UNIVERSITY OF VAASA

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FEASIBILITY OF ACTIVATED CARBON VIA HYDROTHERMALLY CARBONIZED SEWAGE SLUDGE

Master's Thesis in

Economics and Business Administration

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DEDICATION

This research paper or thesis is dedicated to my:

Parents: *Deacon & Pastor Mrs. Philip Ugbebor*

and

Relatives: *Dr. & Mrs. Charles Osifo for their unflinching support, care, altruism and above all, prayers.*

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In all candor, this thesis wouldn’t have been completed to an enormous deal of accuracy and professionalism within the set time without the supervision, guidance, fortitude and tremendous input of my supervisor, Prof. Petri Helo. On this very note, I say a big thank you to Prof. Petri Helo. I would also like to thank Mr. Tapani, the CTO of Woima Corporation, whom since the inception of my thesis, has always extended his open arms of friendship and assistance whenever the need arose. To the rest of my teachers and the non-academic staff of the university of Vaasa, whom have in one way or the other extended some form of support to my course, I say a very big thanks to you all.

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TABLE OF CONTENTS

TABLE OF FIGURES AND TABLES

ABBREVIATIONS

AC	Activated Carbon
BET	Brunauer, Emmett, and Teller
EPA	Environmental Protection Agency
EJ/y	Exajoules per year
FC	Fixed Carbon
HHV	Higher Heating Value
HTC	Hydrothermal Carbonization
kWh/d	Kilowatt-hour per Day
MC	Moisture Content
MD	Mechanical Dewatering
MJ	Megajoules
TD	Thermal Drying
TOC	Total Organic Content
VM	Volatile Mater
WtE	Waste to Energy

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ABSTRACT:

Hydrothermal Carbonization can be defined in the simplest of terms as a thermochemical process for the conversion of wet/moist biomass into high-energy density solid fuels that can serve as, precursors to produce activated carbon for pollution remediation, solid fuels, soil remediation application, and other carbonaceous materials. The popularity of hydrothermal carbonization process can comfortably be attributed to its availability and ability to process/convert wet biomass into solid fuels and other by-products without any form of pre-treatment. This research paper as a request from Woima Corporation, investigated the viability of producing 100 kg of activated carbon for the treatment of effluents from waste to energy incineration plants through carbon activation of sewage sludge and subsequent steam activation. Qualitative and quantitative research methods were employed to respond appropriately to the material balance, energy balance and the economic/financial implication objectives of this research. From the material and energy balance results of this research, which indicated 2120 kg of waste water sewage sludge, 1059.22 kg of H_2O and 2520 MJ of energy required, and the calculations on the economic/financial implication of this project, which estimated € 91 as the production cost for 100 kg of activated carbon with BET surface area of 226 within a 4 hours' time frame and a 9.66% rate of return with A.C selling price being the most influential variable with respect to variations in estimated forecast, it was concluded that within the explicitly stated delimitations of this research, the production of 100 kg of activated carbon via hydrothermal carbonization of sewage sludge and subsequent steam activation is viable.

KEY WORDS: Hydrothermal Carbonization, Carbon Activation, Sewage Sludge, Hydro-char and Activated Carbon.

1. INTRODUCTION

1.1. Background

For decades now the quest for alternative sources of energy in the world have received tremendous amount of interest and research, with the major purpose being to curb global warming and other pertinent environmental hazards while others include meeting global energy demand due to radical technological advancements and global population increase, economic benefits, global power tussle etc. The global Energy consumption was estimated to be 574.84 Exajoules in 2017, a +2.3% increase in comparison with 1.1% in 2016 (Enerdata, 2018). The U.S International Energy Administration, also estimated a 27% (3,743 Mtoe or 156.71 Exajoules) increase in global energy demand from 2017 to 2040 (Global Energy Institute, 2018). These estimates induce concerns that have been suggested to be effectively annulled by considering diversification of energy sources/generation from the 19th century fossil fuel-based generation to green energy sources which are characterized as renewable, sustainable and eco-friendly. Excluding the limited nature of fossil-fuel, the most pressing challenge posed by the consistent use of fossil-fuel based energy sources is the negative impact it has on the environment (Global warming, Ozone layer depletion etc.). On the 20th of Sept. 2017, hurricane Maria, a category 4 hurricane, hit Puerto Rico causing an enormous deal of devastation in its wake with documented death toll of 64 people at the time which was later estimated by a new Harvard study in May 29th, 2018, to 4,600 deaths (World Vision, 2018). Hurricane Maria just like other devastating environmental disasters has been attributed to global warming, the major consequence of fossil-fuel based energy sources.

Global warming as it has been well established is caused by the presence of different concentrations of greenhouse gases in the atmosphere. The greenhouse gases include Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) and fluorinated gases with Carbon Dioxide making up 76% followed by Methane 16%, Nitrous Oxide 6% and Fluorinated gases 2% of Global greenhouse gas emissions (U.S EPA, 2017). From the Anthropogenic perspective, Carbon Dioxide with the highest concentration in the atmosphere is majorly produced as a by-product during the combustion of fossil-fuel and minorly produced through forestry and agricultural practices like deforestation, clearing of grasses for farming etc. Also, others like Methane and Nitrous Oxide are in parts, fossil-fuel combustion and transportation by-products. These greenhouse gases influence the temperature of the Earth by absorbing tremendous (depending on the gas's GWP) amount of energy without easily releasing the energy back into space and as a result, increases the temperature of the Earth. Consequential events such as excessive rainfall, floods, droughts, drastic variations in climate etc., have been credited to global warming. In other to mitigate this unwanted event, scientists all over the world reckons that the usage of fossil-fuel based energy sources which are financially unfriendly, limited and adversely impact our environment, should be reduced to the barest minimum or stopped if possible. In other to follow through the recommendation, alternative sources of energy such as Wind, Tidal, Solar, Geothermal, Biomass etc. have been in the fore front of active research and development in global energy sector.

The recyclability property and abundance of biomass/biomass waste across the world has made it possible to considered biomass to play multiple roles in sustainable development which integrates eco-friendliness and renewability. Waste to Energy (WtE) processes as a popular option in utilizing biomass waste for sustainable development, entails energy recovery from the biomass waste either as generated electricity or heat or fuel source with methods such as incineration, hydrothermal carbonization, gasification, pyrolysis, anaerobic digestion etc. Waste to Energy methods just like combustion of fossil-fuel, produces effluents that portends severe harm to the environment. For the incineration of biomass (MSW for example), it has been established that nearly all the carbon content present in the waste biomass are emitted as Carbon Dioxide (CO_2). In other words, the treatment of 1 metric ton of MSW will produce approximately 1 metric ton of CO_2 (Themelius, 2003). Chang et al 2003, in their investigation on the emission factors and removal efficiencies of heavy metals from MSW incinerators in Taiwan, ascertained that the flue gas emission of incinerator furnaces includes carbon dioxide, nitrogen oxides, sulfur dioxide, hydrochloric acid, heavy metals (mercury etc.), and fine particles. In the same research (Chang et al, 2003), it was also established that the adequate cleaning of the flue gases can be effected by the use of activated carbons, acid gas scrubbers, and particle filtration.

Wet biomass as a precursor to hydrothermal carbonization process produces hydro-char which can be combusted directly for energy production, further processed to activated carbon through either physical or chemical activation for carbon sequestration and other numerous uses/applications. Funke et al 2010, defined hydrothermal carbonization as an exothermic process in which, through mainly dehydration and decarboxylation both the oxygen and hydrogen content (molecular O/C and H/C ratio) of the feed are lowered. In the same research (Funke et al, 2010) it was estimated that HTC process was achieved by applying temperatures within the range of 180 – 240^0C to a suspension of biomass in water at saturated pressure for several hours. Other researchers estimated a temperature range of 150 – 350^0C as a generally used hydrothermal carbonization temperature which is dependent on the type of starting materials (feed/biomass) and their decomposing temperatures (Liu et al, 2010). In recent years little attention has been paid to hydrothermal carbonization processes for production of hydro-char simply because coal (hydro-char) as an energy carrier is inferior to liquid or gaseous fuels but from the perspective of other applications of hydro-char such as, being a precursor for activated carbon production, hydrothermal carbonization process becomes expedient. In comparison with other processes for producing a stable and non-toxic fuel, HTC process requirements are low, and this feature extends an edge when considering a decentralized application on a small-scale basis.

The activation of hydro-char to produce activated carbon is a subsequent step after the yield and extraction of hydro-char from the HTC reactor. Carbon activation can be achieved in two ways. The first being physical (or thermal) activation while the second is chemical activation. The former is achieved by the application of CO_2 or steam at 800 – 900^0C for a period while the latter is achieved by applying a choice chemical ($ZnCl_2$, H_3PO_4, KOH etc.) at 450 – 650^0C for a period (Jain et al, 2016).

This research was proposed by WOIMA CORPORATION, an international company whose beam is focused on the mitigation of waste-induced problems across the globe through the decentralization of waste-to-energy power plants (designing, building and selling modular waste-to-energy power plants) thereby tremendously extenuating global warning and its consequent effects. With respect to the optimization of the WtE process, WOIMA corporation is considering the feasibility (both economic and pragmatic) of internally generating resources needed for the WtE process with the focus on the air pollution control unit of the WtE power plant. In other meet the air pollution requirement from pertinent regulatory bodies, the current air pollution control unit is based on a dry APC-system with Hydrated Lime ($Ca(OH)_2$) and activated carbon dozing systems and reactor that are combined with fabric filtration system (wasteWOIMA, 2019). The idea is to consider wet biomass as a precursor to produce activated carbon through hydrothermal carbonization and subsequent carbon activation (either physical or chemical) using Sewage Sludge as the precursor/wet biomass/model.

1.2. Research scope

This research ranges/covers from the input of Sewage sludge and H_20 (at 25^0C and 1bar) into the hydrothermal batch reactor for hydro-char production to the produced activated carbon through steam activation in a reaction column. It doesn't put into consideration other aspects such as logistics and/or supply of the sewage sludge. The flow charts (fig… & …) in the subsequent page will buttress the delimitation comprehensively.

1.3. Research questions and objectives

In other to respond to the research questions below;

- *what are the requirements for the production of 100 Kg of Activated Carbon from Hydrothermally Carbonized Sewage Sludge?'* and
- *How implementable is the production of 100 Kg of Activated Carbon in an Economic sense?',*

Three research objectives have been proposed. The first two research objectives respond adequately to the former research question while the later research question is responded to by the third research objective. These objectives are listed below;

- *Mass/Material balance of the entire process*
- *Energy balance of the entire process*
- *Economic implication/workability of the proposed project.*

1.4. Nature of reactants (Sewage Sludge and Water)

- The sewage sludge under consideration was gotten from municipal waste water treatment plant with a moisture content of (85.94 ± 0.22) % and it was introduced into the reactor at room temperature (25^0C) and pressure (1bar). The time before and during processing or hydrothermal carbonization of the sludge has a direct impact on the chemical composition of the sludge and as such proximate and ultimate analysis of the sludge before and during the entire process was performed and it is presented in table 0.1.1 below.

- The water under consideration is ordinary fresh water at room temperature (25^0C) and pressure (1bar).

Source of the Sewage Sludge

- The sewage sludge under consideration was taken from a waste water treatment plant in Japan.

Available Resource(s)

- Steam at 400 ^{0}C and 40 bars

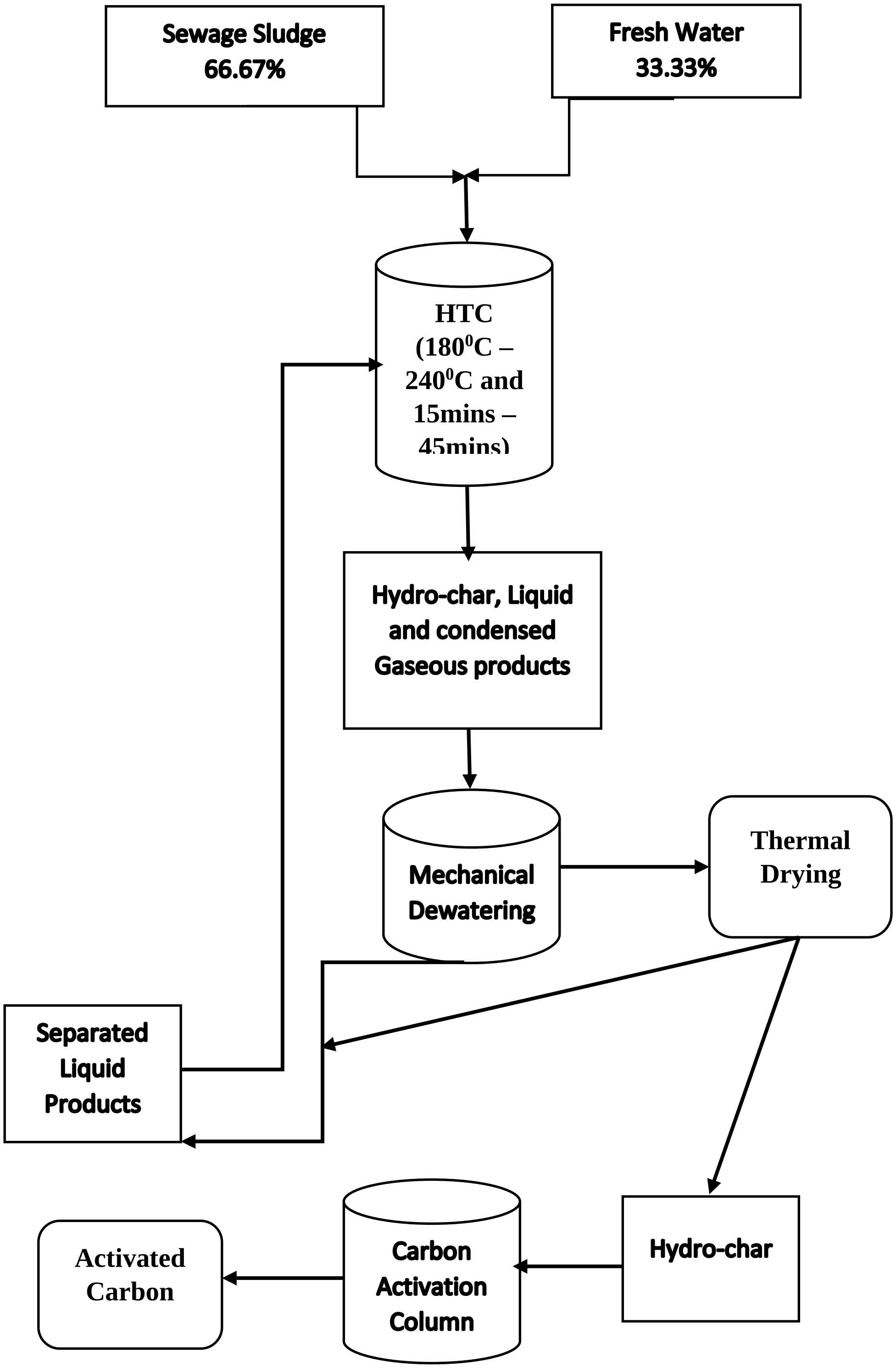


Figure 1. Research flow chart.

