process occurs. The remaining particle in suspension undergoes Brownian movement.

2.5.1.2 Sand Filtration

Sand filtration is to remove suspended matter, as well as particles that can float or sink. The wastewater passes vertically through sand and/or gravel. The pores may or may not be connected, but the focus here is fluid movement through the material, thus only unconsolidated matter with interconnected pores will be considered. The link between suspended particle size and filtering effectiveness is one aspect of the process. Another factor worthy to consider is the size of the suspended particle in comparison to the grain size of the porous bed grains (Craft, 1969). Craft (1969) said in his dissertation that straining is necessary for particles with diameters bigger than about 20% of the grains through which they are filtered. Porosity, packing, grain form and size, and grain size distribution are some of the physical and geometrical characteristics of porous media.

2.5.1.3 Filtration

In this research, the first part of the dewatering procedure was filtration. The initial weight of the raw sludge was measured and the raw sludge was mixed thoroughly. A 200 micron mesh was inserted into a 100 micron mesh (nylon) and then fixed into a plexi glass column with a 25cm deep 0.25mm sand filter. A bucket was weighed and the bucket was placed below the filter column to collect the filtrate. The raw sludge was poured into the mesh. The part of the sludge (residue) which was greater than 100 microns was retained in the mesh. The filtrate was then passed through a 25cm thick 0.25mm sand filter to further remove residual particles and reduce the amount of pathogens. After three (3) hours, the filtration process was done. The residual sludge that was retained in the mesh was taken out and weighed and the filtrate collected in the bucket was also weighed.

Figure 9: Filtration set-up used in sludge dewatering

Figure 10: Raw sludge together with residual sludge and filtrate after filtration

2.5.2 Addition of absorbents

Experiment 1

In the first experiment, the absorbents were added to the residual sludge and making up 500g sludge absorbent mixture in the following percentages;

- 5% (25 g) of SCG in 475 g of Residual sludge
- 10% (50g) of SCG in 450g of Residual Sludge
- 20% (100g) of SCG in 400g of Residual Sludge
- 5% (25g) of WP in 475 g of Residual sludge
- 10% (50g) of WP in 450g of Residual Sludge
- 20% (100g) of WP in 400g of Residual Sludge
- A control sample of 500g of residual sludge

In the combinations of WP, SCG and SA, the absorbents were added to the residual sludge in the following percentages. The 20% (100g) was used as the basis for this calculation.

- 25% (25g) SCG and 75% (75g) WP in 400g of residual sludge
- 75% (75g) SCG and 25% (25g) WP in 400g of residual sludge
- 50% (50g) SCG and 50% (50g) WP in 400g of residual sludge
- 4% (16g) SA 2% (8g) WP and 2% (8g) SCG in 468g of residual sludge

Experiment 2

In the second experiment, a constant amount of residual sludge (400g) was maintained and the various amount of absorbents were added in the following percentages:

- 5% (20g) of SCG in 400g of residual sludge
- 10%(40g) of SCG in 400g of residual sludge
- 20% (80g) of SCG in 400g of residual sludge
- 5% (20g) of WP in 400g of residual sludge

- 10% (40g) of WP in 400g of residual sludge
- 20% (80g) of WP in 400g of Residual Sludge

In addition, a mixture of WP and SCG were also tested as alternatives to find optimal use of resources. In the combinations of WP and SCG, the absorbents were added to the residual sludge in the following combinations. The 20% (80g) was used as the basis for calculation.

- 25% (20g) SCG and 75% (60g) WP in 400g of sludge
- 75% (60g) SCG and 25% (20g) WP) in 400g of sludge
- 50% (40g) SCG and 50% (40g) WP in 400g of sludge

The wood pellets began to swell shortly after the residual sludge was added. The pellets absorbed the water and became bigger in size. After some time, they began to break into pieces.

2.6 Moisture content analysis

Tsang and Vesilind (1990), categorised moisture content in sludge as free water, interstitial water , surface water and bound water. Deng et al., (2011) used four methods in their experiment; drying test, thermogravimetric-differential thermal analysis (TG-DTA), thermogravimetric differential scanning calorimetry (TG-DSC), and water activity test in determining the moisture content of sludge. The type of moisture found in the mechanically dewatered sludge were interstitial water, surface water, and binding water, according to their findings. There is an increase in bond strength of sludge when there is a decrease in moisture preferably when the moisture content is lower than 50% wet basis (Deng et al., 2011).

Moisture content is an important component in the bio drying process because it affects the biochemical activities associated with microbial growth and organic matter biodegradation (Ryckeboer et al., 2003; Cai et al., 2012).

In determining the moisture content of samples in this study, the samples were stirred every morning and evening and samples from each set up were taken for moisture content analysis. A pre-weighed aluminium can was filled with sample. The weight of the aluminium can together with the sludge was measured and recorded. The sample was placed in a heating chamber with a temperature of 105°C for twenty-four (24 hours). The samples were weighed after they had been removed from the heating chamber. The procedure was repeated for samples after every twenty-four (24) hours for a maximum of four days for the first experiment and seven days for the second experiment. Moisture content can be measured based on wet basis and dry basis. However, in this study, the moisture content was calculated on a wet basis.

- $Mw = \frac{Ww}{Wt} * 100$ ……………………….(Equation 4)

Where Mw=Moisture Content Ww= Weight of Water Wt= Total weight of material

- $Md = \frac{Ww}{Wd} * 100$ ………………………..(Equation 5)

Where Md= Moisture content Ww= Weight of Water Wd= weight of dry matter.

https://engineering.purdue.edu/~abe305/moisture/html/page8.htm

2.7 Sludge drying

In Europe, about 21% of sewage sludge is incinerated whilst 53% is reused for agriculture purposes (Escala et al., 2013). The high moisture content is a drawback for the beneficial use of sludge as sludge condensation and dewatering process is not enough to reduce the moisture content of sewage sludge. Due to this high water content, the final product obtained after the dewatering process is highly unacceptable to various wastewater stakeholders (agriculture, power industry) (Flaga, 2005).

Figure 11: Drying of Various Concentrations of SCG and WP

According to Madlool et al., (2011), an alternative fuel source should include less than 20% water .The dewatered sludge needs to be transformed further and given a more advanced treatment. While thickening and dewatering can remove 7% and 35% of the total amount of water, respectively, drying can remove up to 62% more water content if done in succession (Flaga, 2005).

The sludge drying process decreases the product's mass and volume, making storage, transportation, and selling easier. It also allows for sludge incineration (Flaga, 2005). Drying makes sludge beneficial for agricultural use, hygienic (as it reduces microbial organisms to the barest minimum), and improves the market value of the sludge. However, drying may consume much energy making it an expensive process (Kurt et al., 2015; Flaga, 2005).

The commonest techniques used in drying techniques are solar and thermal drying. According to Mujumdar and Zhonghua, (2007), the dry solids content of sludge which has undergone thermal drying can be up to 95%. Fossil fuels are usually used to heat the drying surface. The energy needed for a thermal dryer to dry sewage sludge is 2627 kJ/kg-biosolid (Fonda and Lynch, 2009). The use of fossil fuel and high cost of energy are the demerits of thermal dryers. However, the risk of burning of sludge and ignition during the drying are the challenges of this process (Flaga, 2005).

Solar drying, which uses renewable energy, has become a common alternative to replace thermal dryers (Mathioudakis et al., 2013). Solar drying has been applied in the form of sun drying beds. Solar drying beds are easy to operate, inexpensive, less pre-requisite skills, eco-friendly and do not use fossil fuel like thermal dryers. Despite promising results in warm areas, this technique cannot reach 90% dry solids in tolerable time periods when compared to thermal dryers. As a result, this system may require additional energy to improve the final dry solids. Solar panels can be utilized to supply additional electricity to obtain 90% dry solids or to reduce the amount of sludge drying space required (Mathioudakis et al., 2009). In this study, the sludge was then left to air dry. The mixture of sludge and the absorbents were stirred every morning and every evening to facilitate the drying process. Temperatures were recorded every morning and evening during the experimental period.

2.8 Odor assessment

Odor is one of the major problems every wastewater treatment plant seeks to address. Any site for wastewater treatment has the potential to release unpleasant odor into the environment (Stuetz and Frechen, 2005). Odor emission problem is a great environmental issue to small treatment plants. These treatment sites are mostly near tourist sites and sometimes on-site of residential areas (Zarra et al., 2008). Nonetheless, there is an information gap between odor emissions measurement from various diverse treatment approaches (González et al., 2019). Odor is mostly caused by the presence of a large number of volatile odorants, primarily organic chemicals and sulphur at trace levels (Iranpour et al., 2005). Although odor from Wastewater Treatment Plants has not been found to be a direct cause of diseases, extensive exposure to high-odorant emissions can be detrimental to human health. For instance, it can cause headaches, nausea and respiratory difficulties (Lebrero et al., 2011).

Odor is due to nitrous compounds such as organic nitrogen and ammonia, ketone type organic compounds and sulphurous compounds such as mercaptans, hydrogen sulphide and organic sulphides.

In sludge management, the main sources of odour are mostly thickeners (hydrogen sulphide, ammonia, methanethiol), thermal processing (acetaldehyde, hydrogen sulphide) and dewatering (ammonia, hydrogen sulphide) (Bonnin et al., 1990). In the first units of wastewater treatment plants, hydrogen sulphide is significant whereas in the sludge units, the main contributors of odor turned out to be carbonyls and even toluene (Dincer and Muezzinoglu, 2008).

Hydrogen sulphide is essential to sludge odor signature. The most prominent odor causing compound that takes over the sludge quickly is methanethiol. As the sludge ages, dimethyl sulphide and dimethyl trisulfide are of high concentrations (Son and Striebig, 2003). Human noses were used to measure odor in this study. Five people were selected and were made to assess the extent of odor from the sludge mixture after four days (ninety-six hours). The scale of odor was denoted as follows:

1- No odor; 2- Less odor; 3- Average odour; 4- Strong odor; 5- Intense odor

2.9 Data Analysis

The dataset was analysed statistically using one-way variance analysis (ANOVA) (IBM SPSS Package, Version 21 for Windows). A p-value of 0.05 was used to test the significance of the experiment.

3 Results and Discussion

This chapter illustrates and discusses all results during the study period.

3.1 Sludge Characterization

Before the sludge was dewatered the raw sludge was characterized to know the components of the sludge. Knowing the characteristics of the sludge allows you to make informed decisions about the sludge. The sludge was characterized mainly by its physical and biological parameters.