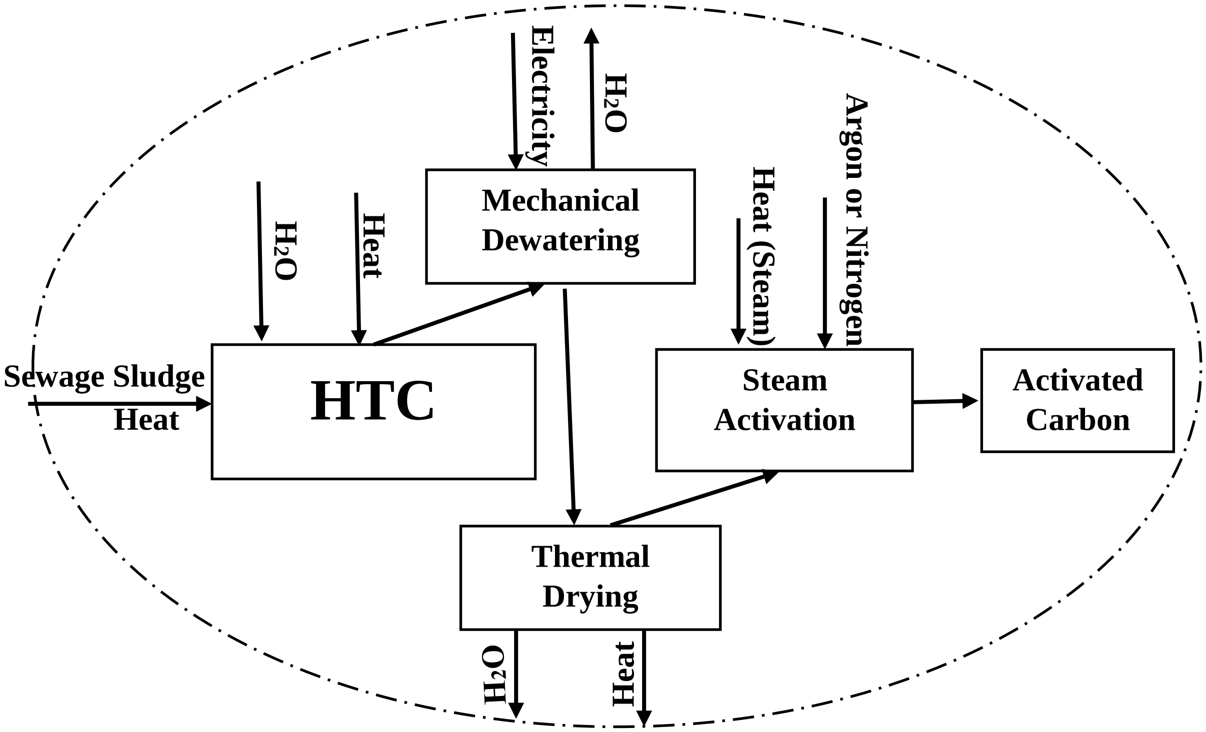


Figure 2. Research scope considered as a control volume or a system.

2. LITERATURE REVIEW

2.1. Biomass overview

Vassilev et al, 2009, defined biomass as non-fossil and convoluted biologically processed organic-inorganic solid product precipitated by natural and anthropogenic processes, and it's made up of:

- Natural components gotten from aquatic and terrestrial based vegetations through photosynthesis or gotten through the food digestion of animals and humans.
- Man made products produced through the processing of either animal and human digested food and/or aquatic and terrestrial vegetations.

Biomass was also simply defined as an organic material from plants and animals with stored chemical energy gotten from sunlight (Heidari et al, 2018). In this context biomass is not considered to be used for food. The EU and UN legal frameworks regard the burning of plant-obtained biomass as renewable energy source even though the combustion reaction emits substantial amount of CO_2 into the environment. This renewable energy source attribute to plant-obtained biomass is consequent of the fact that, during photosynthesis the CO_2 emitted is cycled back into new crops.

Biomass can be used for numerous purposes like energy/heat production, and as precursors for industrial processes to produce an assortment of products (Ur-Rehman et al, 2013). In many developing countries, it has been observed that biomass is the only domestic-use fuel source. Global biomass production has been estimated to be 105 billion metric tons with approximately one half in the ocean and other half on land (Field et al, 1998).

2.2. Types or classifications of biomass

Biomass can be categorized by different features. This research considers only two categories. Vassilev et al, 2009, classified biomass according to fuel sources/resources considering similar source and origin and their biological diversity. Table 2.1 below summarizes it.

Table 1. Biomass classification by source. (S.V Vassilev et al, 2010)

Biomass group	Sub-group of Biomass	Varieties and species of biomass
Wood and woody biomass	Coniferous or deciduous, angiospermous or gymnospermous	Soft or hard, stems, branches, foliage etc.
Herbaceous and agricultural biomass	Annual or perennial and field-based or processed based	Grasses and flowers: bamboo alfalfa, arundo, cane, brassica, etc. Straws: barley, corn, bean, rice, oat, sunflower, wheat, mint etc.
Aquatic biomass	Marine or freshwater algae	Macroalgae: blue, green, brown, red, blue-green. Microalgae: seaweed, kelp, lake weed, water hyacinth, etc.
Animal and human biomass wastes		Bones, meat-bone meal, chicken litter, various manures, etc.
Contaminated biomass and industrial biomass waste (semi-biomass)		Municipal solid waste, demolition wood, refuse-derived fuel, sewage sludge, hospital waste, paper-pulp

		sludge, waste papers, paperboard waste, chipboard, fibre-board, plywood, wood pallets and boxes, railway sleepers, tannery waste, etc
Biomass mixtures		Blends from the above varieties

Biomass can also be classified according to their chemical constituent. Non-lignocellulosic biomass and lignocellulosic biomass.

2.2.1. Non-lignocellulosic biomass

Sewage sludge, animal manure and their likes are classified under non-lignocellulosic biomass. Non-lignocellulosic biomass mostly contains fatty acids, proteins and small amounts of hemicellulose, cellulose and lignin (Achinas et al, 2017).

2.2.2. Lignocellulosic biomass

Lignocellulosic biomass unlike non-lignocellulosic biomass, consist majorly of hemicellulose, cellulose and lignin with some amount of ash and water extractives. Examples includes forest and agricultural farm waste, municipal biological solid wastes and their likes (Acharya et al, 2012). Acharya et al, 2015, in their review on comparative study of dry and wet torrefaction, communicated that although the composition of biomass was profoundly influenced by the type, climate condition and maturity, it could also be said to contain 20 – 40% hemicellulose, 40 – 60% cellulose and 10 – 25% lignin. Fig 2.1 below depicts the structure.

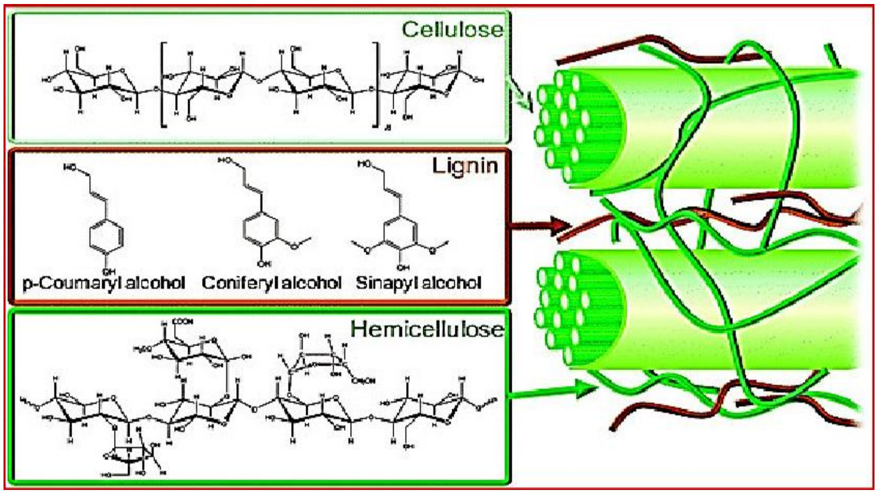


Figure 3. Structure of Lignocellulosic biomass (Alonso et al, 2012).

2.2.2.1. Hemicellulose

Hemicellulose which makes up 20 – 40% of raw biomass (Acharya et al, 2015), is made up of a complex carbohydrate structure. The complex carbohydrate structure is an integration of polymers like sugar acids, hexoses, pentoses, mannose and glucose. With respect to thermal stability, hemicellulose is the least stable among the three lignocellulosic polymers of biomass with a thermal degradation temperature range of 200 – 300^0C (Gronli et al, 2002). At about 180^0C, the solubility of hemicellulose starts under hydrothermal conditions as a result of hydrolysis (Bobleter, 1994; Grrrote et al., 1999).

2.2.2.2. Cellulose

In comparison with softwood and agricultural biomass, hardwood contains the highest percentage of cellulose (Garrote et al., 1999). Generally, the composition of cellulose in lignocellulosic biomass ranges from 40 – 60% which makes it the highest in terms of composition (Acharya et al., 2015). The purest and naturally occurring form of cellulose is a cotton fiber (Kumar, 2010). The strong hydrogen bond of cellulose in conjunction with its crystalline structure affords its thermal degradation to start at a temperature range of 300 – 400^0C (Gronli et al., 2002; Perez & Samain, 2010).

2.2.2.3. Lignin

P-coumaroyl, coniferyl and sinapyl alcohol are the three phenyl-propane group making up lignin which is a crosslinked, complex and amorphous heteropolymer (Hendriks & Zeeman, 2009; Kumar, 2010). In comparison to agricultural biomass and hardwoods, softwoods contain higher percentage of lignin (Garrote et al., 1999), with the main function of providing structural strength, impermeability and resistance against microbial attack (Fengel & Wegener, 1983). In terms of thermal stability, Lignin is the most stable in comparison with other constituents of lignocellulosic biomass with a degradation start temperature of 220^0C (Bobleter, 1994).

2.3. Biomass chemical composition based on ultimate and proximate analysis

The behavior of solid biomass when it is heated is simply determined by its proximate analysis. It provides information about the percentage of material that burns in a gaseous state (volatile matter), liquid state (Moisture content), solid state (fixed carbon) and the percentage of inorganic waste material (ash).

- Moisture content: calculations on different basis (as received, air-dried and oven-dried) of biomass moisture content varies between 3 – 63%, decreasing in the order: WWB > HAG > HAR > HAB > CB > HAS > AB. Tables 2.1.2.0 and 2.1.2.1 displays the result comprehensively. Biomass moisture content was also found to be minerized aqueous solution containing different cations and anions (Vassilev et al., 2010). Moisture content adds unnecessary weight during transportation, constitutes some handling problem and reduces the calorific value and as such, its an important factor in both storage and utilization of the source. Carbon source with high moisture content signifies low ranking carbon source (Pisupati et al, 2017).
- Ash content: Vassilev et al., 2010, in their research estimated the ash yield to vary between 0.1 – 46% on a dry basis at 550 – 600^0C with biomass group decreasing in the order: AB > CB > HAS > HAB > HAR > HAG > WWB. Tables 2.1.2.0 and 2.1.2.1 presents these data comprehensively. For approximating the bulk inorganic matter, prevalent attraction of elements and compounds to inorganic or organic matter and probable contamination of

biomass, ash is an imperative parameter. Because of the dynamic nature of ash at elevated temperatures and when cooled, its amount, nature and behavior at high temperatures affect the design and type of ash-handling system engaged in plants and combustion chambers (Pisupati et al, 2017).

- Volatile matter: materials driven-off when the carbon source is heated in the absence of air under specified conditions are referred to as volatile matter. High volatile matter signifies high ranking carbon source (Pisupati et al, 2017). Light hydrocarbons, CO, CO_2, H_2, moisture and tar are common constituents of volatile matter (Demirbas, 2004). 48 – 86% is interval to which volatile matter content varies on a dry basis calculation (Vassilev et al, 2010).
- Fixed carbon: it is the solid combustible residue that remains after the heating of the carbon source and the expulsion of the volatile matter (Pisupati et al, 2017). The dry basis fixed carbon content in biomass varies from 1 - 38% and decrease in the order: HAR > HAB > WWB > HAS > HAG > AB > CB (Vassilev et al, 2010). Refer to tables 2.1.2.0 and 2.1.2.1

Ultimate analysis on the other hand produces a more comprehensive result. Through ultimate analysis the elemental composition of the carbon/fuel source which includes moisture, ash, carbon, hydrogen, nitrogen, sulfur and oxygen is calculated as a percentage of the total mass of the fuel/carbon source through chemical analysis. Tables 2.2 and 2.3 below expresses the analysis by biomass group.

Table 2. Biomass composition analysis with respect to biomass groups and sub-groups (Vassilev et al, 2010).

Symbol	Order for groups and sub-groups
M (am)	WWB > HAG > HAR > HAB > CB > HAS > AB
VM (db)	HAG > WWB > HAB > HAS > HAR > CB > AB
FC (db)	HAR > HAB > WWB > HAS > HAG > AB > CB

A (db)	AB > CB > HAS > HAB > HAR > HAG > WWB
C (daf)	AB > CB > WWB > HAR > HAB > HAS > HAG
O (daf)	HAG > HAS > HAB > HAR > WWB > CB > AB
H (daf)	AB > CB > HAR > (WWB, HAB) > (HAG, HAS)
N (daf)	AB > CB > HAR > (WWB, HAB) > HAG > WWB
S (daf)	AB > CB > HAR > (WWB, HAB) > HAG > WWB
Cl (db)	AB > HAS > CB > HAG > HAB > HAR > WWB

Table 3. Mean chemical composition of biomass group made up of 86 varieties of biomass based on proximate and ultimate analysis (Vassilev et al, 2010).

Biomass group	Proximate analysis (am)				Proximate analysis (db)			Ultimate analysis (daf)				
	VM	FC	M	A	VM	FC	A	C	O	H	N	S
Wood and woody biomass (WWB)	62.9	15.1	19.3	2.7	78.0	18.5	3.5	52.1	41.2	6.2	0.4	0.08
Herbaceous and agricultural biomass (HAB)	66.0	16.9	12.0	5.1	75.2	19.1	5.7	49.9	42.6	6.2	1.2	0.15
Grasses (HAB)	69.0	14.1	12.6	4.3	79.0	16.2	4.8	49.2	43.7	6.1	0.9	0.13
Straws (HAS)	66.7	15.3	10.2	7.8	74.3	17.1	8.6	49.4	43.2	6.1	1.2	0.15

Other residues (HAR)	64.6	18.6	12.4	4.4	74.0	21.0	5.0	50.2	41.9	6.3	1.4	0.16
Animal biomass (AB)	52.5	12.8	5.9	28.8	55.5	13.6	30.9	58.9	23.1	7.4	9.2	1.45
Mixture of biomass	61.8	14.2	17.3	6.7	75.1	17.2	7.7	52.9	39.6	6.2	1.0	0.28
Contaminated biomass (CB)	63.7	8.0	11.6	16.7	72.0	9.4	18.6	53.6	37.0	7.3	1.7	0.46

The table 2.3 above presents the mean values of the proximate and ultimate analysis of 86 biomass varieties/types categorized under 8 biomass groups. For the complete table which includes the individual biomass variety/type and corresponding chemical composition analysis, please refer to the journal Vassilev et al, (2010).