Table 3: Characterization of filtrate, raw sludge and residual sludge

Parameters	Filtrate	Raw Sludge	Residual Sludge
% Total Solids	0.23	3.79	10.94
Fixed solids	0.11	0.50	0.77
%Fixed solids	69.38	23.36	22.29
Volatile Solids	0.14	1.65	2.68
%Volatile Solids	-	76.64	77.71
TSS (mg/l)	17.55	-	-
pH	5.58	5.8	-
Electrical conductivity at 21°C	1129μS/cm	1105μS/cm	-
Total Phosphorus	<250 ppb	26.82mg/l	-
Total Nitrogen	<250 ppb	20mg/l	-
Moisture content	-	96.21	84.25
Enterolert	233.3	202.5 x10E3	-
Total Coliform	>2.4196 x10E6	142.1x10E6	-
E. coli	119.1 x 10E3	388 x 10E5	-

3.1.1 pH

In the experiment, the pH obtained for the raw sludge was 5.8 which indicates that the sludge is slightly acidic. In an experiment by Liao et al., (2002), with a pH between 2.5-9.5 were reported. Alkaline sludge flocs were more stable as compared to those below a pH of 2.6. The pH range of 2.6–3.6, which is the pH range of the isoelectric point, produced the lowest dissociation constant.

Fine flocs could approach each other closely at the pH range of 2.6–3.6, around the isoelectric point, since repulsive electrostatic interactions were reduced, and the dissociation constants of sludge flocs were also at a minimum (Nelson and Cox, 2000). Electrostatic repulsion is caused by the existence of a net charge on sludge surfaces, which inhibits sludge microorganisms from coming into close contact (Liao et al., 2002). The change in dissociation constants as a function of pH suggests that repulsive electrostatic interactions were involved in sludge floc stability disruption.

The presence of various functional groups, such as carboxyl, amino, and phosphate groups with varying ionization constants, on sludge surfaces might explain the change in dissociation constants with pH (Liao et al., 2002). The water-floc separation characteristics of sludge are enhanced by the release of interstitial water held inside the sludge cells and the stimulation of flocculation, lowering the number of tiny flocs, since cells are broken at both low and high pH (McLoughlin and Vallom, 1984).

3.1.2 Electrical conductivity

The electrical conductivity recorded for the raw sludge and the filtrate at a temperature of 21°C were 1105µS/cm and 1299 µS/cm. This indicates that the filtrate had a higher electrical conductivity compared to the raw sludge. The filtrate had a higher conductivity than the raw sludge because a clearer solution could conduct more electric current than a turbid one.

The difference in the electrical conductivity between the raw sludge and the filtrate is the removal of the humus from the remaining water which occurred during the filtration process. This was observed in the colour change of raw sludge which was turbid indicating the presence of organic matter and a clear filtrate indicating the removal of the humic content from the sludge.

It can be inferred that the sludge is from a domestic source. This is confirmed by the work of Baird et al., (2020) in the United States which observed that natural waters had a conductivity ranging from 50 to 1500 µS/cm and wastewater from domestic sources were closer to these values.

3.1.3 Total Solids

In this experiment, the total solids for raw sludge was 3.78 %. The fixed solids were 23.35% of the TS while the VS was 76.64 % of the TS. The TS for the residual sludge was 10.94% of which 22.29% was fixed solids while 77.71% was VS (as a percentage of the TS). The TS of the raw sludge was low, which indicated that greater part of the sludge was water (Vigneswaran, 2009; Saveyn et al., 2005; Mahmoud et al., 2013).

3.1.4 Total Nitrogen and Total Phosphorus

In this approach, the total phosphorus (TP) and the total nitrogen (TN) for the filtrate were both below 250 parts per billion. However, the TP and TN of the raw sludge were 26.82mg/l and 20mg/l respectively. The sand used in the filtration was not effective in the removal of nitrogen and phosphorus because of the height of the sand filter. It is assumed that the nitrogen and phosphorus remained in the residual sludge. Based on this assumption, the residual sludge obtained from this process could be used as a possible fertilizer for agricultural purposes (Tsybina & Wuensch, 2018).

3.1.5 Pathogens

The pathogen content of the raw sludge was higher than that of the filtrate (Table 3). This can be attributed to the sand used in the filtration process. Pathogen removal is achieved through the process of adsorption. The pathogens are adsorbed to the surfaces of the sand particles reducing the amount of pathogens in the filtrate.

The colilert-18 test used in the pathogen analysis used MUG and ONPG as nutrient indicators to identify coliforms and E. coli. The change from colourless to yellow indicated the metabolism of ONPG by coliforms using their β-galactosidase enzyme. E-coli is the only microorganism among the coliforms that can produce a specific enzyme which reacts with MUG to produce fluorescence. The nutrient indicator in enterolet fluoresces when metabolized by enterococci (American Water Works Association, 2003).

3.2 The filtration process

Table 4 illustrates the outcome of the filtration process in the removal of free water from the sludge. In all, about 14.08kg out of 27.81kg sludge was recorded as the filtrate representing about 50.6% of the total sludge. The total amount of residue which contained other forms of water representing 44.56% of the total sludge.

Table 4: Results after filtration

Raw sludge for characterisation	0.57kg
Total residue	12.40kg
Sludge in setup	0.77 kg
Total filtrate	14.08kg

Total raw sludge	27.81 kg

The main driving force used in the filtration process was the gravitational force which required no form of electrical energy or pump. This process was possible due to the difference in elevation between the sides of the effluent and the influent as this provided much more gravity for the separation of the liquid and solid part of the sludge. This is confirmed by the work of Chen et al., (2005).

The filtration process was conducted at three different times due to the size of the plexi glass used. This meant in an instance, about 10kg of sludge could undergo the filtration process. The height of the plexi glass column was 90 cm with a diameter of 14 cm. The filtration process lasted for three hours. The larger particles which formed the sludge residue were maintained in the mesh by the process of straining and sedimentation (Chen et al., 2005). There was an increase in pressure in the column, and this resulted in the compression of the sludge particles. The compression forced out the free water and

other particles less than 100 microns through the filter media (Wakeman, 2007). The mechanisms used in the filtration process were straining, interception, inertia, sedimentation, diffusion and hydrodynamic forces (Chen et al., 2005; Yao et al., 1971.; Amirtharajah, 1988). The particles larger than 100 microns were retained on the mesh while particles lesser than 100 microns were able to move through the mesh and then move into the sand layer. The mesh prevented the early clogging of the sand layer. The sand media which acted as a filter media was able to achieve filtration due to its even grain size and high porosity making the filtration process very fast (Craft, 1969). As the water (filtrate) passed through the sand it was observed that the filtrate was clearer compared to the initial colour of the sludge.

3.3 Wood pellet performance in experiment 1

Figure 12 illustrates the effectiveness of mixing the wood pellet at different wood pellet: sludge ratio in the dewatering process and drying of sewage sludge at low temperature (ca 16 ^{o}C). The moisture content reduction after 1, 24, 48, 72 and 96 hr were significant with increasing wood pellet: sludge ratio. After 1 hr, the moisture content of the control (0%), 5% WP, 10% WP and 20% WP were 89.82%, 85.83%, 79.88% and 69.07% respectively. A comparison between the control experiment with the various treatments of WP from the first hour, showed that the action of the WP was evident. This assertion is backed by the work of Wiedenhoeft, (2010) which claims that the wood pellet swells after it comes into contact with a liquid. The swelling of the wood pellet led to the breaking down of the wood pellet to create a large surface area for air to pass through the sludge mixture.

There was also a significant difference among the various sludge absorbent ratios. At the end of the 96th hour, 5% WP had an average moisture of 70.30% while 20% WP had 45.63%. The difference between moisture reduction of the 5% and 20% WP is very significant. This is an indication of the difference in sludge: absorbent ratio. There is also a similar trend between 5% WP and 10% WP as well as 10% WP and 20% WP.

It was observed during the experiment that the highest percentage of the wood pellet (20% WP) performed better than the other concentrations. This is confirmed by the work of Lehtikangas, (2000)

which reported that increasing the number of pellets also increases the moisture uptake. A p-value of 0.005 was obtained at 95% confidence level indicating the significance of the difference in sludge: absorbent ratio. At 24 hours in the experiment, it was expected that the moisture content of the sample treated with WP would reduce. However, the moisture content of 20% WP increased from 69.07% to 70.47%. This could be as a result of wrong sampling.

The highest reduction in average moisture content for the 20% WP was recorded from the twenty-fourth (24th) hour to the forty-eighth (48th) hour. 10% WP had its highest reduction in average moisture content from from the seventy-second (72nd) hour to the ninety-sixth (96th) hour. 5% WP had its highest reduction in average moisture content from 79.88% to 74.03% (5.85% reduction) from the forty-eighth (48th) hour to the seventy-second (72nd) hour. In the drying of the dewatered residual sludge, a large rectangular bowl of dimensions 30x19x11 cm (3.6)L was used in a mixture of 500g of sludge and natural absorbents. The size of the bowl created much space for air to pass through the sludge mixture.

In an experiment by Kuffour et al., (2019), where 0% (control), 50%, 100% and 150% of sawdust by weight of total solids of the faecal sludge were mixed separately with faecal sludge. They observed that 0%, 50%, 100% and 150% dewatered at 5.6, 5.3, 4.9 and 3.9 days respectively. The faecal sludge with 150% of sawdust had the highest moisture content removal. This buttresses the earlier claim that increasing the amount of absorbents quickens the dewatering process. In an experiment conducted by Kangumenawe, (2020) in Uganda where coarse sawdust and fine sawdust were used to dewater faecal sludge, the moisture content recorded were 31.4% and 33.3% respectively.

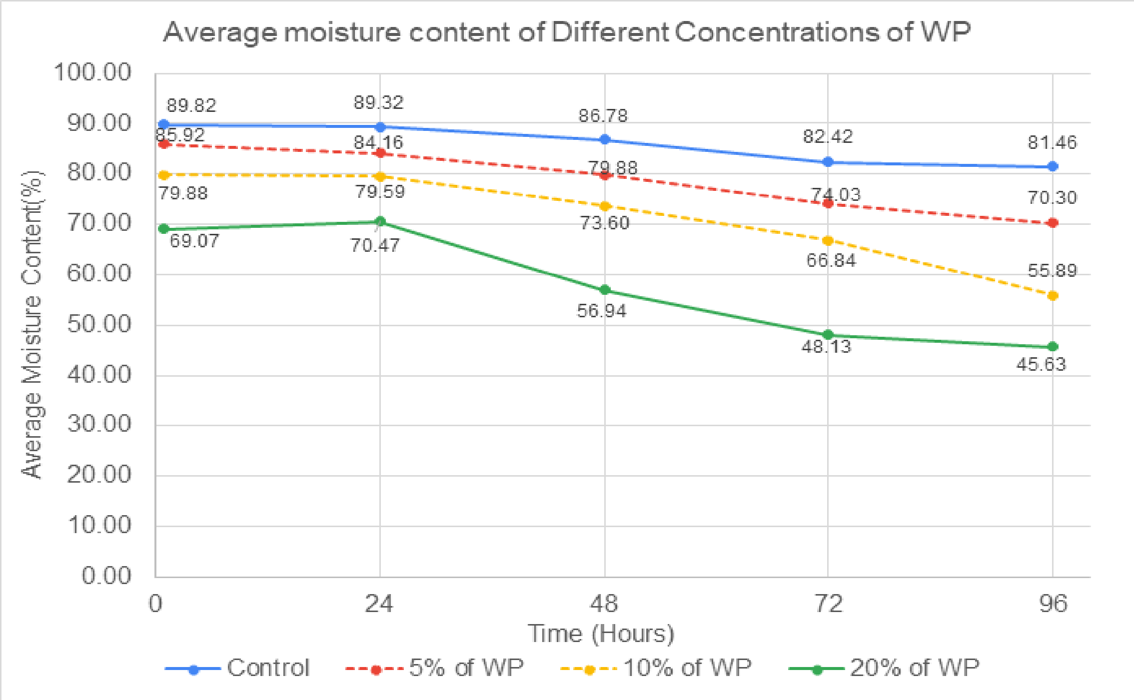

Figure 12: Treatment of Residual sludge with various concentrations of Wood Pellet.

3.4 Performance of SCG in residual sludge samples in experiment 1

Figure 13 illustrates the average moisture content reduction in residual sludge after ninety-six (96) hours when 5% SCG, 10% SCG and 20% SCG was added to the residual sludge at a temperature of about 16 ºC. The various SCG percentages showed a significant difference when compared to the control. There was also a disparity in the moisture content of the various percentages of the SCG. The p-value obtained within the group (5%, 10%, 20% SCG) was 0.005 at 95% confidence level. 20% SCG had its highest percentage reduction from forty-eight (48) hours to seventy-two (72) hours, that is, from 65.43% to 52.09% (13.34% reduction). 5% and10% SCG had its highest average moisture content reduction from the twenty-fourth (24th) hour to the forty-eighth (48th) hour, that is, from 79.91% to 73.12% (6.79% reduction). The samples had a significant reduction in the first hour with the exception of the control. Since there was no significant reduction in the control sample, it could be inferred that, when the other samples were treated with the various percentages of Spent Coffee Grounds, it (SCG) aided in the removal of moisture from the sludge mixture.

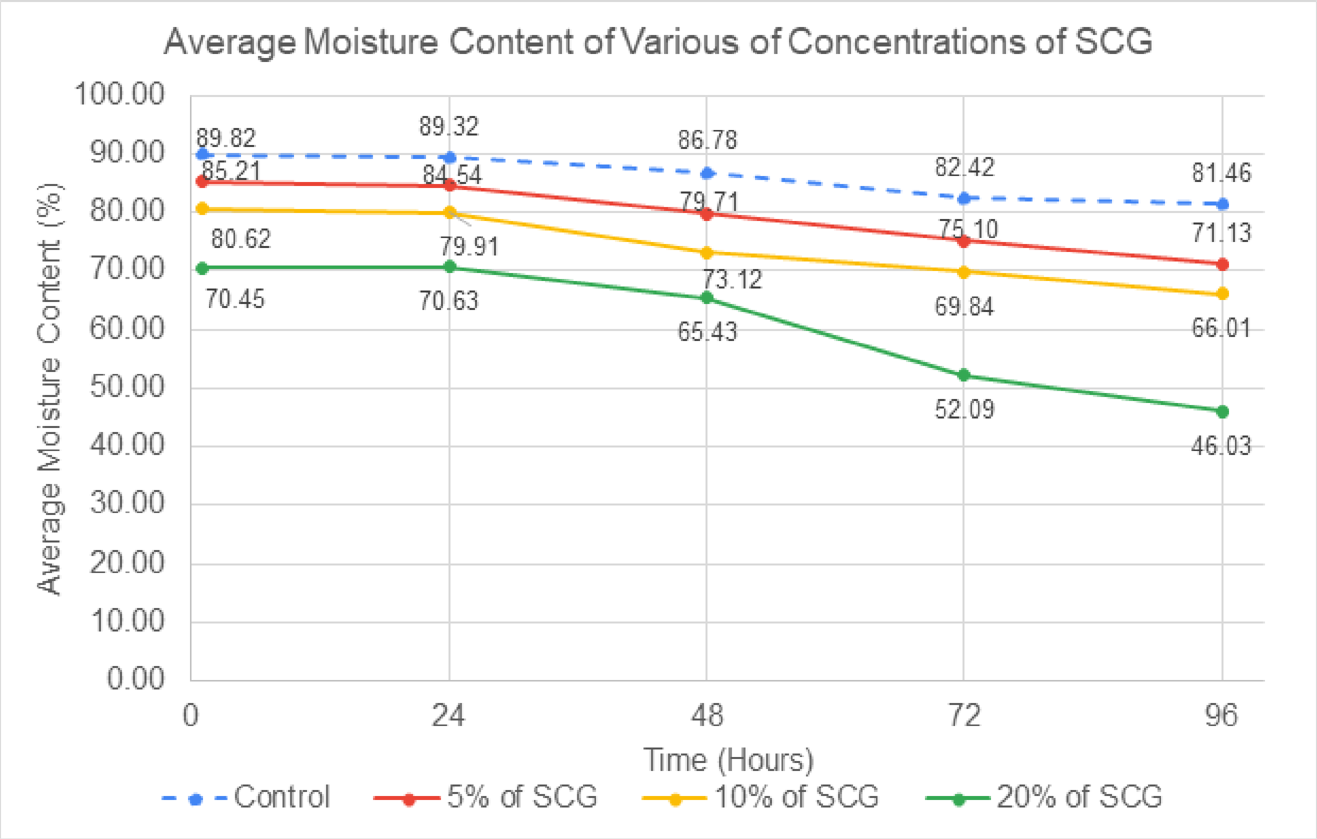

Figure 13: Residual sludge treatment with various concentrations of SCG

Figure 14 clearly indicates no significant difference in the average moisture content of 5% SCG and 5% WP. The 5% SCG and 5% WP mixed samples recorded a more or less similar average moisture content reduction pattern reaching 71.13% and 70.3% at the end of ninety-six hours compared to the 81.46% of the control sample without SCG or WP.

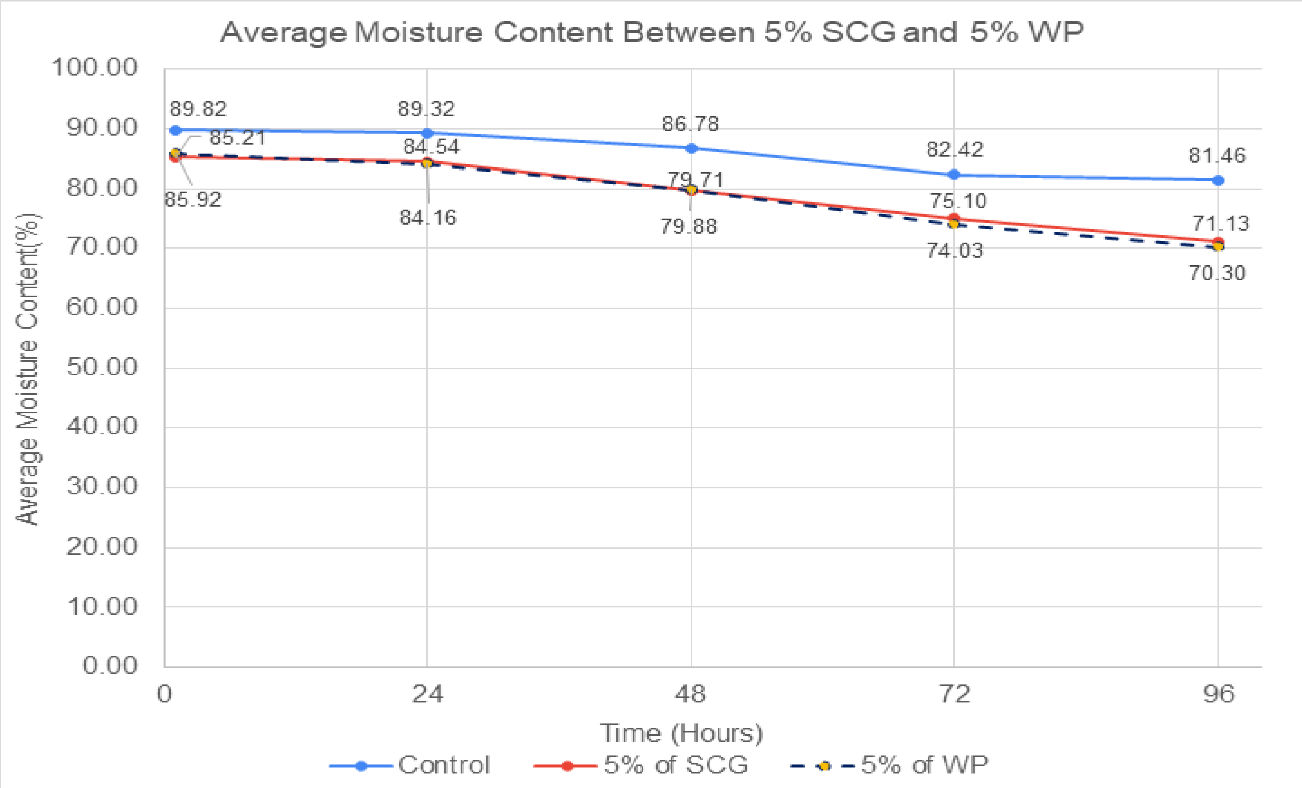

Figure 14: Comparison Between 5% SCG and 5% WP

Similarly, Figure 15 shows the comparison between 10% WP and 10% SCG. Although both 10% WP and 10% SCG showed a decrease in average moisture content as time increased, it was observed that 10% WP had the highest reduction in average moisture content, that is, 55.89% at ninety-six (96) hours followed by 66.01% of 10% SCG treated sample compared to the 81.46 % of the control. A p-value of 0.428 (at 95% confidence) level was obtained when comparing the efficiency of both WP and SCG. The p-value gives the indication that the type of absorbents (WP or SCG) used does not matter in the removal of the moisture as both wood pellet and spent coffee grounds were effective in the removal of water (moisture) from the residual sludge.