2.4. Conversion methods of Biomass

Conversion of biomass simply entails the transformation of biomass into desired/useful products in solid, liquid and/or gaseous forms. Kucuk et al, 1997, in their research on biomass conversion processes considered three main procedures for the conversion of biomass to useful/desired products namely; thermochemical, chemical and biochemical procedures.

2.4.1. Thermochemical conversion of Biomass

Thermal conversion simply entails a conversion in which heat is used either with or without the presence of oxygen in other to convert biomass materials or feedstocks into other forms of energy. Thermochemical conversion processes take advantage of the relationship between heat and chemical action to extract and create products and energy.

The figure 2.2 below depicts the branches/types of thermochemical conversion process.

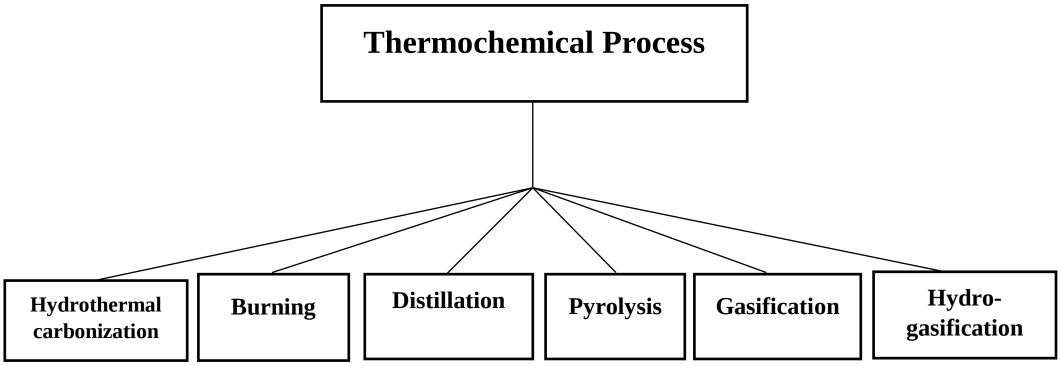


Figure 4. Thermochemical biomass conversion processes.

2.4.1.1. Hydrothermal carbonization

Jain et al, 2016, defined hydrothermal carbonization as a thermochemical conversion technique which uses subcritical water for the conversion of wet/dry biomass to carbonaceous products through fractionation of the feedstock. It can be achieved by applying high temperatures (180 – 220^0C) to biomass suspension with water under saturated pressure for several hours (Funke et al, 2010). In other research, a temperature range of 150 – 350^0C was reckoned for the process which is dependent on the type of biomass and its decomposition temperature (Jain et al, 2016). The products of this process include; Gas, liquid and solid products.

2.4.1.2. Direct combustion of solid biomass

Direct combustion of solid biomass is a thermochemical process that entails burning of solid biomass to generate energy or heat. A general combustion rule for complete combustion stipulates the requirement for the three T's. High enough temperature, strong turbulence of the air-gas mixture, and a long residence time of the mixture in the fire chamber (Kucuk et al, 1997). For example, wood biomass combusts to form carbon dioxide and water vapor. The chemical equation is presented below;

$$C_{42}H_{60}O_{28} + 43O_2 \rightarrow 42CO_2 + 30H_2O$$

2.4.1.3. Biomass pyrolysis

Biomass pyrolysis is a thermochemical process that encompasses the thermal decomposition of biomass in the absence of oxygen. At 350 – 550^{0}C the thermal decomposition of the organic components in biomass begins and goes up to 700 – 800^{0}C without oxygen/air. Biomass pyrolysis products include biochar, bio-oil and gases such as CH_4, H_2, CO, CO_2. (Zafar, 2018).

A gradual degradation, decomposition and charring on heating at lower temperatures and a speedy volatilization in conjunction with the formation of levoglucosan at higher temperatures are the two types of reaction making up the thermal degradation of cellulose. These reactions are influenced by the temperature and period of heating, the ambient atmosphere, and the composition and physical nature of the substrate (Kucuk et al, 1997).

2.4.1.4. Biomass distillation

Destructive distillation of biomass is a subset of pyrolysis process just like torrification, torrefaction, slow pyrolysis, airless drying and fast pyrolysis.

2.4.1.5. Biomass gasification

Gasification is a thermochemical process by which gas is produced from organic matter through thermal decomposition in the absence of air/oxygen and secondary reaction of the resulting volatiles from the first reaction. Alongside the produced gas are char and tar which are combustible (Kucuk et al, 1997).

2.4.1.6. Hydro-gasification

According to Kucuk et al, 1997 in their research on ‘biomass conversion processes’, hydro-gasification thermochemical conversion process aims at maximizing liquid yields. Normally, a slurry made up of biomass or wood is injected into a high-pressure reactor, using a synthetic oil or water carrier. The reaction pressure and temperature vary respectively from 5 to 28MPa and 623 to 693K. Sodium carbonate or nickel carbonate catalysts are used in some cases.

2.4.2. Chemical conversion process

Chemical conversion of biomass involves mainly acid degradation which results in pentoses, hexoses and lignin-processing. Many researches in the past have used different/several hydrolyzing agents such as dilute and concentrated hydrochloric acid and anhydrous HCl gas (Kucuk et al, 1997). Lignocellulosic biomass is made up of three primary chemical fractions: hemicellulose which is chiefly pentose containing sugar polymer, cellulose which is a polymer of glucose and lignin, a complex polyphenol.

Cellulose → Glucose → Degradation products.

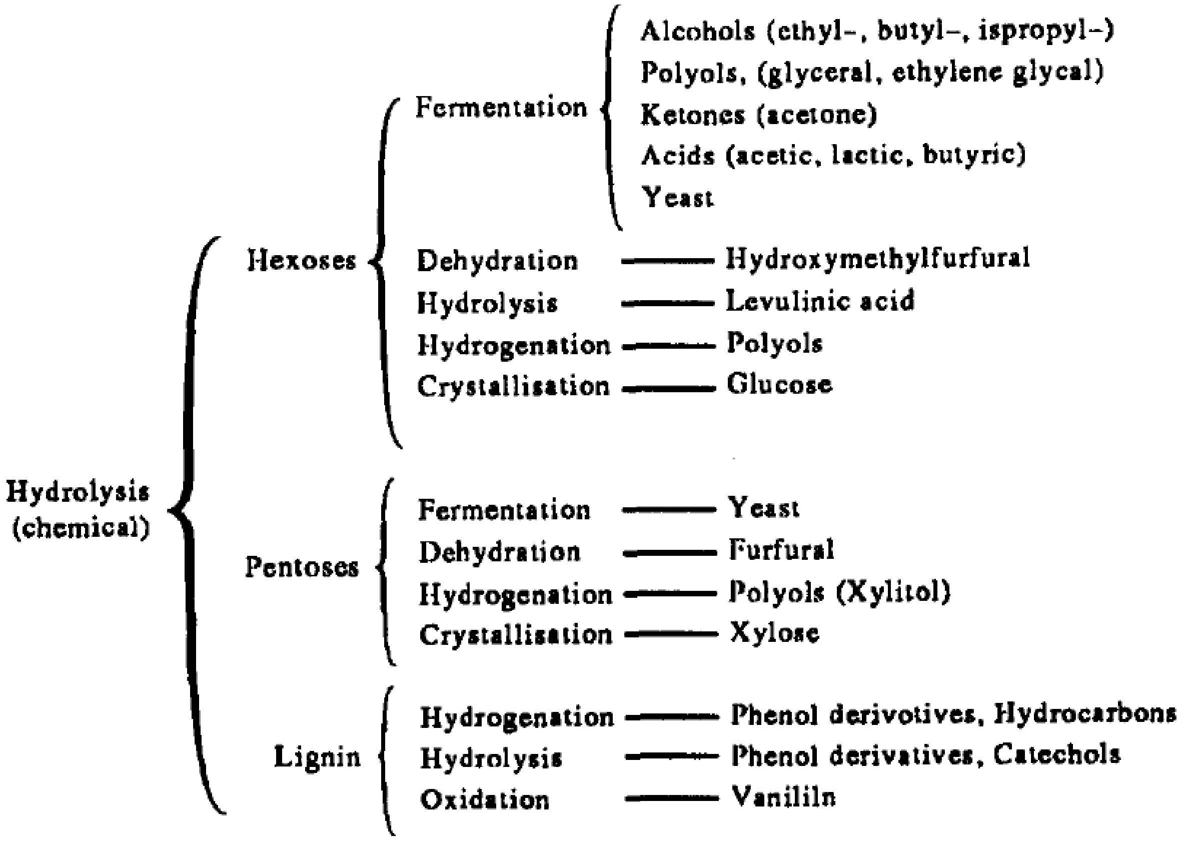


Figure 5. Chemical conversion processes for Biomass (Kucuk et al, 1997).

2.4.3. Biochemical conversion process

Biochemical conversion entails the use of microorganisms to convert biomass to gas (CO_2/CH_4), waste (compost or fertilizer) and water (or C_2H_5OH). Biochemical processes include:

- Aerobic fermentation for producing compost, carbon dioxide and water.
- Anaerobic fermentation for producing fertilizer and gas (methane or carbon dioxide).
- Alcoholic fermentation for producing ethanol (C_2H_5OH), carbon dioxide and waste (Kucuk et al, 1997).

2.5.0. Hydrothermal Carbonization of Biomass

HTC process in its entirety is a sustainable and eco-friendly process (Fig 2.5 displays the sustainable view of HTC process, its products and applications). HTC as a thermochemical process converts different groups/types of biomass into high carbon content solid fuels that burns smokeless (Chembukulam et al, 1981). HTC was first introduced by Bergius in the year 1913. In its wholeness, HTC process mimics natural coalification (Funke et al, 2010). Xiao et al (2012) studied the HTC of biomass in the presence of water under high temperatures (180 – 250^{0}C) and pressure (2 – 10MPa). The alluring nature of HTC process is attributed to its ability to convert wet biomass into different useful products without the hassle of pre-drying.

From a wide range of literature reviews on HTC of biomass, it is worth stating that there is no common definition of hydrothermal carbonization. Funke et al, 2010 outlined a range of operational conditions that collectively defines hydrothermal carbonization:

- Due to physical and chemical reasons, HTC operation should be confined to subcritical conditions of water (Siskin & Katritzky, 1991).
- First reactions are observed at temperature range above 100^{0}C, and as such the process temperature must be above 100^{0}C. According to Bobleter 1994, at a temperature of about 180^{0}C, substantial hydrolysis starts.
- At least saturated pressure is mandatory for there to exist a liquid water phase (Hengel & Macko, 1993).
- The feed needs to be submerged during the entire process (Hengel & Macko, 1993).

- As alkaline conditions result in a significantly different product, the pH value of the process solution should be below 7 (Khemchandani et al, 1994). Although the acidic nature of the HTC process by-products automatically drops the pH value of the mixture.
- By virtue of unknown reaction rates in HTC processes, the residence time cannot be appropriately and accurately defined. But from published research articles residence times varied between 1 and 72hours.

HTC process occurs in the subcritical region of water. During temperature increase above 200^0C but below 374^0C water may be seen as an acid or a base due to heightened dissociation of its molecules into acidic hydronium ions (H_3O^+) and basic hydroxide ion (OH^-) and as such subcritical water can afford the luxury of being an excellent medium/solvent for the acid catalyzed reaction of organic compounds without added acid (Savage, 1999 ; Marcus, 1999). Wang et al (2018) in their research on ‘A review of the hydrothermal carbonization of biomass waste for hydro-char formation: Process conditions, fundamentals, and physicochemical properties’, established the fact that HTC process is not restricted to lignocellulosic biomass but can also be performed with other feedstocks such as animal manures, food wastes, municipal solid wastes, sewage sludge, aquaculture and algal residue etc. The distribution and properties of the solid (hydro-char), liquid (bio-oil plus water) and gas (majorly CO_2) products of HTC of biomass is highly influenced by the feedstock (biomass) and operating/process conditions. As a consequence of the hydrophobic and homogeneous nature of the HTC process desired product, hydro-char, its separation from the entire product suspension is easily achieved (Hoekman et al, 2012). In other to comprehensively under the big picture underlying the chemical and physical properties and the possible applications of hydro-char, it is but imperative to understand HTC process parameters and the hydro-char formation reaction mechanisms.

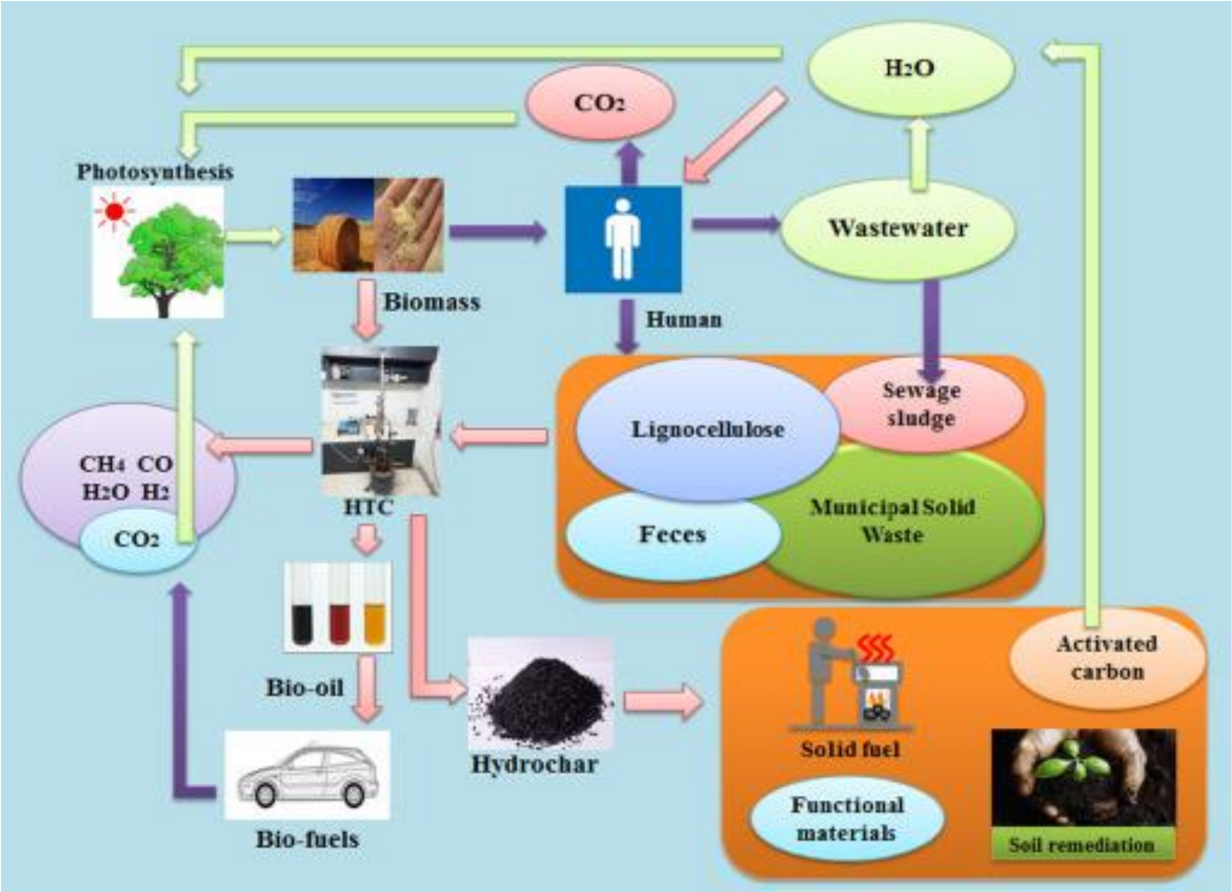


Figure 6. HTC process, its products and applications from the perspective of sustainability (Wang et al, 2018).

2.5.1. HTC process reaction mechanisms

From the literature review of renowned research papers on HTC process, many reaction mechanisms were mentioned, but detailed analysis have only been reflected on a few and they are; hydrolysis, dehydration, decarboxylation, condensation, polymerization and aromatization reaction mechanisms.

- **Hydrolysis:** hydrolysis can be defined basically as a chemical reaction in which water is used to break down the bonds of a substance. With respect to HTC process, hydrolysis is the addition of a mole of water to effect the cleavage of mainly ester and ether bonds of the biomacromolecules (Funke et al, 2010). Above approximately 200^0C, cellulose hydrolyzes significantly under HTC conditions (Peterson et al, 2008). At around 180^0C, hemicellulose readily hydrolyzes with thorough reaction pathways less understood (Funke et al, 2010). At around 200^0C lignin is most probably hydrothermally degraded due to the magnitude of ether bonds present. Product range which includes oligo-saccharides of cellulose and phenolic fragments of lignin are realized via hydrolysis reaction mechanism (Funke et al, 2010).

- **Dehydration:** A dehydration reaction is basically a type of condensation reaction between two compounds where one of the products is water. In HTC process dehydration incorporates both chemical reactions and physical processes. The physical process also referred to as dewatering, deals with the removal of water without any effecting any chemical changes in the reacting substances while the chemical aspect of dehydration involves biomass carbonization by lowering the H/C and O/C ratios (Funke et al, 2010). The elimination of hydroxyl groups generally explains dehydration (Behar & Hatcher, 1995).
- **Decarboxylation:** A carboxyl group is simply a carbon atom double-bonded to an oxygen atom. Decarboxylation reaction on the other hand involves the removal of a carboxyl group from a molecule. Above 150^0C in HTC processes, carboxyl and carbonyl groups degrade rapidly to yield CO_2 and CO respectively (Murray & Evans, 1972).
- **Polymerization:** When relatively small molecules referred to as monomers chemically combine to produce a very large network molecule (polymer), the chemical reaction involved is called polymerization reaction. In HTC processes the elimination of carboxyl and hydroxyl groups creates the unsaturated compounds that polymerize easily (Terres, 1952). Kabyemela et al. (1999), in their research on ‘glucose and fructose decomposition in subcritical and supercritical water: detailed reaction pathway, mechanisms, and kinetics’, concluded that condensation polymerization mainly characterized the formation of HTC-coal during hydrothermal carbonization.
- **Aromatization:** Aromatization can simply be defined as the conversion of non-aromatic hydrocarbons to aromatic hydrocarbons. Aromatic hydrocarbons on the other hand are hydrocarbons that contains one or more benzene rings. The formation of aromatic structures has been found to be favored by alkaline conditions (Nelson et al, 1984) and temperature or reaction severity (Sugimoto et al, 1997). Under hydrothermal conditions aromatic structures exhibits high stability.

2.5.2. HTC process parameter influence

Process parameters generally refers to the apparent measured value of a specific part of a process which is been investigated, monitored or controlled. In the context of this research or process (hydrothermal carbonization process), it refers to the observed changes within the HTC system as a consequence of changes in the magnitude of quantities such as temperature, pressure, reaction/holding time, biomass to water ratio, biomass particle size, process water recycling etc. With respect to waste water sewage sludge as the biomass been considered, this research takes only a few quantities into account due to the magnitude of their influence over the HTC process result or yield. These quantities or process parameters are:

- **Temperature**: the influence of temperature over hydrothermal carbonization process is overwhelming. Temperature parameter determines the degradation reactions. Low temperatures favor ionic reaction while high temperatures favor homolytic bond cleavage. High temperature leads to higher yields of gases and a wide range of products (Moller, 2011). Ying et al, (2012) also discovered that the solid product of cellulose decreased due to improved decomposition by the fragmentation of large molecules into components (such as liquids and incondensable low molecular gas) as the operating temperature was increased above 200 ^{0}C. Liu et at, (2012) & Sun et al, (2010) from their research result demonstrated that at temperatures below 200 ^{0}C, the rates of solid products were very high. Also, as the temperature increase from a range of 200 – 250 ^{0}C to temperatures > 280 ^{0}C the solid products decreased.

  Jain et al, (2016) in their research on ‘HTC of biomass to AC with high porosity’ established the fact that the quantity and significant presence of OFGs (oxygenated functional groups) is paramount with respect to processing biomass for the single purpose of producing activated carbon with considerable porosity. From their research it was understood that the OFG of biomass being processed via HTC increased as the operating temperature increased until a certain temperature was attained after which a decrease in OFG was recorded.

  In summary, the choice of opting for an operating temperature is dependent on the knowledge of the composition of the biomass under consideration, as different biomass tends to behave differently under different temperature condition. In general, carbonization at lower temperatures produces higher amount of solid. At higher temperatures liquid and gaseous carbonization products are enormously favored at the expense of solid products.

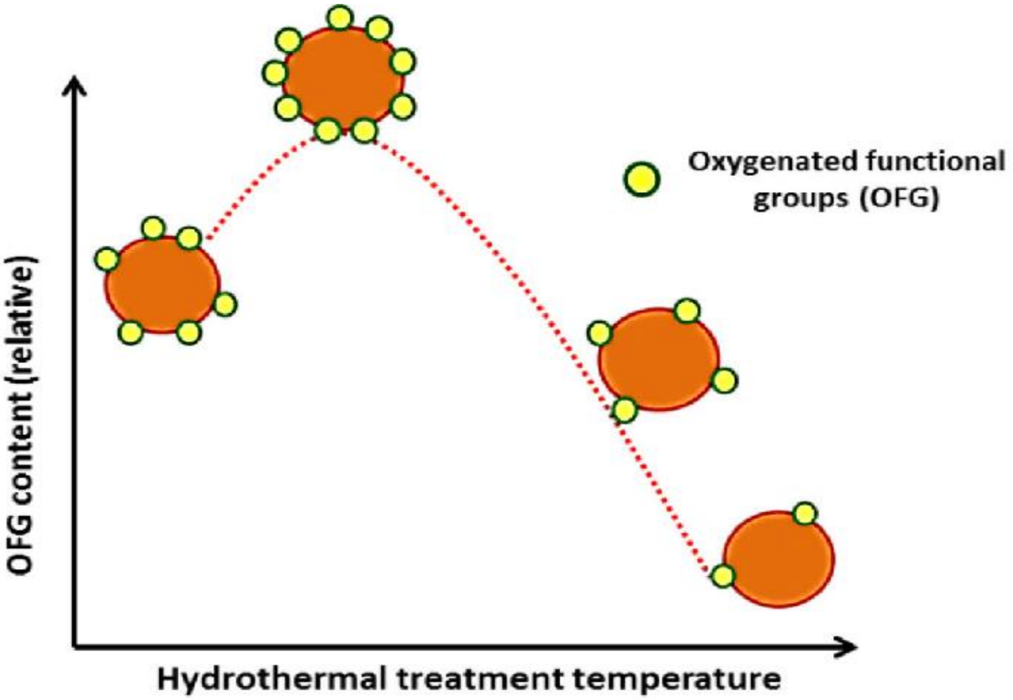


Figure 7. Changes in OFG content with respect to changes in HTC operating temperature (Jain et al, 2016).

- **Reaction/holding time:** reaction time in hydrothermal carbonization of biomass refers to the time duration of the mixture or suspension of biomass with water or under supercritical conditions in a hydrothermal carbonization reactor operated at a choice temperature. Reaction time just like temperature plays an important role in HTC process in determining the extent of reaction and the distribution of different type and quality of products.

He et al, (2013), from their research result, discovered that as reaction time increased from 4 h to 12 h, the OFG content of the sewage sludge been carbonized decreased from 5.09 to 4.21 mmol/g. The research also reckoned a peak value for OFG after which steady decline was observed. This curvilinear variation in the OFG content of sewage sludge biomass was attributed to either excessive dehydration/carbonization and formation of stable oxygen surface groups.

Jain et al, (2016) from their study, concluded that as reaction time increased the greater the formation of high BET surface area, porosity and pore volume. But in general, higher reaction time to an extent favors the stability of the HTC solid products and invariably the formation of more gaseous and liquid products.

2.5.3. HTC product composition

The different reaction mechanisms taking place in the HTC of biomass process is held responsible for the variety of products formed during the process. The distribution of these products depends on both the biomass type/composition and HTC operating conditions. In this section, the products of HTC process were presented according to their state of aggregation which are;

- **Solid product:** the solid product is called ***hydro-char*** and it is the main product of HTC which retains most of the carbon contents of the initial feed. Proximate and ultimate analysis, HHV, mass and energy density, hydrophobicity, BET surface area etc. are some of the ways almost all studies on HTC process characterize the HTC solid product (hydro-char) (Kambo et al, 2014).
- **Liquid product:** many studies show that the liquid product of HTC process comprises of H_2O, high loads of inorganics and organics (sugars and their derivatives, organic acids, furanoid and phenolic compounds) many of which represent potentially valuable chemicals and unless they are been recovered, they are considered to be major losses. The quantity of produced H_2O in comparison with CO_2 produce is significantly higher.
- **Gaseous product:** as it has been well established in the previous section of this chapter (literature review), higher temperature favors the precipitation of more gaseous products at the expense of the solid product (hydro-char). Gaseous products comprise of compounds such as CO_2, CO, CH_4, and H_2 in which 70 – 90% of their total concentration is maintained by CO_2 (Ramke et al, 2009). The below figure expresses comprehensively the HTC process products with respect to their state of agglomeration.

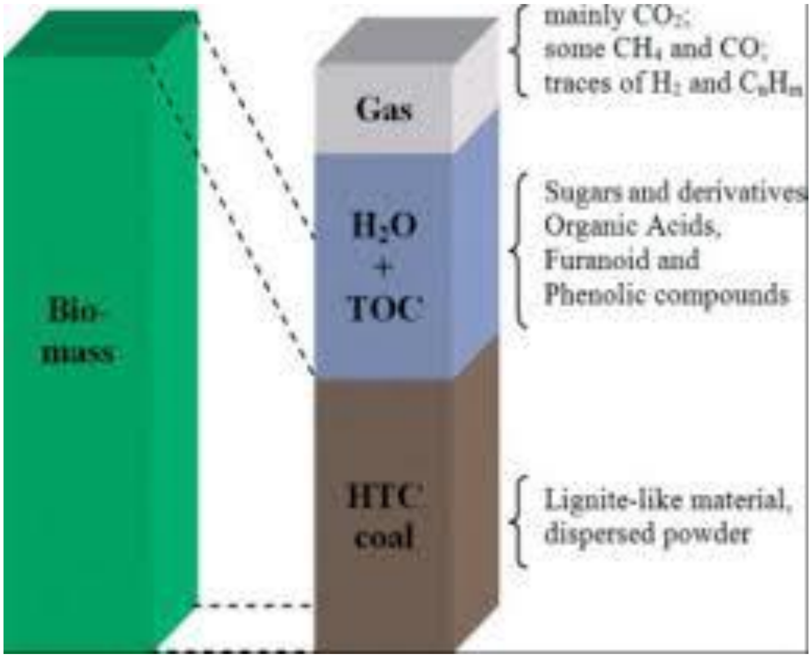


Figure 8. HTC process products according to their agglomeration state (Funke et al, 2009).

2.6.0. Carbon activation

Carbon activation in the simplest form of definition refers to the process of activating carbonaceous materials or production of activated carbon. Activated carbon on the other hand is a form of carbon that has been processed to make it extremely porous and thus to have a very large surface area available for adsorption and chemical reaction (New World Encyclopedia, 2018).

Sewage treatment, gas purification, water purification, metal extraction etc. are some of the applications of activated carbons. Their absorption ability which is an exothermic process by which a gas, liquid or solute binds to the surface of a solid or liquid, called adsorbent, forming a film of molecules or atoms called the adsorbate affords them the luxury of those previously mentioned applications.

2.6.1. Production of activated carbon

There are two methods of activating carbonaceous materials. The methods are physical and chemical activation.

- **Physical Activation:** this method is the most widely used method or process because it is generally used to activate both coconut shell and coal-based carbons. Basically, this method comprises of two distinct stages which are the carbonization stage and the activation or oxidation stage.
  - **(1) Carbonization:** at this stage the feed or biomass is treated through a thermochemical process (hydrothermal carbonization, pyrolysis etc.) operated at appropriate conditions (pyrolysis temperature range of 600 – 900^{0}C or hydrothermal carbonization temperature range of 180 – 350^{0}C which may vary based on the biomass composition) in an inert atmosphere for the purpose of reducing the volatile content of the source material. At the end of this process a coal-like product is formed which possesses pores that are either too restricted or small to be used as an adsorbent.
  - **(2) Activation:** in this stage the carbonized material from the first stage is activated with either carbon dioxide, steam or oxygen by exposure in an inert atmosphere usually in the operating temperature range of 600 – 1200 ^{0}C. The purpose of this stage is to increase or enlarge the pore structure of the carbonized material, increase its internal surface to enhance its absorption properties (Haycarb, 2017 & New World Encyclopedia, 2018).

- **Chemical Activation:** this method of activation is carried out by mixing or impregnating the feed or biomass with acids (hydrochloric acid, phosphoric acid etc.), bases (sodium hydroxide, potassium hydroxide etc.) or salts (zinc chloride, potassium chloride etc.) followed by carbonization operated at a temperature range of 450 – 900 ^{0}C.

2.7.0. Project management cost estimation

The life span of any project is hinged on its budget. The integration of pertinent/requisite project features such as materials and labor, technically defines a project. A project’s materials and labor essentially come at cost (monetary).

Smartsheet, (2019), defines cost estimating as the practice of forecasting the cost of completing a project with a defined scope. Cost estimation has been considered as a basic element of project cost management, which in turn is a knowledge area that involves the planning, monitoring and controlling of a project’s monetary costs. When or if a project’s budget is authorized, its costs is managed by the use or application of cost estimate (Smartsheet, 2019).

Cost estimation accounts for each component required for a project from a monetary perspective. Should a project’s cost estimation come quite high, pruning the project to fit resources becomes inevitable depending on the gravity of the project. Once in motion, a project’s affiliated costs are managed by the project’s cost estimate in order to ensure that the project’s budget encompasses it (Wrike, 2018). Cost estimates are usually revised and updated as the project’s risks are known and as the project becomes more precise.