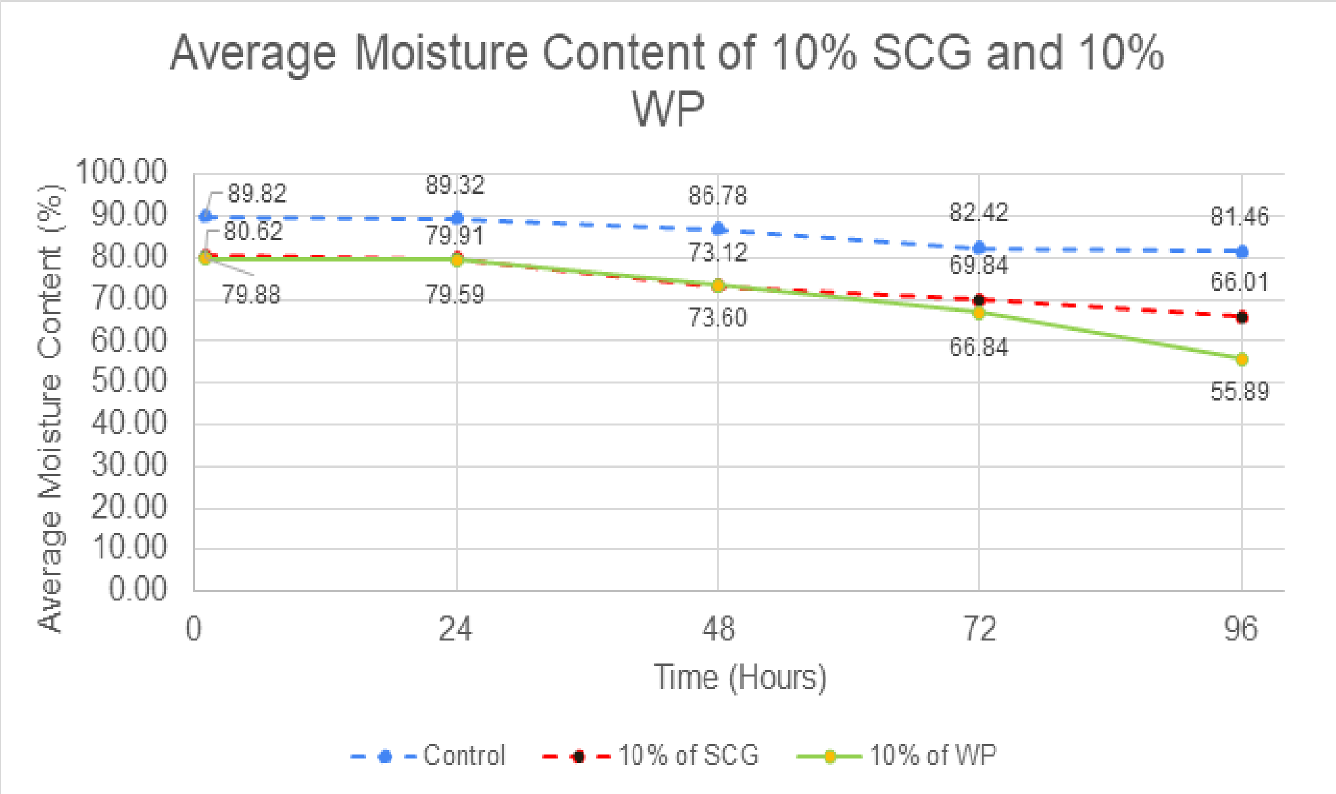

Figure 15: Average moisture content comparison between 10% WP and 10% SCG

Figure 16 shows the comparison between 20% WP and 20% SCG . Although both 20% WP and 20% SCG showed a decrease in average moisture content as time increased, it was observed that 20% WP had the highest reduction in average moisture content, that is, 45.63% at 96hr, followed by 20% SCG which recorded 46.03%. In the analysis of variance (ANOVA), a p-value of 0.428 was obtained at a 95% confidence level indicating that the type of absorbent used is not significant as there is no clear difference between the effectiveness of 20% WP and 20% SCG.

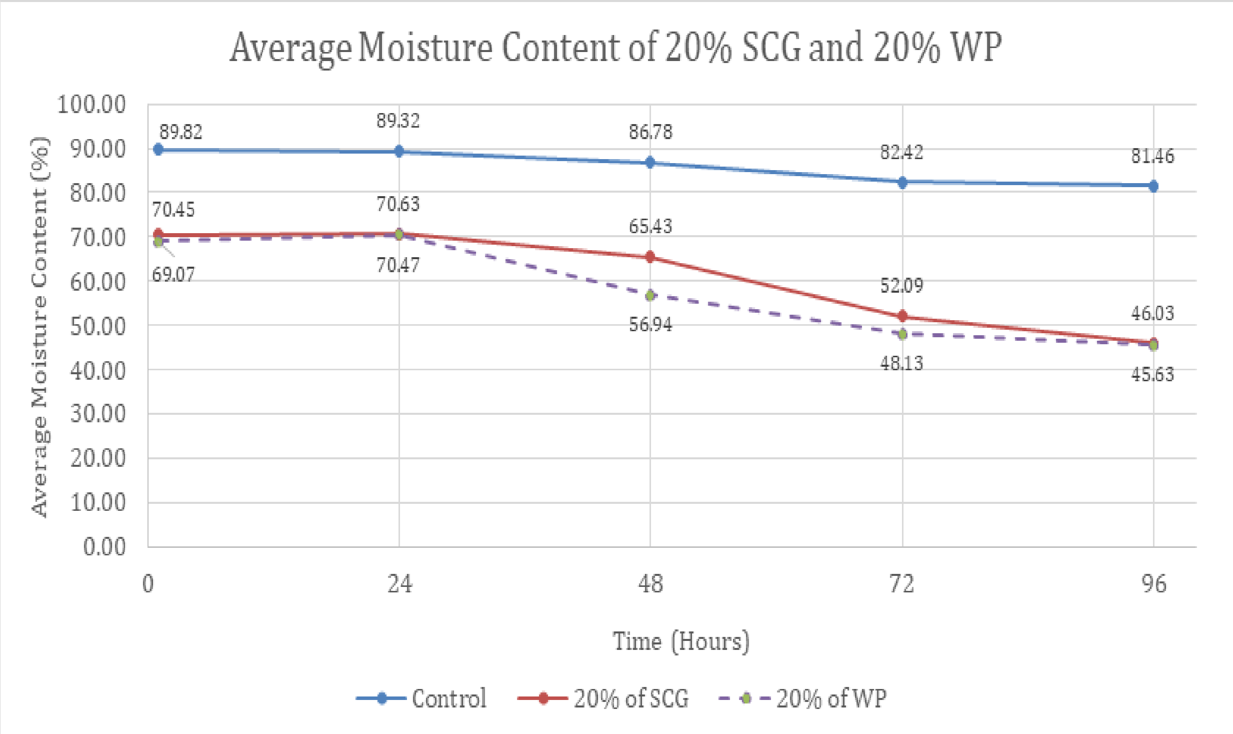

Figure 16: Moisture Content of 20% WP and 20% SCG

3.5 Performance of Various of Combinations of Absorbents

The performance of the various combinations (25% SCG 75% WP, 75% SCG 25% WP and 50% SCG 50% WP, 2% SCG 4% SA 2%WP) is illustrated in figure 17. The maximum values of 25% SCG 75% WP, 75% WP 25% SCG and 50% SCG 50% WP, 4%SA 2%SCG 2%WP, and the control (0%) were 74.02%, 68.9%, 71.87%, 82.26% and 89.8% respectively. The minimum values recorded for 25% SCG 75% WP, 75% WP 25% SCG and 50% SCG 50% WP, 4% SA 2% SCG 2% WP, and the control (0%) were 51.29%, 52.14%, 49.64%, 9.01% and 82.94%.