2.7.1. Components of a project’s cost estimate

Throughout a project’s lifecycle, the cost estimate sums up all costs required to achieve success (equation 1). Cost estimation process addresses two key types of costs, direct and indirect costs.

- Direct costs: those cost directly linked to a single project or department or area or product are referred to as direct costs. Example includes; materials, equipment, fixed labor etc.
- Indirect costs: this cost incorporates or embodies costs incurred by an organization at large. Unlike direct costs, it does not respond to any specific project, but it responds to all projects been handled by an organization both simultaneously and consecutively. Examples include; utilities, quality control, security costs etc.

Considering the two types or categories of cost estimate, more specific categories can be extracted. These are:

- Labor: the human resource cost in terms of wages and time with respect to expended energy and time.
- Materials: the cost of a project’s resources required to yield a product.
- Equipment and facilities: the cost of needed equipment, services and location, which integrates renting, buying and maintenance costs.
- Services: the cost of engaging third-party contractors or vendors.
- Contingency or risk costs: a project’s cost added to respond to unplanned events (Smartsheet, 2019 & Wrike, 2018).

Project Cost Estimate = Direct + Indirect Costs (1)

2.7.2. Asset depreciation

Depreciation is defined with respect to accounting, as the reduction of the recorded cost of a fixed asset in a systematic manner until the assets value becomes negligible. Fixed assets examples include; buildings, furniture, office equipment, machinery etc. (Harshal, 2018).

A portion of the cost of a fixed asset is allocated to the revenue generated by the fixed asset through depreciation. In the accounting period of a project, according to the matching principle, it is mandatory to record revenues with their associated expenses (Harshal 2018).

2.7.3. Calculations in depreciation

The methods commonly used for assets depreciation calculations are;

- **Straight line method**: in this method, an even rate of asset depreciation is allocated over the useful life of the asset. The formula is expressed below (equation 2).

  Annual Depreciation expense = (Asset cost – Residual Value) / useful life of the asset (2)

- **Unit of production method**: this made consists of two steps in which equal expense rates are assigned to each unit produced. Equations 3 & 4 below expresses them.

  Per unit Depreciation = (Asset cost – Residual value) / Useful life in units of production (3)
  Total Depreciation = Per unit Depreciation * Units Produced (4)

- **Double declining method:** this method is an accelerated depreciation method that counts expenses twice as much as the book value of the asset every year. The formulas are presented below (equations 5 & 6);

Depreciation = 2 * Straight line depreciation percent * Book value at the beginning of the accounting period (5)

Book value = Cost of the asset – Accumulated Depreciation (6)

2.7.4. Sensitivity analysis

Sensitivity analysis or what – if analysis can simply be defined as a financial modeling tool that is used to analyze variations in dependent variables due to changes in independent variables. For example, how changes in selling price will affect product quality. EduPristine, (2018), defined sensitivity analysis as a technique used to determine how independent variable values will impact a dependent variable under a given set of assumptions. Sensitivity analysis can be done either manually or with a software like excel.

2.7.4.1. Germane features of sensitivity analysis

- Experimental Design: it entails the parameters to be varied. Integrated in the experimental design are number and type of parameter that needs to be varied at any given point in time, value assigning etc.
- What to vary: Parameters such as; the number of activities, the objective in relation to the risk assumed and the profits expected, technical parameters and the number of constraints and its limits could be chosen to vary in the model.
- What to observe: quantities to be observed during sensitivity analysis include; the value of the decision variables, the value of the objective with respect to the strategy and the value of the objective function between two strategies adopted.

2.7.4.2 How to carryout sensitivity analysis

- The first step is to define the base case output B1
- Next step is to calculate the output value at a new input value of B2 while keeping other inputs constant
- Third step is to find the percentage change in the output and input.

- The fourth step entails calculating the sensitivity by dividing the percentage change in output by the percentage change in input.
- In the fifth stage and subsequent stages, a repetition of the process with another input variable while the other input variables are kept constant is repeated until the sensitivity figure for all or each of the input variables is obtained.

2.7.4.3. Importance or applications of sensitivity analysis

It helps in;

- making decisions
- indicating the sensitivity of simulation to uncertainties in the input values of a model
- predicting outcome of a decision
- assessing the riskiness of a strategy
- identifying the influence of independent variables over dependent variables
- making informed and appropriate decisions.

2.7.4.4. Annualize rate of return

Annualized rate of return is the equivalent annual return an investor receives over the time period the investment was held. While regular rate of return describes the gain or loss, expressed in a percentage of an investment over an arbitrary time period, the annualized rate of return also known as the ***compound annual growth rate*** is the return of an investment over each year. The formula for hand calculation is given below (equation 7 or 8);

Annualized Rate of Return = [Ending value of Investment / Beginning Value of Investment**]** $^{\mathbf{1/yrs.}}$ – 1 (7)

OR

AROR = [(Estimated profit / Production cost)$^{1/\text{no of years}}$] – 1 (8)

2.8.0. Linear regression analysis

Linear regression generally entails predictive analysis with the purpose of investigating the validity or the extent of accuracy with which a predictor or input variable predicts an outcome or a dependent variable, the purpose of determining the level of significance several independent variables have over a dependent or predictor variable and the purpose of forecasting an effect (Statistical-solutions, 2013).

According to Johnson, (2018), the main objective of many statistical investigations is to make predictions preferably on the basis of mathematical equations. In utilizing linear regression tool, the first step is to determine the level or degree of linearity or whether or not there exist a linear relationship among dependent and independent variables. In his book, Johnson, (2018), mentioned the application of a scatter plot for the determination of linearity. Software for carrying out regression analysis include SPSS, Excel, Stata, JMP etc.

The simplest form of a regression equation with one dependent and one independent variable is defined by the below formula (equation 9)

$$y = c + b*x \quad (9)$$

Where y = the estimated dependent variable

c = constant or intercept

b = regression coefficient

x = the independent variable

2.8.1. Types of linear regression analysis

- **Simple Linear Regression**: carried out between one interval or ratio dependent variable and one interval or ratio or dichotomous independent variable.
- **Multiple Linear Regression**: carried out among one interval or ratio dependent variable and two or more interval or ratio or dichotomous independent variables.

- **Logistic Regression**: carried out among one dichotomous dependent variable and two or more independent ratio or interval or dichotomous variables.
- **Ordinal Regression**: carried out between one dependent ordinal variable and one independent nominal or dichotomous variable.
- **Multinominal Regression**: carried out between one dependent nominal variable and one independent interval or ratio or dichotomous variable (Statistics-solution, 2013).

2.8.2. Validity of regression models

The applicability or validity of a regression model generated by any regression software such as Excel, SPSS etc. is determined by the magnitude or value and the interpretation of the regression analysis software features such as the *Multiple R, R squared (for simple linear regression), Adjusted R-squared (for multiple linear regression), Standard Error, and F significance.*

3. METHODOLOGY

This research based its methodology on a qualitative and quantitative analysis of two secondary data. The first data was gotten from the research conducted by Zhao et al, (2014) on the carbonization of waste water sewage sludge while the second was gotten from Rio et al, (2006) on the carbon activation of sewage sludge.

3.1. Quantitative analysis

For the technical aspect of this research the quantitative methodology responded to the ***'how much or amount or magnitude'*** of the desired products (hydro-char and subsequently activated carbon) that were produced by ***'how much or amount or magnitude'*** of energy and feed (sewage sludge + H_2O) through the application of the choice amount of the operating or process parameters (operating temperature and holding or reaction time for both the carbonization stage and the activation stage) opted for from the result or conclusion of the ***qualitative analysis*** of this research while, the economic aspect was quantitatively analyzed via a cost estimation of the processes (energy and equipment cost of the carbonization and activation processes) in their entirety on a daily, yearly and 100 kg production of activated carbon basis within the boundaries or scope of this research. For the sake of lucidity, the subsequent paragraph of this section will present the quantitative methodology details in a succinct manner.

For the technical aspect of this research***, correlation, scatter plot and regression analysis tool*** from ***excel software*** were used to conduct appropriate analysis on the secondary data in other to respond to the ***energy and material balance objectives*** of the carbonization stage of this research while direct measurements and conversion through ***thermochemical calculations*** were applied for the activation stage. For the carbonization stage, the quantitative analysis was broken down into four sub-stages (HTC reactor, mechanical dewatering, thermal drying and a combination of the three sub-stages). For the first analysis which is the combination sub-stage, the input or dependent variables were the operating temperature and holding or reaction time while the response or independent variable was the produced hydro-char yield % (ratio of the mass of the mass of hydro-char produced to the combined mass of H_2O + sewage sludge multiplied by 100). The excel statistics software tools mentioned initially were appropriately applied to explain the relationship (***qualitative***) between the input variables and the response variable and to model a mathematical equation for estimating the amount (***quantitative***) of desired or response variable (in this case hydro-char yield %) corresponding to the carbonization choice operating temperature and holding or reaction time (210 ^{0}C & 30 mins). For the other three carbonization sub-stages, this process was repeated with just changes in the response variable. For the HTC reactor, mechanical dewatering, and the thermal drying sub-stages, the response variables were reactor yield %, mechanically dewatered residuals % and thermally evaporated liquids % respectively. The energy balance was also a replica of the material balance analysis process with changes only made to the response variables for each of the four sub-stages.

For the energy balance, different data for the response variables were used. These data were based on the energy input or requirements of the four sub-stages (HTC reactor, mechanical dewatering, thermal drying and a combination of the three sub-stages) under consideration. The applicability and validity of the results from the excel software for both energy and material/mass balance of the carbonization process were first established before application.

For the carbon activation stage, data such as the percentage conversion of the hydro-char to activated carbon, the steam flow rate, the operating temperature and holding or activation time were applied directly. Thermochemical formulas were used to calculate the total energy required for the activation stage.

3.2. Qualitative analysis

The quantitative analysis of this research responded to the ***why*** and ***how*** questions related to the influence of the independent variables or process or operating parameters such as temperature and holding time on the nature of the products both for the carbonization and activation stages. The qualitative analysis in its wholeness was majorly reflected in the literature review of this research.

Subsequent sections of this chapter will present the experimental procedures (carbonization and activation process) with which the secondary data was retrieved or gotten.

3.3. Hydrothermal carbonization of sewage sludge

For the sake of clarity and to avoid ambiguity a reiteration of an imperative information stated in the previous sections of this research is that the data analyzed was gotten from the research conducted by Zhao et al, (2014) and Rio et al, (2006), based on reasons that are cogent enough to be inevitable. This part of the research is divided into two parts, the first being the methodology for the hydrothermal carbonization of sewage sludge to produce dry hydro-char while the second part is the carbon activation of the hydrothermally carbonized sewage sludge i.e. the carbon activation of the hydro-char produced from the hydrothermally carbonized sewage sludge. For the first part of the methodology, hydrothermal carbonization of sewage sludge, pertinent information with respect to the materials (reactants or inputs) and equipment are;

- 90 g of dewatered activated sludge with 85.94 ± 0.22 % moisture content gotten from a waste water treatment plant at room temperature and pressure.
- 45 g of ordinary pure water at room temperature and pressure.
- 1.5 m^3 volume of a batch-type HTC reactor with vessels made up of SM400B low-carbon steel. The reactor comprises of a boiler, a control unit, piping and incidental components.
- Forced convective dryer operating at 30.4 ± 0.4 ^{0}C and 1.34 ± 0.04 m/s velocity.
- Filter press mechanical dewatering device operating at 0.6 MPa pressure and 12 min dewatering time.

The hydrothermal carbonization process was initiated by first pre-mixing the sludge with pure water in the ratio 2:1(90 g + 45 g of sludge and water respectively) and then the mixture was poured into a 0.5 L glass tube. The glass tube containing the mixture was put into the reactor that was heated electronically. Subsequently the reactor was sealed and in other to avoid complications due to combustion or any related unwanted reaction(s), argon with a 99.99% purity was injected or supplied into the reactor. The reactor with its load or inputs/reactants were heated by an electronic heat jacket up to the required temperature and then kept constant for the corresponding holding or reaction time. In this research 180 to 240 ^{0}C operating temperature at intervals of 20 ^{0}C and 15 to 45 min holding/reaction at 15 min intervals were applied. As a result of the steady stirring by the reactor mixer which switched direction after every 5 min, the uniformity of the temperature in the HTC reactor was assured. After each reaction run, the heater was switched off, and with a condenser, the residual steam was cooled down. The remaining products in the reactor was giving adequate time to cool down and fall to room temperature and atmospheric pressure. The condensed gases were poured into the HTC reactor products and then the reactor products in its entirety was kept in a bottle for appropriate investigation. In other to reduce experimental error to the barest minimum, each reaction run at its corresponding operating condition was repeated at least three times.

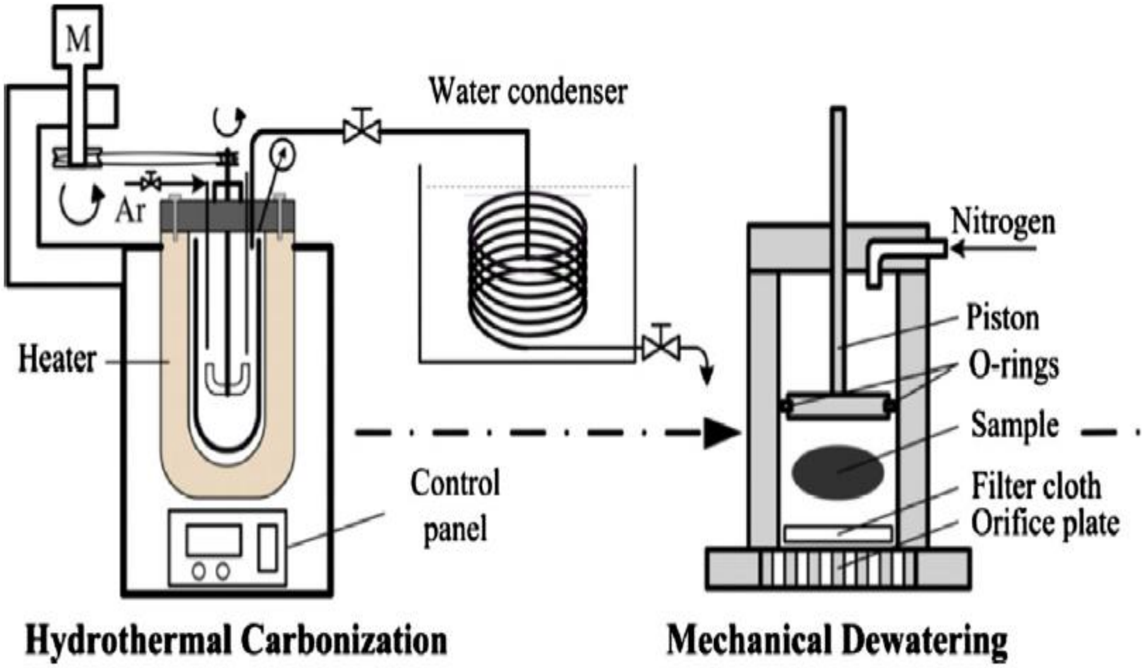


Figure 9. Sewage sludge processing from HTC batch reactor to Mechanical dewatering stage (Zhao et al, 2014).

3.4. Carbon activation of produced hydro-char

Required materials;

- 8 L volume, vertical three heat zone furnace Carbolite TZF 15/610
- Steam flowrate of 2.5 L min^{-1} or 2.5 Kg min^{-1} or 150 Kg hr^{-1}

20 g of the hydro-char produced via hydrothermal carbonization from the first stage of the experiment was placed inside a porous platinum crucible suspended in an alumina tube. Subsequently, steam flowing at the rate of 2.5 Kg/min was injected into the vertical three heat zone furnace carbolite in which the porous platinum crucible suspended in the alumina tube is placed. This experiment was carried out under operating conditions of 750 – 850 ^{0}C for temperature and 30 – 90 min activation time.

Figure 10. Carbolite tube furnace for steam activation (R.E.D, 2000).

3.5. Economic/financial implication(s) of the proposed project (100Kg of activated carbon via hydrothermal carbonization of sewage sludge)

The economic implication of the proposed project encompassed the ***production set-up cost (project cost estimation)***, ***sensitivity analysis and rate of return on investment*** in its entirety. The main reason for this section or research objective is to envisage the economic expediency of the production of activated carbon via hydrothermal carbonization of sewage sludge. These financial calculations are comprehensively based on the experimental results of this research. The research steps or stages include;

- Sewage sludge carbonization at operating conditions of 210 ^{0}C and 30 min holding/reaction time.
- Mechanical dewatering of products from the hydrothermally carbonized sewage sludge (hydro-char + water + trace amount of organic liquids) at operating conditions of 0.6 MPa and 12 min dewatering time.
- Thermal drying of the residual product (moist/wet hydro-char) from the mechanical dewatering device at operating conditions of 30.4 ± 0.4 ^{0}C and 1.34 ± 0.04 m/s for 2 hrs.
- Carbon activation of the hydro-char produced from the hydrothermal carbonization of sewage sludge at operating 760 ^{0}C and 30 min activation time.

3.5. Project cost estimation

In other to satisfactorily achieve the economic objective of this research, project management cost estimation and revenues were evaluated. From literature or generally the project cost estimation encompasses the sum of all direct costs (fixed direct cost such as; labor costs, equipment costs, set-up cost etc. & variable direct costs such as; electricity, water, materials costs etc.) and indirect costs such as; corporate tax, fringe benefit tax, operational cost, office cost, equipment depreciation cost, insurance cost etc. Smartsheet, (2019). For this project, most indirect costs were difficult or impossible to evaluate due to data sufficiency problems and as such, only those with enough data were evaluated. The quantities on which the project cost estimation was based are:

- Equipment costs (HTC reactor, Filter Press Mechanical Dewatering machine, Forced Convective Thermal Dryer and Carbolite Furnace for Activation)
- Equipment Linear Depreciation on a 3 years project life assumption
- Maintenance Cost (usually 1% of cost of equipment)
- Energy cost
- Cost of Steam for Carbon Activation

Pertinent formulas or methods for the evaluation of these quantities were reflected in the literature while the application was presented in chapter 4.

3.5.2. Sensitivity analysis

Sensitivity analysis which can be carried out with either the use of *‘**what if’*** tool in ***excel software*** or ***manually*** based on an estimated yearly profit from sales of activated carbon produced from this project. Assumptions and pertinent information were explicitly stated before the analysis in subsequent chapter. The aim was to understand the implications of variations in the projected financial estimate in other to cushion against negative outcomes as a result of changes in ***selling price*** per unit of A.C produced and A.C ***units of production*** on a one-year basis. ***Unit Price (price/100 kg of produced Activated Carbon)*** and ***units of production*** or ***number of sales*** where chosen as the independent variables while ***operating or estimated profit*** was chosen as the dependent variable. In this research, the sensitivity analysis was conducted manually.

3.5.3. Rate of return on investment

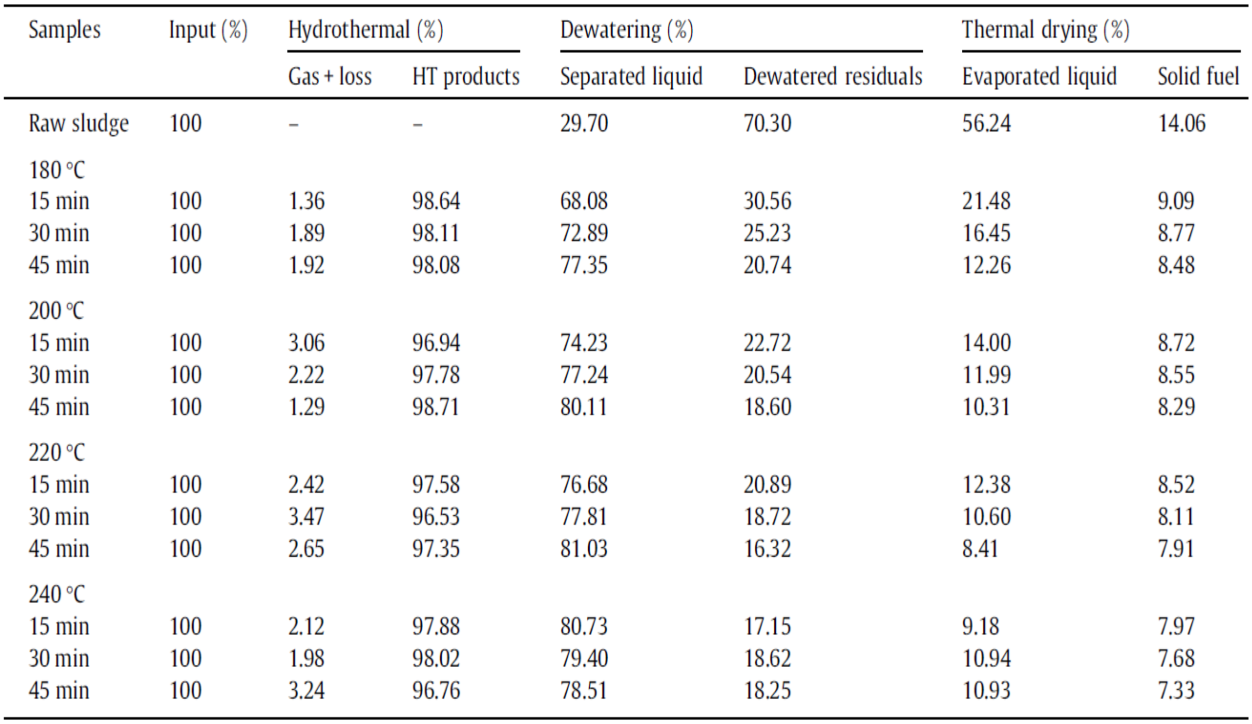
Annualized rate of return on investment for a period of 3 years was evaluated based on the formula below or from literature. The aim is to present a succinct statement on the rate in percentage at which investment dividends is made annually throughout the assumed project lifetime (3 years).

$$\text{Rate of Return} = \left[(\text{Ending value of investment}/\text{Beginning value of investment})^{1/\text{years}} - 1\right] * 100 \quad (9)$$

4. RESULT AND DISCUSSION

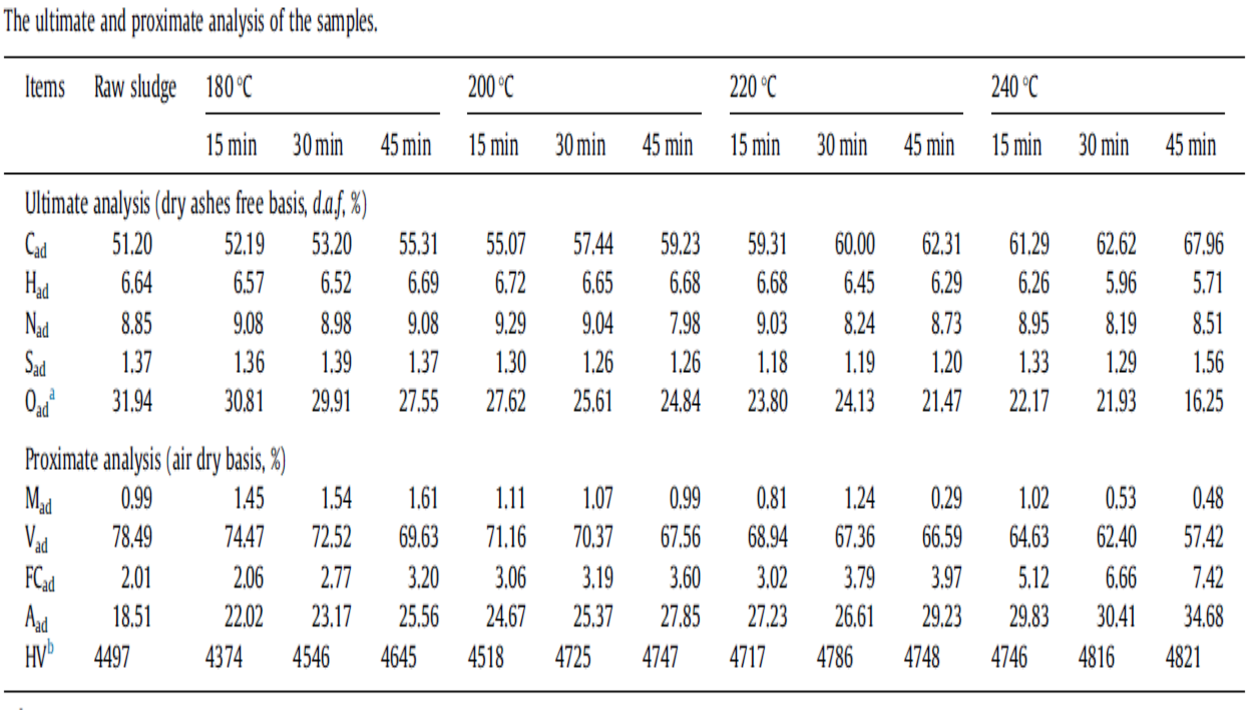
4.1 Material/mass balance of the entire process

For the material/mass balance of the entire process, from the hydrothermal carbonization of sewage sludge to the carbon activation of hydro-char, two secondary data were analyzed. The first data which responds to the hydrothermal carbonization of sewage sludge was gotten from the experiment conducted by Zhao et al (2014) while the second data responding to the carbon activation of hydro-char was gotten from the experiment conducted by Rio et al, (2006). A **38%** conversion of the activated carbon precursor (Hydro-char) to activated carbon was derived experimentally (Rio et al, 2006). Fig 11 & 12 below presents the sewage sludge hydrothermal carbonization experimental data and the chemical properties of the sewage sludge processed, respectively.



Samples	Input (%)	Hydrothermal (%)		Dewatering (%)		Thermal drying (%)	
		Gas + loss	HT products	Separated liquid	Dewatered residuals	Evaporated liquid	Solid fuel
Raw sludge	100	–	–	29.70	70.30	56.24	14.06
180 °C							
15 min	100	1.36	98.64	68.08	30.56	21.48	9.09
30 min	100	1.89	98.11	72.89	25.23	16.45	8.77
45 min	100	1.92	98.08	77.35	20.74	12.26	8.48
200 °C							
15 min	100	3.06	96.94	74.23	22.72	14.00	8.72
30 min	100	2.22	97.78	77.24	20.54	11.99	8.55
45 min	100	1.29	98.71	80.11	18.60	10.31	8.29
220 °C							
15 min	100	2.42	97.58	76.68	20.89	12.38	8.52
30 min	100	3.47	96.53	77.81	18.72	10.60	8.11
45 min	100	2.65	97.35	81.03	16.32	8.41	7.91
240 °C							
15 min	100	2.12	97.88	80.73	17.15	9.18	7.97
30 min	100	1.98	98.02	79.40	18.62	10.94	7.68
45 min	100	3.24	96.76	78.51	18.25	10.93	7.33

Figure 11. Sewage sludge Hydrothermal Carbonization Experimental Data (Zhao et al, 2014).



The ultimate and proximate analysis of the samples.

Items	Raw sludge	180 °C			200 °C			220 °C			240 °C		
		15 min	30 min	45 min	15 min	30 min	45 min	15 min	30 min	45 min	15 min	30 min	45 min
Ultimate analysis (dry ashes free basis, *d.a.f*, %)													
C_{ad}	51.20	52.19	53.20	55.31	55.07	57.44	59.23	59.31	60.00	62.31	61.29	62.62	67.96
H_{ad}	6.64	6.57	6.52	6.69	6.72	6.65	6.68	6.68	6.45	6.29	6.26	5.96	5.71
N_{ad}	8.85	9.08	8.98	9.08	9.29	9.04	7.98	9.03	8.24	8.73	8.95	8.19	8.51
S_{ad}	1.37	1.36	1.39	1.37	1.30	1.26	1.26	1.18	1.19	1.20	1.33	1.29	1.56
O_{ad}^{a}	31.94	30.81	29.91	27.55	27.62	25.61	24.84	23.80	24.13	21.47	22.17	21.93	16.25
Proximate analysis (air dry basis, %)													
M_{ad}	0.99	1.45	1.54	1.61	1.11	1.07	0.99	0.81	1.24	0.29	1.02	0.53	0.48
V_{ad}	78.49	74.47	72.52	69.63	71.16	70.37	67.56	68.94	67.36	66.59	64.63	62.40	57.42
FC_{ad}	2.01	2.06	2.77	3.20	3.06	3.19	3.60	3.02	3.79	3.97	5.12	6.66	7.42
A_{ad}	18.51	22.02	23.17	25.56	24.67	25.37	27.85	27.23	26.61	29.23	29.83	30.41	34.68
HV^{b}	4497	4374	4546	4645	4518	4725	4747	4717	4786	4748	4746	4816	4821

Figure 12. Ultimate and Proximate Analysis of Sewage Sludge (Zhao et al, 2014).

A mathematical model was designed via the use of regression analysis in other to effect calculations on the material balance of this research. In addition to a material balance calculated for the produced hydro-char in yield % (material balance based on the integration of HTC reactor, mechanical dewatering and thermal drying stage), material balance on the individual stages for the purpose of comprehension and professional presentation was also calculated.

After establishing the relationship between the input/independent variables (Temperature & Holding/Reaction Time) and the response/dependent variable (Hydro-char yield), the material balance was first conducted involving only three stages (depicted in the figure below) by appropriate calculations from known to unknown quantities.