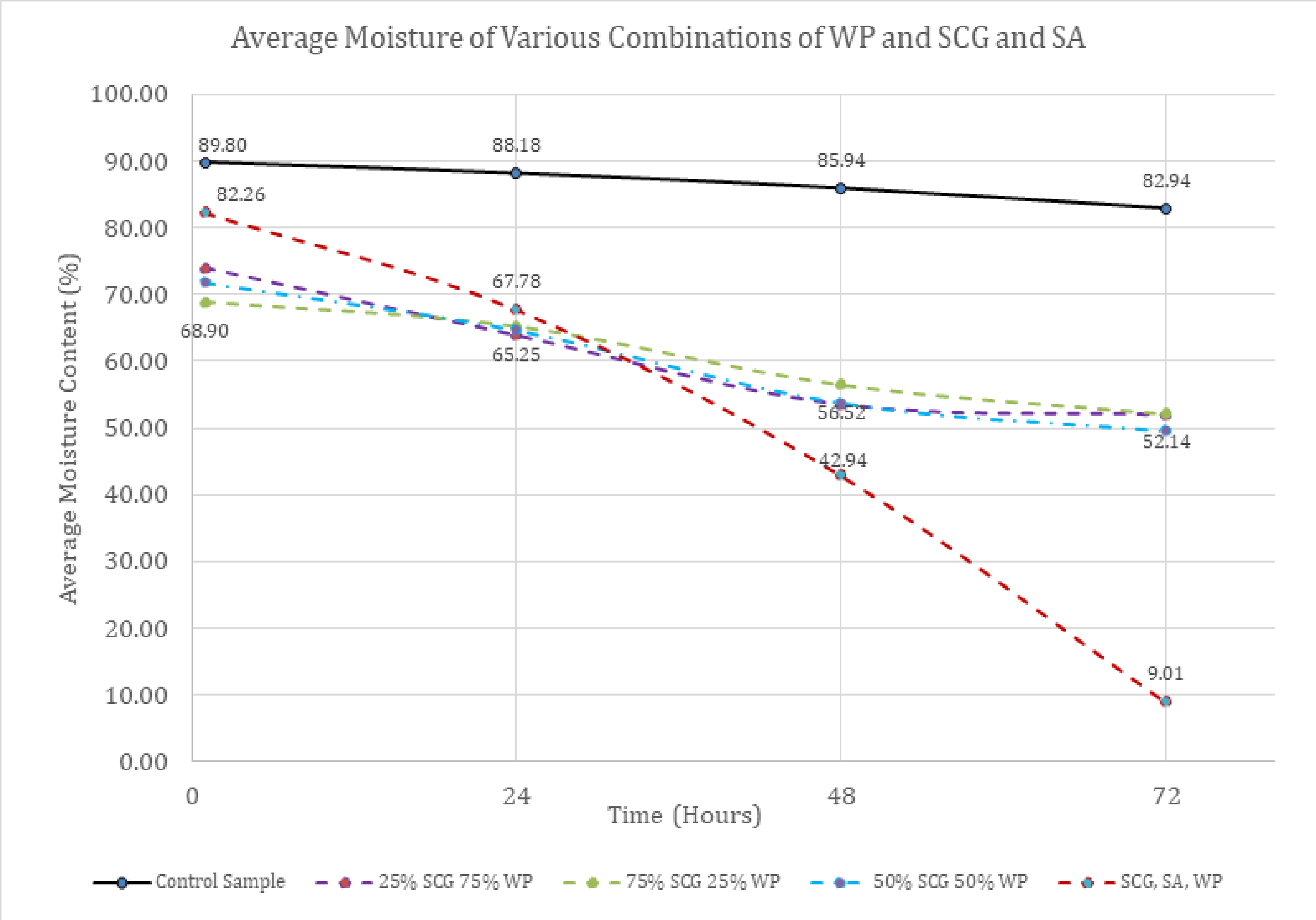

Figure 17: Moisture Content for Different Combinations of WP, SCG and SA.

After the experiment, it was observed that 4% SA 2% SCG 2% WP had the highest reduction of the average moisture content. The various combinations of WP, SCG and SA were effective in the removal of moisture from the residual sludge. The sample which contained 8% of SCG-SA-WP mixture (4% SA 2% WP and 2% SCG) showed significant effect in the removal of tightly held sludge water as it had a moisture content of 9.01% in 72 hours. This was possible because of the presence of the super absorbent polymer as it made a difference compared to the other samples which had only WP and SCG as their combination in the sample. The performance of the 8% of SCG-SA-WP mixture absorbents was significant as compared to the 20% SCG and WP mixture absorbents.

The super absorbent polymers have high water absorption capacities as 1g of SA can absorb up to 1500 g of water (Mechtcherine & Reinhardt, 2012). However, most SA are persistent in the environment, expensive, and have adverse effects on the environment, therefore it has to be used in smaller quantities or in combination with other natural absorbents (Yang et al., 2017). Statistical analysis indicates the effectiveness of the various combinations of WP, SCG and SA. A p-value of 0.037 was obtained which shows the effectiveness of the various combinations of absorbents in removing moisture from the residual sludge.

The absorbents (25% SCG 75% WP, 75% SCG 25% WP and 50% SCG 50% WP) did not show any significant difference among the various groups as the three were effective in the removal of moisture from the residual sludge. The time used (p-value of 0.000 at 95% confidence level) for the experiment was effective in the removal of water from the residual sludge among the various groups as time played a critical role in the effective reduction of moisture in sludge.

3.6 WP and SCG in experiment 2

In the second experiment, the amount of sludge used was kept constant as the amount of absorbents differed. Figure 18 illustrates an approach using 5% SCG, 10% SCG and 20% SCG in the residual sludge. The maximum average moisture content for the control (0%), 5% SCG, 10% SCG and 20% SCG were 89.03%, 85.07%, 80.96% and 73.37% respectively after 1 hour. However, the minimum average moisture content for the control (0%), 5% SCG, 10% and 20% were 42.31%, 26.83%, 24.43% and 21.95% respectively after 168 hours. The control (0%), 5% SCG, 10% SCG and 20% had their highest reduction between the hours of 144 and 168. After the experiment, it was observed that 20% SCG recorded the highest average moisture reduction among the various concentrations of SCG.

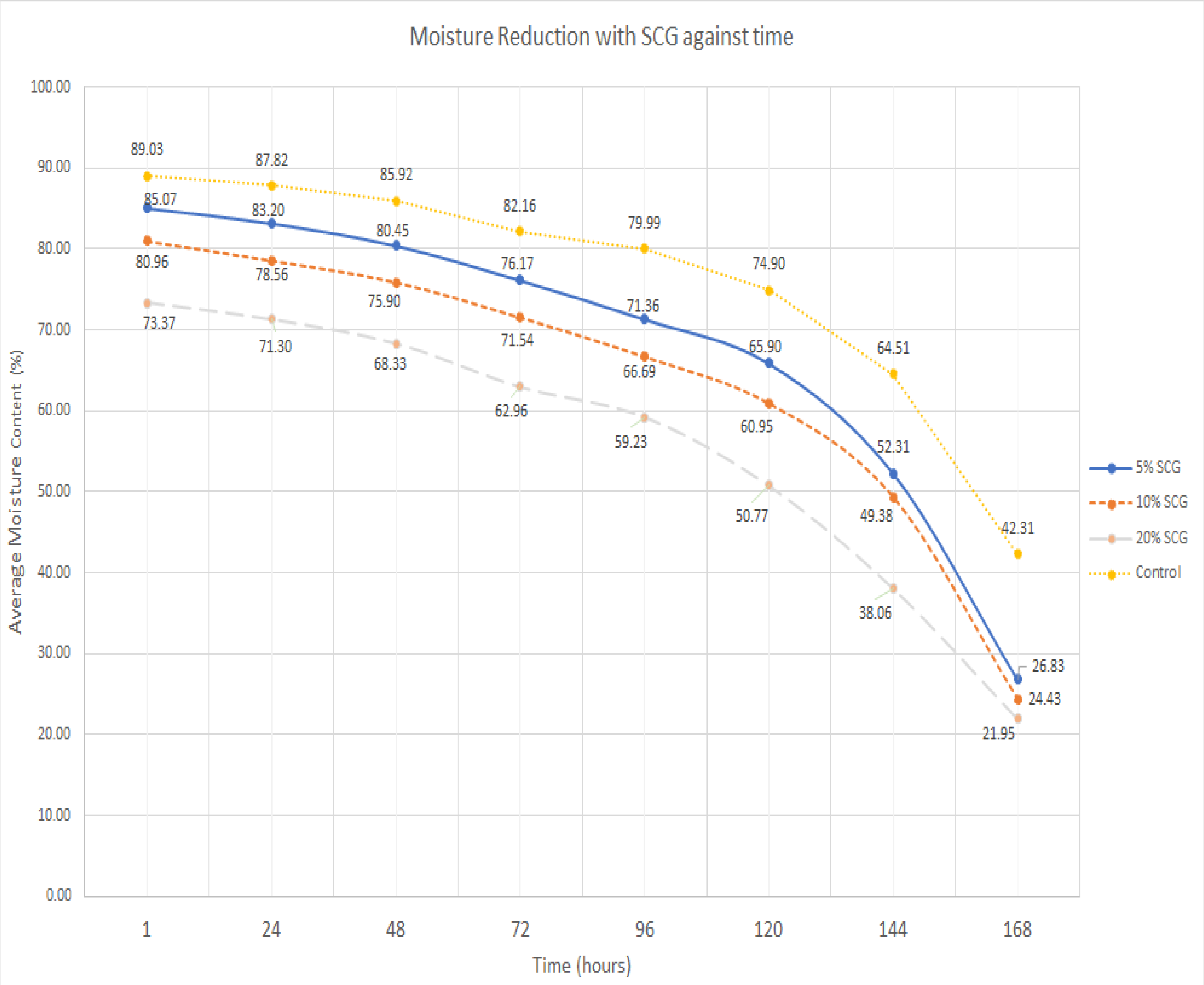

Figure 18: Average Moisture Content of Various concentrations of SCG

Figure 19 below illustrates the various moisture content reduction in residual sludge using WP as an absorbent. At one hour, the control, 5% WP, 10% WP and 20% WP recorded 89.03%, 85.00%, 81.02% and 74.49% as their average moisture content. The average minimum moisture content for the control (0%), 5% WP, 10% WP and 20% WP were 42.31%, 36.31%, 23.34 and 21.51% after 168 hours. However, 5% WP, 10% WP, 20% WP had their highest average reduction between the hours of 144 and 168 (54.11% to 36.31%; 44.79% to 23.34%; 37.40% to 21.51%).

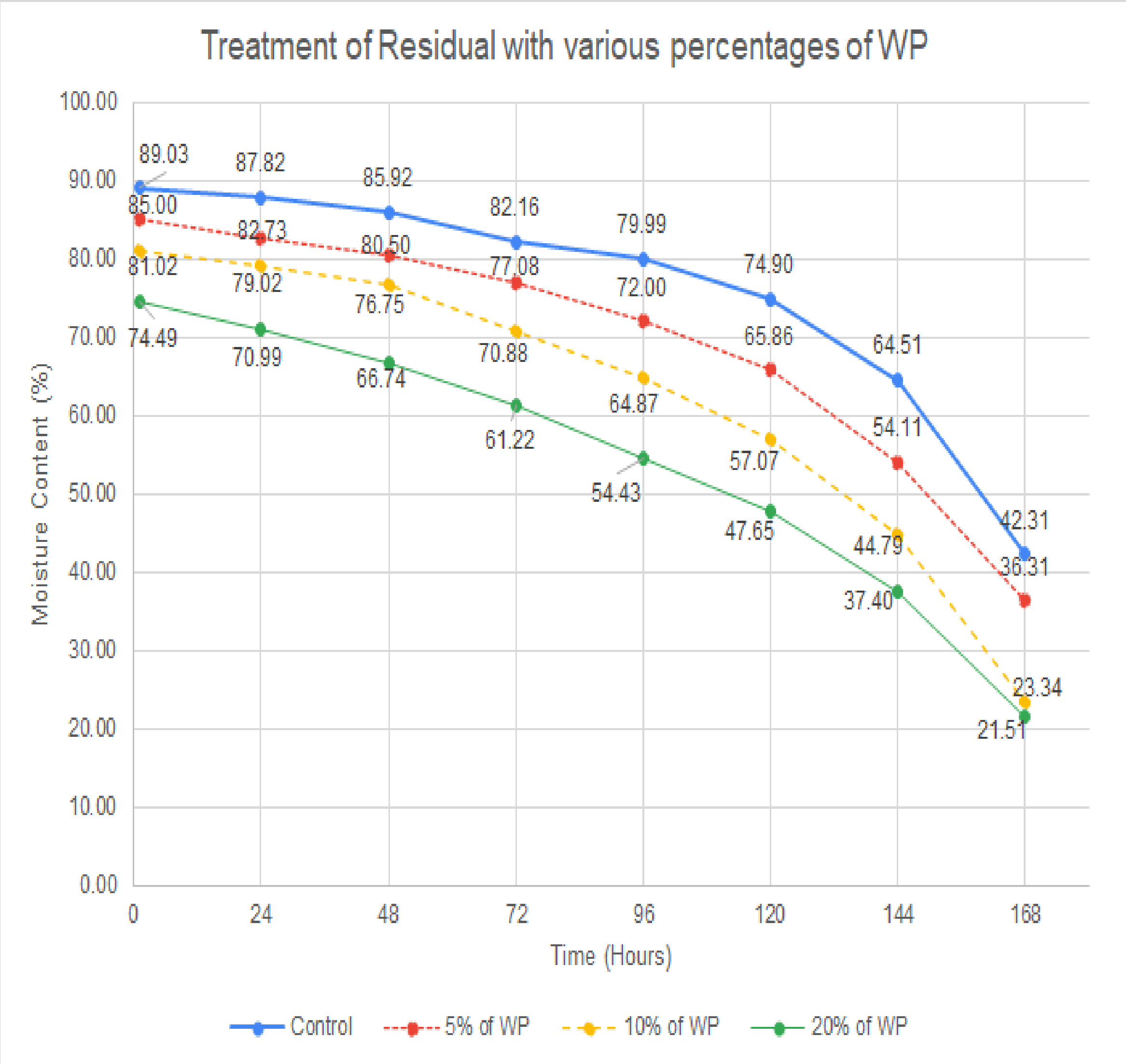

Figure 19: Average moisture reduction using various concentrations of WP

Figure 20 below is an illustration of the comparison between the average moisture content reduction of the control set up, 5% WP and 5% SCG at various times. Comparatively, at the end of the one hundred and sixty-eighth (168th) hour, the lowest average moisture content was seen in 5% SCG, that is, 26.83%. There was no significant difference between the effectiveness of the 5% WP and that of 5% SCG. Similarly, the 10% WP and 10% SCG were not different.

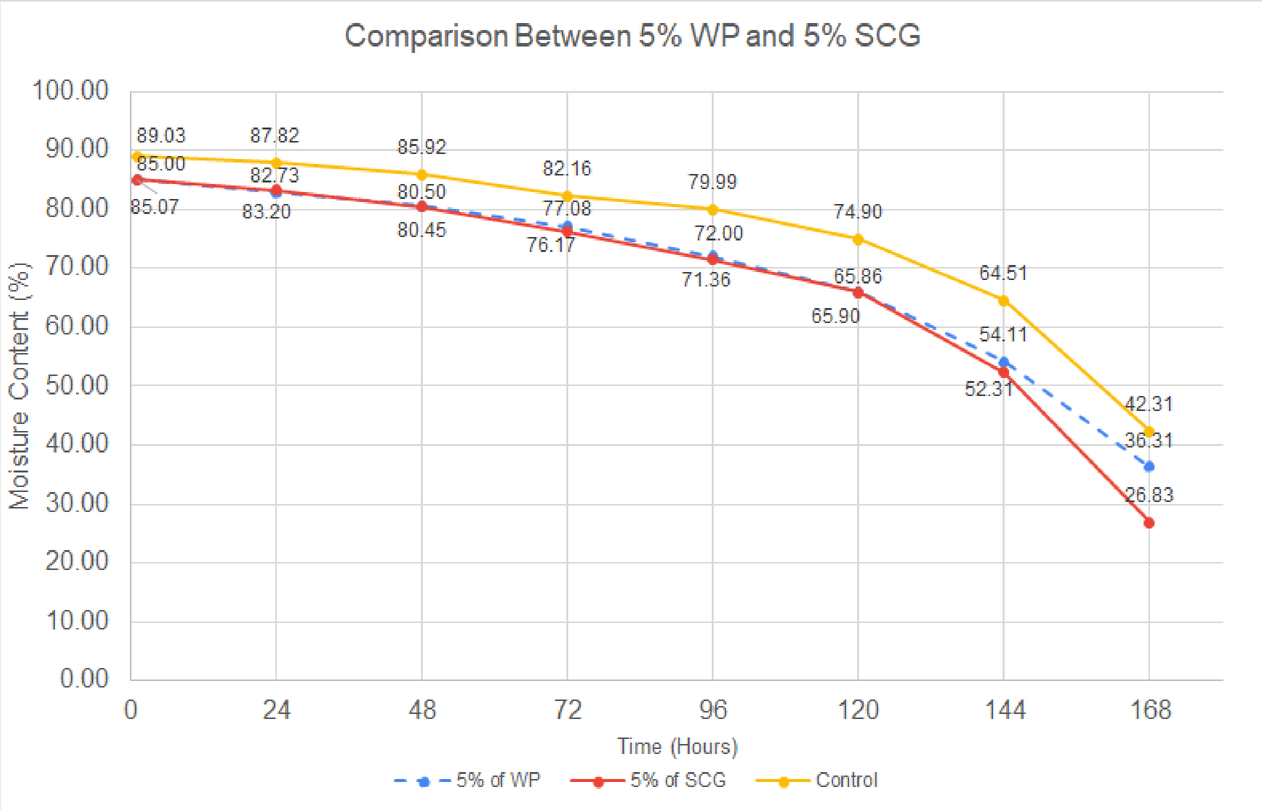

Figure 20: Average moisture content between 5% WP and 5% SCG

Figure 21 below gives a vivid description on performance of 10% WP against 10% SCG. During the first one hour of the experiment, 10% WP and 10% SCG showed an average moisture reduction of 80.96% and 81.02% respectively. At the end of the experiment, it was observed that there is no clear-cut distinction between the performance of 10% WP and 10% SCG.

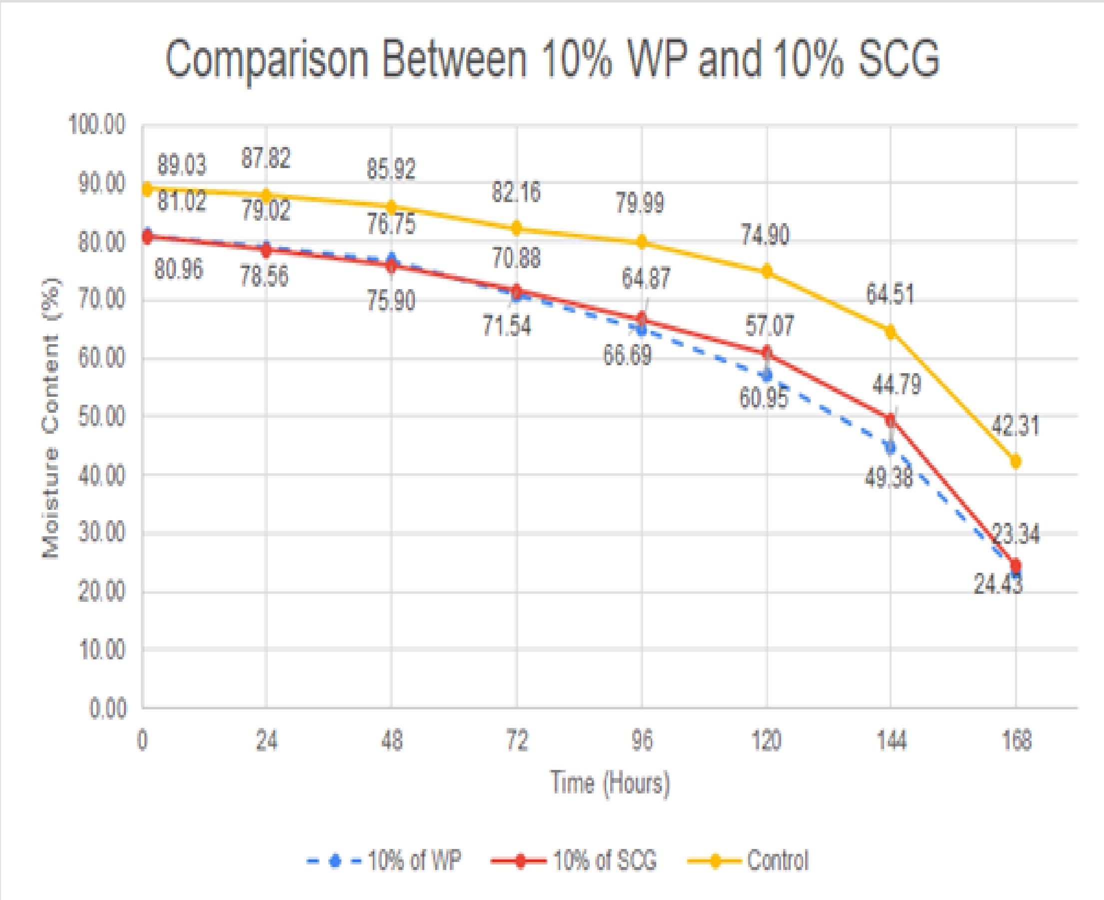

Figure 21: Average moisture content between 10% WP and 10% SCG

Figure 22 below shows a relation between the control set up, 20% SCG and 20% WP. It was observed that generally, there was a decrease in the average moisture content of the control, 20% WP and 20% SCG as the time increased. Comparatively, the lowest average moisture content was seen in 20% WP, that is, 21.51% at the end of the one hundred and sixty-eighth (168th) hour. Similarly, to the various percentages stated earlier, 20% WP and 20% SCG had similarities in the reduction of moisture.