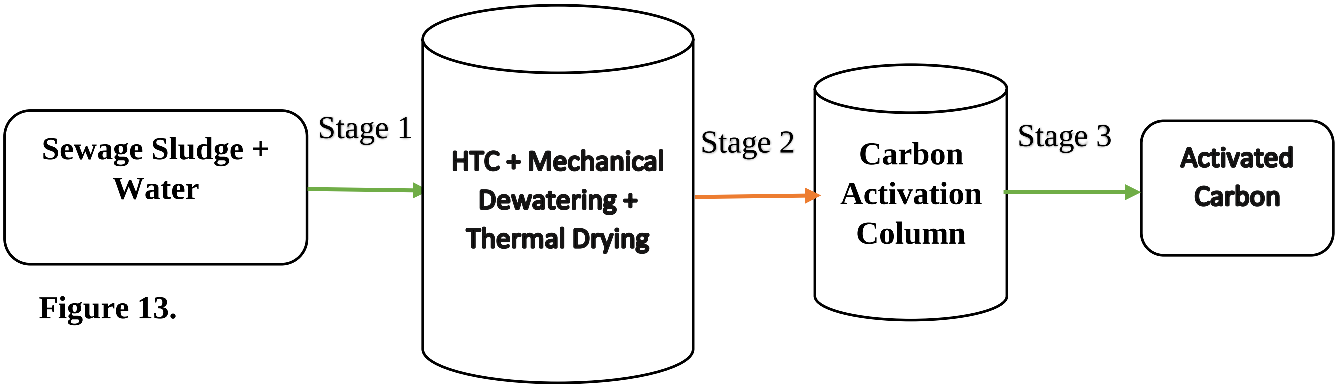


Figure 13.

- **Individual and collective relationship between operating parameters (Temperature and Reaction time) and the desired product (Hydro-char).**

Table 4. Experimental Data of the carbonization operating parameters and product (hydro-char).

Temperature (^{0}C)	Reaction time (Minutes)	Hydro-char Yield (%)
180	15	9.09
180	30	8.77
180	45	8.48
200	15	8.72
200	30	8.55
200	45	8.29
220	15	8.52
220	30	8.11
220	45	7.91
240	15	7.97
240	30	7.68
240	45	7.33

4.1.0. Relationship between hydro-char yield (%) and temperature (^{0}C)

From figure 14 below, the R-squared (or coefficient of determination) value is 0.7375 and this can be translated to mean that ~74% of the proportion of the changes/variance of the response/dependent variable (Hydro-char yield %) is explained by the independent variable (Temperature ^{0}C) while the slope with a magnitude of -0.0185 means that for every 1^{0}C rise in temperature there is a 0.0185% decrease in yield. The correlation coefficient, r, was also calculated to be 0.8587 and is indicative of the fact that there exist a strong linear relationship between the Hydro-char yield and Temperature.

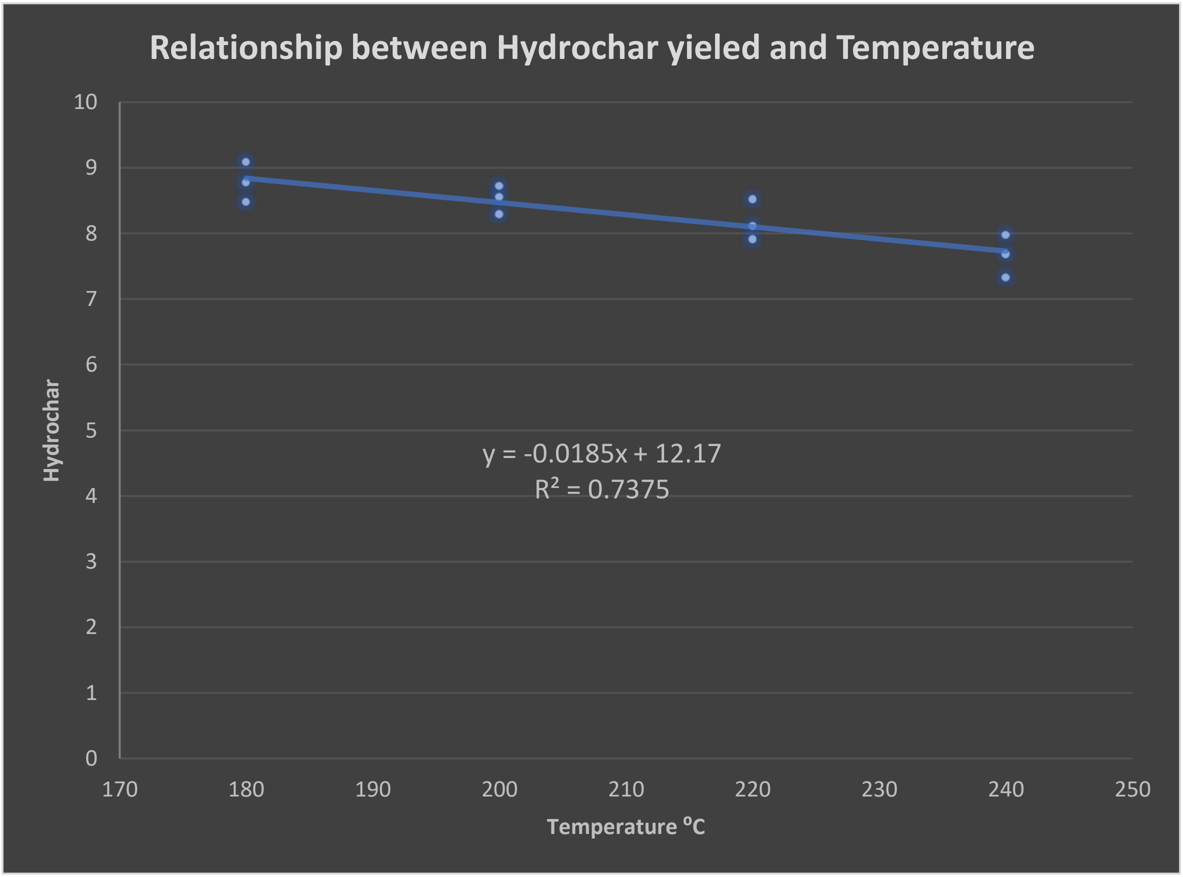


Figure 14. scatter plot between hydro-char (%) and temperature (^{0}C).

4.1.1. Relationship between Hydro-char yield (%) and Reaction time (minutes)

From the statistical relationship expressed in the form of a scatter plot in figure 15, it can be seen that there exist a negative linear relationship (-0.0191) between Hydro-char yield and reaction time with coefficient of determination, R^2 , of 0.2354, and this implies that ~24% of the changes/variations in the amount of Hydro-char produced is determined or explained by changes in the reaction time of the entire process.

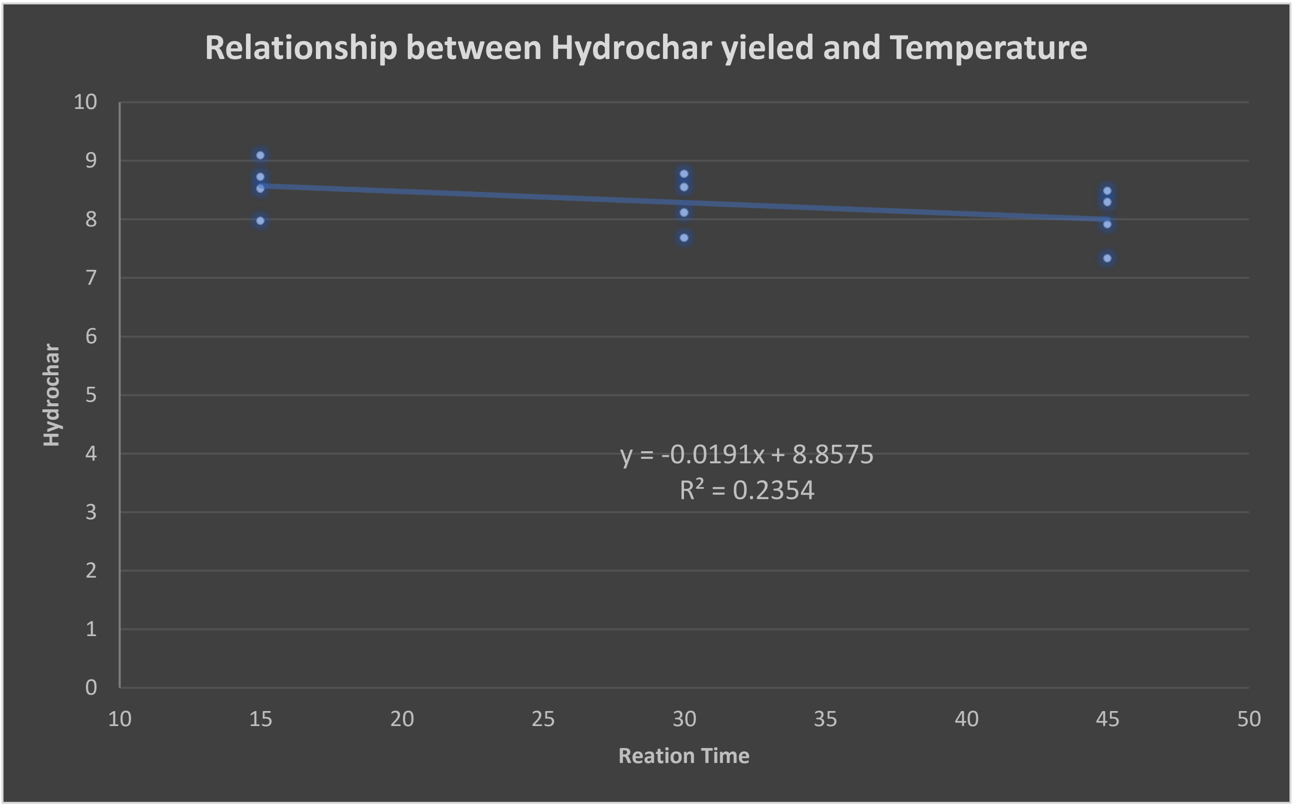


Figure 15. Scatter Plot between Hydro-char yield (%) and Reaction/Holding Time (min).

4.1.2. Combined relationship between operating parameters (temperature-^{0}C, reaction time-mins and hydro-char yield-%).

The scatter plot below (Fig 16) displays the joint relationship between the considered operating parameters (Temperature and Reaction time) and hydro-char yield. From the plot it is obvious that with respect to influencing power on the percentage of solid sewage sludge converted to hydro-char, variations temperature wields much more sway than reaction time. To further buttress the influencing strength of temperature and reaction time on the percentage of hydro-char produced, the pie chat (fig 17) constructed with respect to the individual coefficient of variation, R^2, of the operating parameter simplifies their impact. As can be clearly seen, hydro-char yield in more influenced by the operating temperature (~74%) than reaction time (~24%).

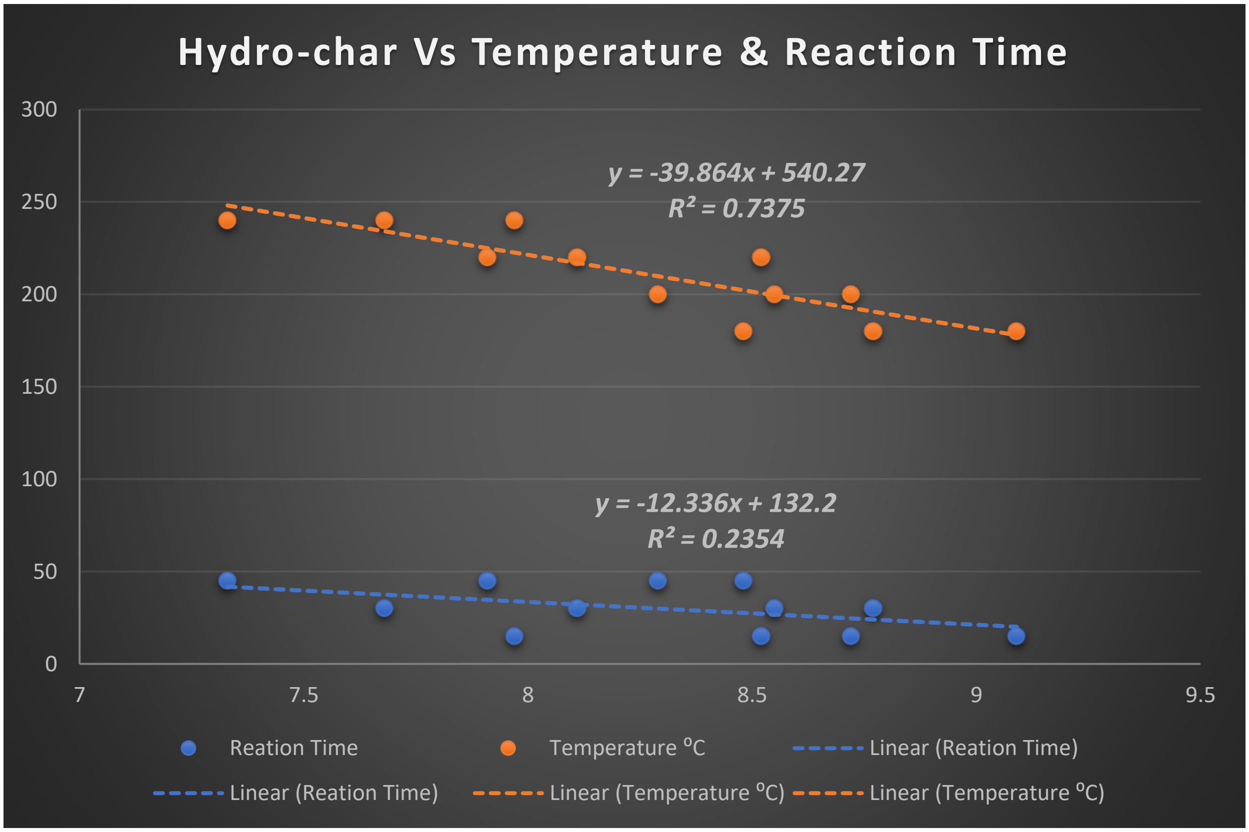


Figure 16. Combined scatter plot among hydro-char yield (%), temperature (^{0}C) and reaction Time (min).