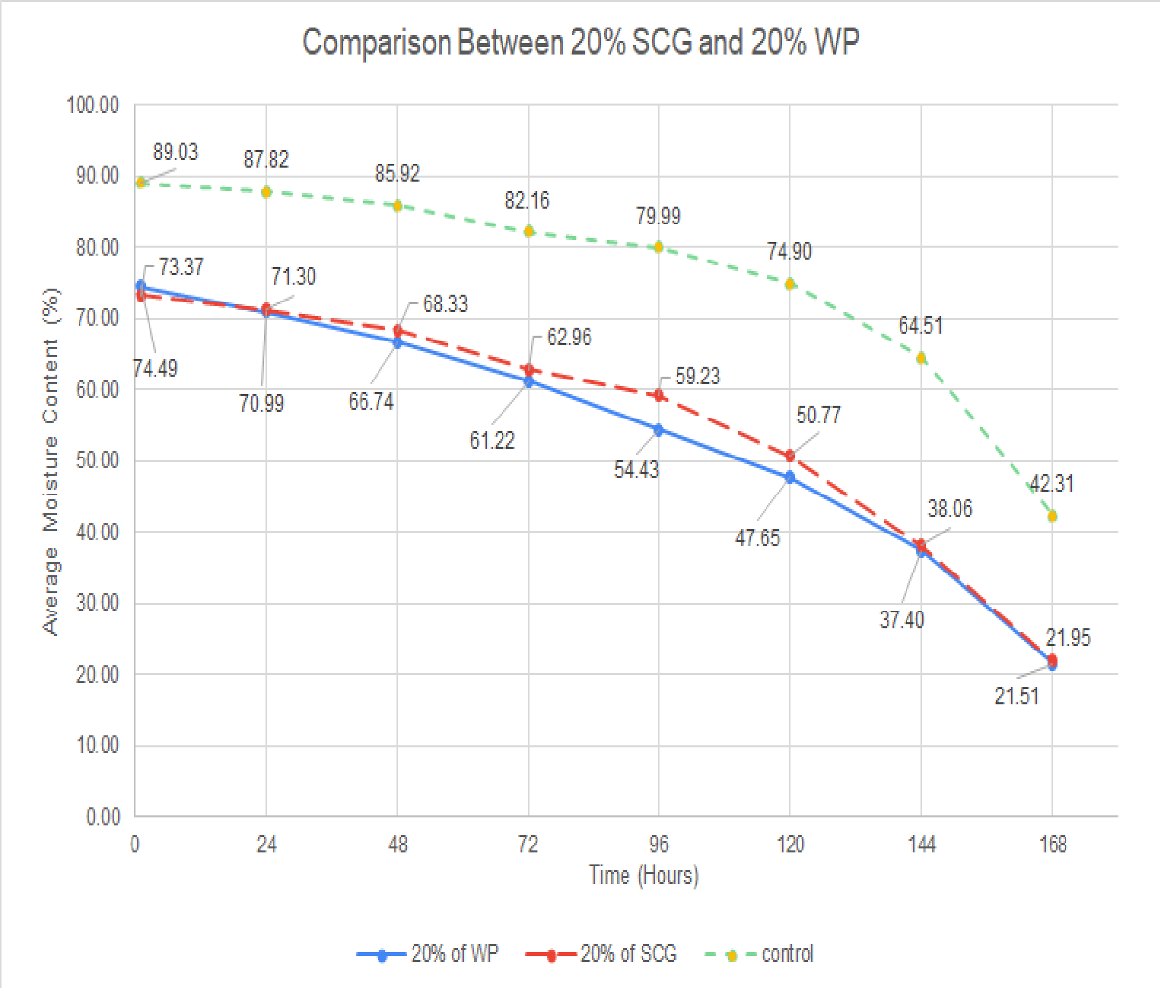

Figure 22: Average moisture content between 20% SCG and 20% WP

Figure 23 below describes the average moisture content reduction in 25% SCG 75% WP, 75% SCG 25% WP and 50% WP 50% SCG. The average moisture reduction among 25% SCG 75% WP, 75% SCG 25% WP and 50% WP 50% SCG at 1 hour were 72.16% 73.69% and 72.36% respectively. At 168 hours the average moisture content reduction in 25% SCG 75% WP, 75% SCG 25% WP and 50% WP 50% SCG were 22.70%, 21.61% and 18.97% respectively. 50% WP 50% SCG gave the best performance among the three combinations.

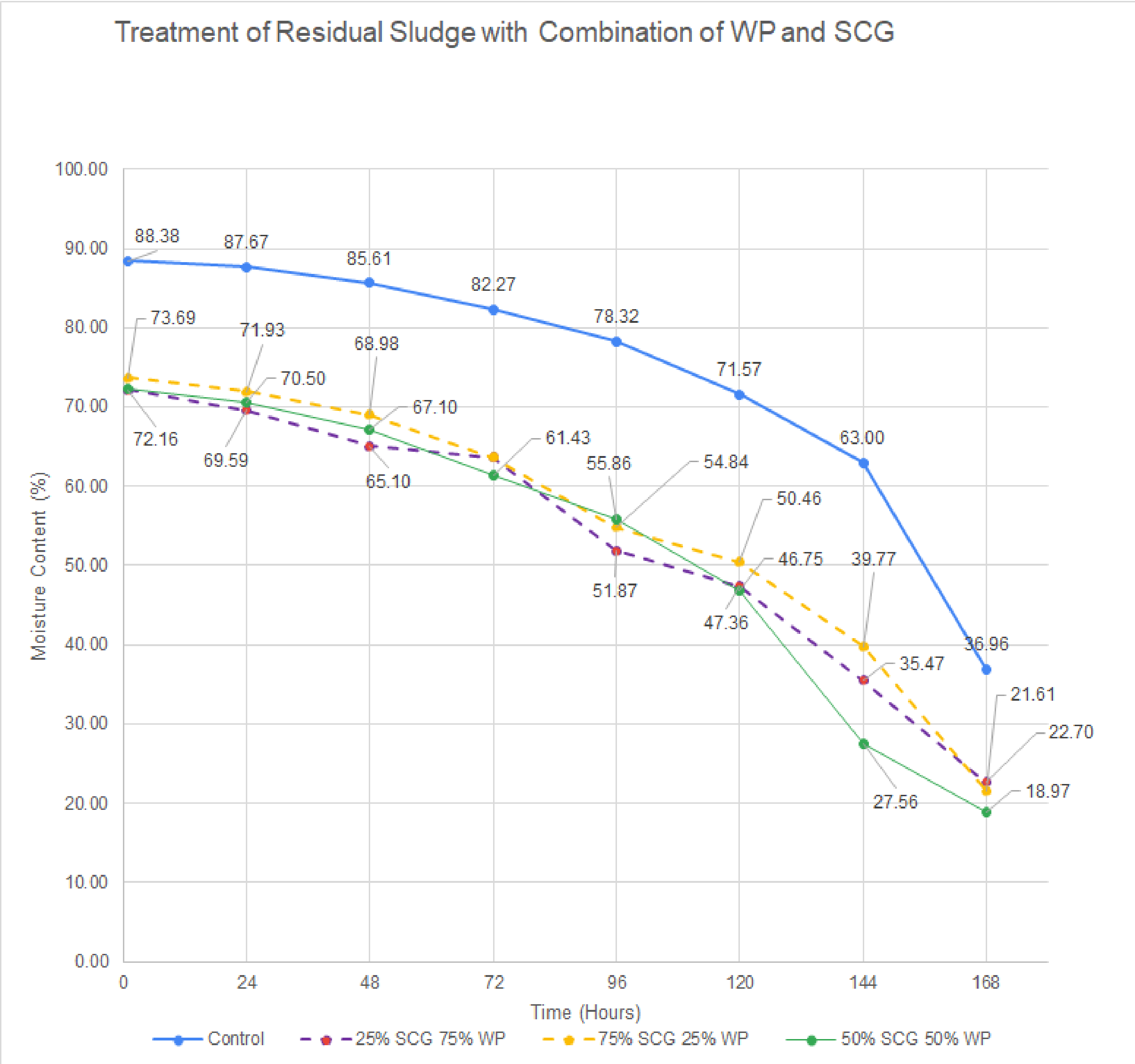

Figure 23: Average moisture content of 25% SCG 75% WP, 75% SCG 25% WP and 50% WP 50% SCG.

3.7 Performance of SCG and WP in the experiment 2

For the setups where WP and SCG were combined, the highest percentage of absorbents (20%) used in the experiment was the reference point for calculations. In that, the highest amount of absorbents used was 80g against 400g of sludge. In the combinations of WP and SCG, 80g was shared between WP and SCG in various percentages. For instance, 75% WP and 25% SCG meant 75% 0f 80g which is 60g for WP and 25% of 80g which is 20g for SCG. All the figures related to experiment 2 showed a similar trend. In that, the moisture content reduced with increasing time. Generally, all the different concentrations of absorbents were effective for the removal of moisture from the sludge (Lehtikangas, 2000; Loulidi et al., 2021). This was typically observed in the early stages throughout the experiment (Figures 18, 19 and 23). This was evident in the swelling of wood pellets when they came into contact with the water in the sludge and the breaking of the pellets into pieces which created spaces in the sludge mixture (Wiedenhoeft, 2010; Hyvönen et al., 2005; Craven et al., 2015). These absorbents can release the bound water in the sludge because of their hydroxyl groups which give them their physicochemical properties (Hyvönen et al., 2005). The samples with the highest amounts of absorbents (20%) were observed to have high reductions in moisture content. This indicated that high amounts of absorbents facilitated the dewatering and drying process (Lehtikangas, 2000).

Experiment 2 showed a significant value of 0.000 which clearly indicates the effectiveness of the various absorbents in the removal of water from the sludge. The absorbents created a large surface area for air to move through the sludge and absorbent mixtures. The time taken is of much essence in relation to the removal of moisture as it gives a significant value of 0.000. The concentrations among the various combinations were not significant (p-value=0.163) because all the combinations proved effective in the reduction of the moisture content in the sludge residue.

3.8 Comparison between experiment 1 and experiment 2

Experiment 1 and experiment 2 gave similar results and the effectiveness of WP and SCG were proven in both experiments. The sludge biomass obtained at the end of the experiment (especially 10% and 20% absorbents) can be used as a feedstock for the local production of biochar because of their low moisture content. In conventional pyrolysis, it is difficult to use samples with high moisture content because a high amount of moisture will absorb much energy (Li et al., 2016). The required moisture content for a biomass to be used in conventional pyrolysis is 10% to 20% (Joseph et al., 2018). However, a new type of pyrolysis, microwave assisted pyrolysis (MAP), is tolerant to water unlike the conventional pyrolysis which requires a low moisture content. Microwave assisted pyrolysis does not require pre-heating (Budarin et al., 2011).

Large amounts of energy can be saved because preheating accounts for about 55% of energy of the entire conventional pyrolysis as reported by Iribarren et al., (2012). Without preheating, the cost of the process can be reduced. In microwave assisted pyrolysis, not only does it produce biochar, but also biofuel, distilled water and syngas.

3.9 Temperature

Table 5 indicates the average temperatures obtained during experiment 1. The highest and the lowest temperature obtained during sample drying were 15.6 °C and 13.6 °C respectively.

Table 5: Average Temperature during the period of Experiment 1

Day	Temp (morning)	Temp (Evening)	Average Temperature
1	12.6	14.5	13.6
2	14.2	16	15.
3	13.5	17.1	15.3
4	14.4	16.7	15.6

The highest temperature recorded for experiment 2 as shown in Table 6 was 21.1°C while the lowest temperature obtained was 16.0°C. The average temperature during the second experiment was 19 °C.

Table 6: Average Temperature during the period of Experiment 2

Day	Temperature (°C) (morning)	Temperature (°C) (Evening)	Average Temperature(°C)
1	14.3	17.6	16.0
2	15.4	19.8	17.6
3	16.9	23.6	20.3
4	17.1	21.4	19.3
5	16.4	21	18.7
6	17.6	21.5	19.6
7	18.5	23.7	21.1

3.10 Odor Measurements

The odor was measured using human smell sense in the absence of an olfactometer. The odor assessment was conducted after four days of the experiment by inviting correspondents. The scale of odor was connoted as follows: 1- No odour; 2- Less odour; 3- Average odour; 4- Strong odour; 5- Intense odour. After the four days, all the correspondents indicated that the raw sludge gave a strong smell. Table 8 indicates the various responses of the correspondents.

Table 6: Odour Measurement by Different Persons

Correspondent	Raw Sludge	5% SCG	10% SCG	20% SCG	5% WP	10% WP	20% WP
1	4	2	2	1	2	1	1
2	4	3	2	2	2	1	1
3	5	2	1	2	2	2	1
4	4	3	2	2	2	2	1
5	4	2	2	2	2	2	1

The smell from the 5% SCG was moderate and had a smell of coffee in it. The smell of 10% SCG and the 20% SCG had no smell except that the 10% SCG smelled a bit of coffee. The 5% WP had less smell as indicated by the correspondents. The correspondents indicated that 20% WP had no smell. Measurement of odor sometimes appears to be a big task because the nature of human odor perception is highly subjective. Different people perceive the same odour concentrations differently (Gostelow et al., 2001a). The olfactometer can be used to replace the human nose in future experiments.

4 Conclusions

This study has demonstrated low-cost technologies and and utilization of locally available materials to enhance sludge dewatering and drying without energy input. The effect of locally available wood pellets (WP) and Spent Coffee Grounds (SCG) as sludge conditioners in enhancing sludge dewaterability has been investigated. SCG was obtained from coffee shops at no cost while WP is cheaper than conventionally used polymers. Both SCG and WP have shown significant effect in the removal of tightly held sludge water.

Increasing the quantity of WP and SCG resulted in more rapid removal of sludge moisture and decreased the dewatering and drying time. Thus, adding 20% WP and 20% SCG by weight had the higher potential to reduce dewatering and drying time compared to the control and 5% addition. The moisture content of the sludge mixed with 10% and 20% WP and SCG are suitable for pyrolysis after 96 hrs of drying and the sludge biomass can be used as a feedstock for local biochar production.

When mixing both SCG and WP to the same sludge sample, the average moisture content for the different mixing ratios one hour after startup varied from 72.2% to 73.7% compared to 88.4% for the control. At 168 hours the average moisture content was 19.0% to 22.7% compared to 39% for the control. This shows that there was a a significant effect regarding dewaterability of adding SCG or WP to the sludge, but also that there was a small difference in the dewatering ability of the different mixing ratios of SCG and WP. Thus, selection between SCG and WP can be made depending on resource availability. Adding a small amount of superabsorbent facilitated reduction of the amounts of SCG and WP and achieved a moisture content reduction down to 9.0% after 72 hours.

The moisture content of the sludge after treatment with 10% and 20% WP and SCG or with addition of superabsorbent is suitable for pyrolysis and the sludge biomass obtained from this can be used for local biochar production.

Use of sludge in the form of biochar for agricultural purposes reduces the environmental and public health risks compared to current sludge handling as the process of pyrolysis inactivates all forms of microorganisms and immobilizes most of the heavy metals. Moreover, when producing biochar from sewage sludge, the addition of natural absorbents such as SCG and WP will improve the carbon content of the sludge and thereby increase the biochar yield and its calorific value. The biochar obtained from the pyrolysis of the dewatered sludge can also be used as a source of energy.

These laboratory investigations demonstrate that adding SCG or WP, with or without a superabsorbent, can be a cheap and energy efficient way of sludge dewatering that should be of interest for decentralized applications specifically in low income areas whe circular economy and environmental protection is emphasized. However, further studies at larger scale are suggested to verify the results indicated in this thesis work.

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Appendix

Appendix A

Table A1: Univariate Analysis of Variance of Various Concentrations of SCG and WP

Tests of Between-Subjects Effects					
Dependent Variable: Moisture content					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Conc	5925.6	2	2962.7	503.1	.000
Time	5242.	4	1310.5	222.5	.000
Absorbent	86.9	1	86.935	14.8	.000
Conc * Time	339.1	8	42.384	7.2	.000
Conc * Absorbent	32.1	2	16.033	2.7	.074
Time * Absorbent	41.8	4	10.457	1.8	.146

Conc * Time * Absorbent	146.5	8	18.314	3.1	.005
Error	353.361	60	5.889		
Total	12167.360	89			

Table A2: ONEWAY Moisture Content By Absorbent

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	86.935	1	86.935	.633	.428
Within Groups	12080.425	88	137.278		
Total	12167.360	89			

Table A3 :OneWay ANOVA of moisture content with time

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5242.0	4	1310.5	16.1	.000
Within Groups	6925.4	85	81. 5		
Total	12167.4	89			

Table A4: OneWay ANOVA between moisture content and concentration

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5925.6	2	2962.8	41.296	.000
Within Groups	6241.782	87	71.745		
Total	12167.360	89			

Table A5: Univariate analysis of combinations of WP, SCG and SA

Tests of Between-Subjects Effects

Dependent Variable: Moisture content					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8809.991[a]	6	1468.332	14.951	.000
Intercept	161638.892	1	161638.892	1645.849	.000
Conc	913.116	3	304.372	3.099	.037
Time	7896.875	3	2632.292	26.803	.000
Error	4026.612	41	98.210		
Total	174475.494	48			
Corrected Total	12836.603	47			
a. R Squared = .686 (Adjusted R Squared = .640)					

Table A6: ONEWAY Moisture content with absorbent (SA, WP, SCG)

ANOVA					
Moisture content					
	Sum of Squares	df	Mean Square	F	Sig.

Between Groups	913.116	3	304.372	1.123	.350
Within Groups	11923.487	44	270.988		
Total	12836.603	47			

Table A7: One way ANOVA Between Moisture Content and Time

ANOVA					
Moisture content					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7896.875	3	2632.292	23.447	.000
Within Groups	4939.728	44	112.267		
Total	12836.603	47			

Table A8: Univariate Analysis of Variance of The Different Concentrations of WP and SCG

Tests of Between-Subjects Effects

Dependent Variable: Moisture content					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	47261.871[a]	10	4726.187	1254.880	.000
Intercept	556660.236	1	556660.236	147802.395	.000
Conc	4225.236	2	2112.618	560.935	.000
Absorbent	7.426	1	7.426	1.972	.163
Time	43029.209	7	6147.030	1632.137	.000
Error	500.911	133	3.766		
Corrected Total	47762.781	143			
a. R Squared = .990 (Adjusted R Squared = .989)					

Table A9: ONE WAY ANOVA of Moisture content by Concentration

ANOVA
Moisture content

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4225.236	2	2112.618	6.842	.001
Within Groups	43537.545	141	308.777		
Total	47762.781	143			

Table A10:ONE WAY ANOVA of Moisture content with Time

ANOVA					
Moisture content					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	43029.209	7	6147.030	176.610	.000
Within Groups	4733.572	136	34.806		
Total	47762.781	143			

Table A11: One-Way ANOVA of Moisture content with Absorbent

ANOVA					
Moisture content					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7.426	1	7.426	.022	.882
Within Groups	47755.356	142	336.305		
Total	47762.781	143			

Table A12:ONE WAY Moisture Content By concentration

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	117.214	2	58.607	.185	.831
Within Groups	21826.033	69	316.319		
Total	21943.247	71			

Appendix B

Table B1:Average moisture content of different percentages of WP and SCG in Experiment 1

Time (hrs)	(0%)Control	5% WP	10% WP	20% WP	5% SCG	10% SCG	20% SCG
1	89,81	85,92	79,88	72,48	85,21	80,6	73,66
24	89,32	84,16	79,59	70,47	84,54	79,91	70,63
48	86,78	79,88	73,61	56,94	79,71	73,12	65,43
72	82,42	74,03	66,84	48,13	75,1	69,84	52,09
96	80,76	70,3	55,89	45,63	71,13	66,01	46,03

Table B2: Average moisture content of various combinations of SCG and WP in Experiment 1

Time (hrs)	(0%) Control	25% SCG 75% WP	75% SCG 25% WP	50% SCG 50% WP	4%SA, 2% SCG,2%WP
1	89,8	74,02	68,9	71,87	82,26
24	88,18	63,94	65,25	64,75	67,78
48	85,94	53,57	56,52	53,84	42,93
72	82,94	51,29	52,14	49,64	9,01

Table B3: Average moisture content for sludge in Experiment 2

Time (hrs)	Control	5% of WP	10% of WP	20% of WP	5% of SCG	10% of SCG	20% of SCG
1	89.03	85.00	81.02	74.49	85.07	80.96	73.37
24	87.82	82.73	79.02	70.99	83.20	78.56	71.30
48	85.92	80.50	76.75	66.74	80.45	75.90	68.33
72	82.16	77.08	70.88	61.22	76.17	71.54	62.96
96	79.99	72.00	64.87	54.43	71.36	66.69	59.23
120	74.90	65.86	57.07	47.65	65.90	60.95	50.77
144	64.51	54.11	44.79	37.40	52.31	49.38	38.06
168	42.31	36.31	23.34	21.51	26.83	24.43	21.95

Table B4: Average moisture content of various combinations of SCG and WP in Experiment 2

Time (in hours)	Control	25% SCG 75% WP	75% SCG 25% WP	50% SCG 50% WP
1	88.49	71.77	73.72	72.71
24	87.78	69.62	72.06	70.67
48	85.50	65.81	68.96	66.59
72	81.76	63.58	64.19	62.40
96	78.85	47.77	52.43	58.30
120	71.01	49.11	52.58	47.20
144	60.28	35.42	38.64	28.01
168	33.76	24.99	21.68	19.26

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