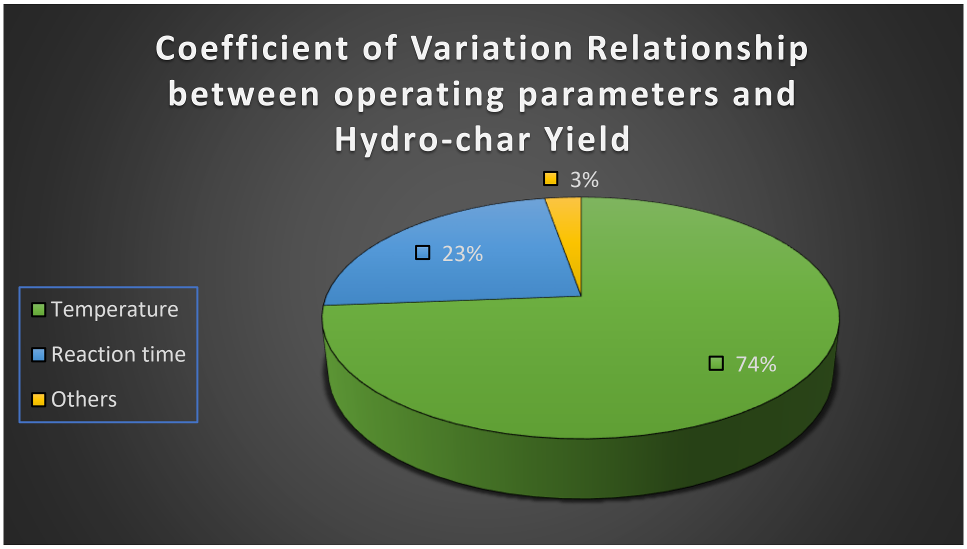
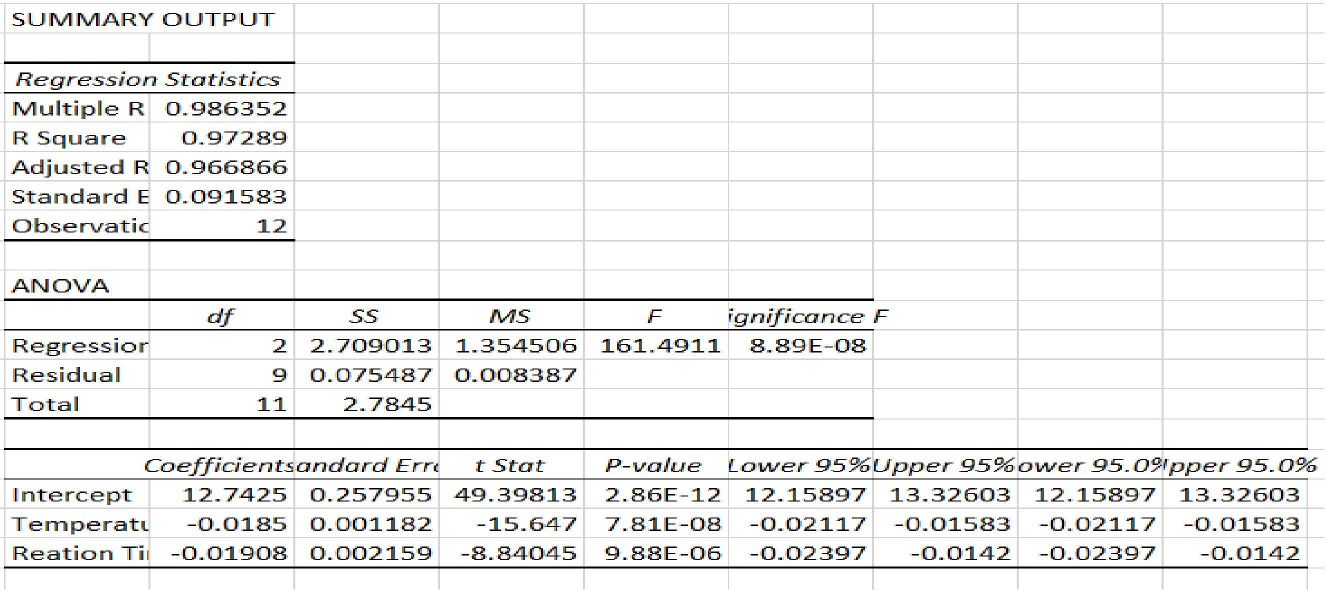


Figure 17. Coefficient of Variation Relationship between Temperature, Reaction Time & Hydro-char Yield.

4.2.0. Mathematical model (regression analysis) for the relationship between operating parameters and hydro-char Yield.

In other to accommodate available resources and perhaps optimize the process, a mathematical model was developed using linear regression function from excel software to analyze the experimental data presented in table 4.0 The results are presented in figure 18 below



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.986352
R Square	0.97289
Adjusted R	0.966866
Standard E	0.091583
Observatic	12

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regressior	2	2.709013	1.354506	161.4911	8.89E-08
Residual	9	0.075487	0.008387		
Total	11	2.7845			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	12.7425	0.257955	49.39813	2.86E-12	12.15897	13.32603	12.15897	13.32603
Temperatu	-0.0185	0.001182	-15.647	7.81E-08	-0.02117	-0.01583	-0.02117	-0.01583
Reation Ti	-0.01908	0.002159	-8.84045	9.88E-06	-0.02397	-0.0142	-0.02397	-0.0142

Figure 18. Excel Software Regression Output for Hydro-char Vs. Temperature and Reaction Time.

$Y = 12.7425 + (-0.0185X_1) + (-0.01908X_2)$ (9)

Equation (9) above represents the regression equation with a precision of ~ ±0.1 extracted from the results presented in table 18. From the equation (9), variable ‘Y’ represents the hydro-char yield in solid weight%, variable ‘X_1’ represents the operating temperature of the entire process in degree Celsius (^{0}C) while variable ‘X_2’ represents the reaction time of each run.

4.2.1. Validity of the regression model

Under the Anova section of figure 18, the significance of the regression analysis was calculated to have a magnitude of 8.89*10^ (-8), which is far less than (almost negligible in comparison with) 0.05 and 0.01 significance level (α), this establishes the fact that the regression analysis/equation is valid or highly significant and as such, can be applied.

Summary output from table figure 18 presents the Adjusted R^2, Multiple R and the Standard Error to be 0.966866, 0.986352, and 0.091583 respectively. From the results presented it can be explained that ~97% (Adjusted R^2) of the variations in the Hydro-char yield (%weight) is attributed to variations or changes in the operating temperature (^0C) and reaction time (minutes) of each run. It can also be interpreted that there is a very strong negative linear relationship (Multiple R ~0.99) between the response variable (Hydro-char yield) and the input variables (operating temperature and reaction time). The standard error (~0.0986) expresses the precision of the regression model (equation 9).

From the regression result presented in figure 18 above and its interpretation, it becomes apparent that the regression model is valid and can be ***applied within the data points*** to make estimates of any variable among the constituent variables based on manipulations to suit available resources or planned objectives.

It should be unequivocally known that the applicability of any regression model in this section and subsequent sections of this research falls within the data points of the operating parameters (temperature and pressure) and choice response variable.

4.2.2. Material/mass balance for both the carbonization and activation stage

For the mass balance around the HTC reactor, different statistical analysis were used to understand and explain the relationship among pertinent variables (both input and response variables) and to model an energy balance equation.

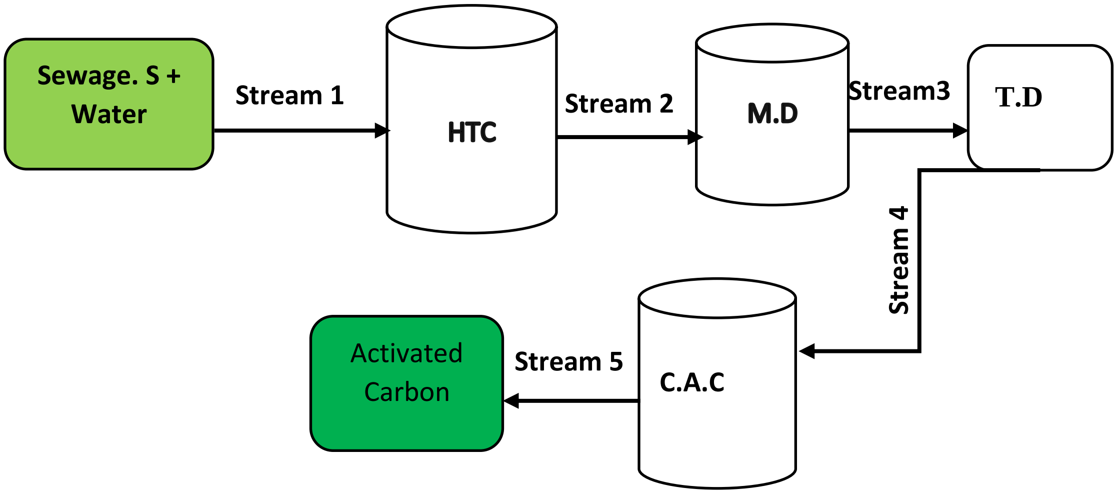


Figure 19. Process Flow Chart.

Pertinent Details

- Material balance based on 100Kg/hour
- 100Kg of Activated carbon, A_c, (stream 5)
- 38% conversion of Hydro-char from stream 4 to stream 5
- Choice of operating parameter: 210^0C and 30mins'. Biomass to Water ratio 1:2
- Applying the mathematical model of equation (4.1) at $X_1 = 210^0$C and X_2 = 30mins:

  $Y = 12.7425 + (-0.0185X_1) + (-0.01908X_2)$.

  $Y = 12.7425 – (0.0185 * 210) – (0.01908 * 30)$

  $Y = 8.28 \pm 0.13$

  Where 'Y' is the hydro-char produced or % conversion of the feed (Sewage sludge + Water)

Material Balance from stream 5 to stream 1

Let F = Mass of feed (H_20 + Sewage Sludge), Kg

S_s = Mass of Sewage Sludge, Kg

W = Mass of water (H_20), Kg

H_c = Mass of Hydro-char, Kg

A_c = Mass of Activated Carbon, Kg

38% of Hc = A_c (10)

At 210^0C and 30Mins,

H_c = 8.28% of F (11)

S_s = 66.67% of F (12)

W = 33.33% of F (13)

Stream 5 to Stream 4

Hydro-char (H_c) makes up stream 4 which is the input to the Activation column while the output (stream 5) is made up of Activated Carbon (A_c).

The objective is to produce 100Kg of Activated Carbon. That is;

A_c = 100Kg

Applying equation (10)

H_c = 263.15 Kg

Stream 4 to Stream 1

Stream 4 to 1 encompasses the three processes (Hydrothermal Carbonization, Mechanical Dewatering and Thermal Drying) taken to produce dry Hydro-char. The input here, stream 1, is the Feed (Water + Sewage Sludge), F, while stream 4 is the produced Hydro-char, H_c.

H_c = 0.0828 * F

Substituting the value of Hc from the previous calculation we have;

F = 263.15/0.0828 = 3178.23 Kg

F ~ 3178 Kg.

Stream 1

Stream one is made up of the feed, F, which is a combination of the sewage sludge and water with mass ratio of 1:2.

$S_s = 0.6667 * F = 0.6667 * 3178 = 2118.77$ Kg

$W = 0.3333 * F = 0.3333 * 3178 = 1059.22$ Kg

From the above calculations, in other to produce **100Kg of Activated carbon**, approximately **2119 Kg** of Sewage Sludge and **1059.22 Kg** of Water are needed.

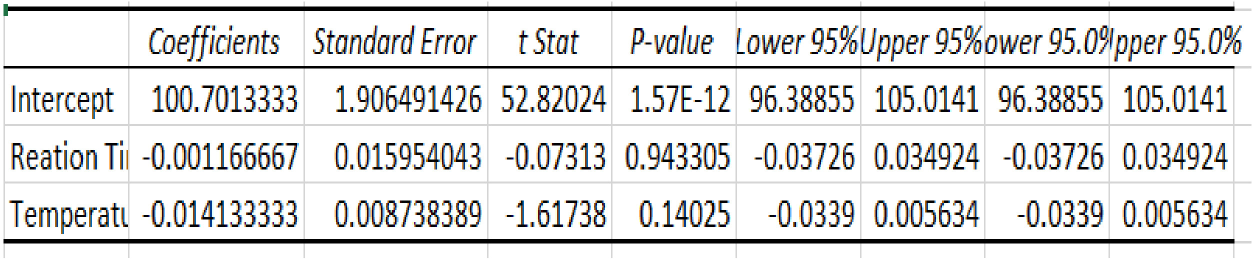
4.2.3. Material/mass balance around the HTC reactor

For the mass balance around the HTC reactor, a regression model was established from excel software analysis of the experimental data presented in table 5 below. Table 5 is a subset of data from figure 11 which is the experimental data retrieved from the hydrothermal carbonization of sewage sludge biomass conducted by Zhao et al (2014). The output or products from the reactor comprises of only liquids and solids and they are expressed as a percentage of the total input or materials or reactants (sewage sludge + water).

Table 5. HTC Experimental Data for Reaction Time, Temperature and HTC Reactor Yield

Reaction Time (Mins)	Temperature (^oC)	Reactor Yield (%)
15	180	98.64
30	180	98.11
45	180	98.08
15	200	96.94
30	200	97.78
45	200	98.71
15	220	97.58
30	220	96.53

45	220	97.35
15	240	97.88
30	240	98.02
45	240	96.76



	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	pper 95.0%
Intercept	100.7013333	1.906491426	52.82024	1.57E-12	96.38855	105.0141	96.38855	105.0141
Reation Ti	-0.001166667	0.015954043	-0.07313	0.943305	-0.03726	0.034924	-0.03726	0.034924
Temperatu	-0.014133333	0.008738389	-1.61738	0.14025	-0.0339	0.005634	-0.0339	0.005634

Figure 20. Excel Software Regression Output for HTC Reactor Yield Vs. Temperature and Reaction Time.

From the regression analysis result presented in fig 20 a valid regression model was established and applied within the data points to make estimates of variables among the constituent variables based on manipulations to suit available resources or planned objectives. The model is thus presented below

$Y = 100.7013333 – 0.0141333X_1 - 0.0011666X_2$ (14)

Where X_1 = Temperature variable in ^{0}C (Degree Celsius)

X_2 = Reactor Holding Time in Min (minutes)

Y = HTC reactor yield (%)

Applying the chosen operating conditions, $X_1 = 210^0$C and X_2 = 30Mins, to equation 14 above in other to find/calculate Y, we have;

$Y = 100.7013333 – (0.0141333 * 210) – (0.0011666 * 30) = 97.698$ %

Taking into consideration the regression model highest residual of 0.91, Y becomes;

$Y = 97.698 \pm 0.91$ % of F_1 (the HTC reactor Feed)

Where F = 3178 Kg

$Y = 3104.8 \pm 28.9$ Kg

Therefore, at the operating conditions of temperature ***210^0C*** and ***30 Mins*** reaction/holding time, the magnitude of the processed sewage sludge by the hydrothermal carbonization reactor after factoring in the already calculated value of F (3178 Kg) is ***3104.8 ± 28.9 Kg.***

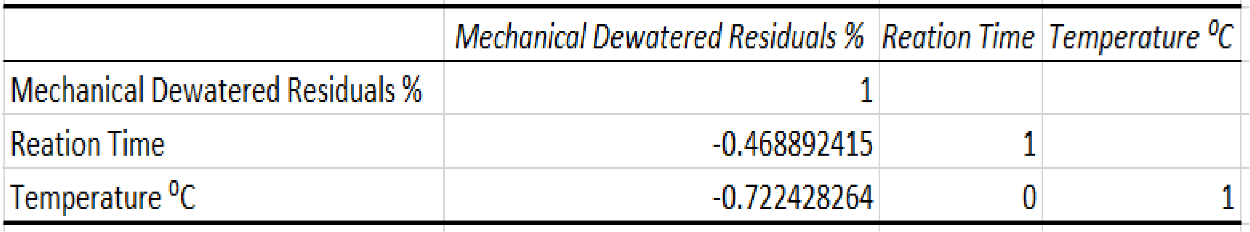
4.2.4 Material/mass balance around the mechanical dewatering device (Press Filter)

For the mass/material balance around the mechanical dewatering device, different statistical analysis were used to understand and explain the relationship among pertinent variables (both input and response variables) and to model a material balance equation. Table 6 below, a subset of data from fig 11, was used for the different statistical analysis. The output or products from the mechanical dewatering unit comprises of only dewatered residues and removed/separated liquids and they are expressed as a percentage of the total input (hydro-char + liquids).

Table 6. HTC Experimental Data for Reaction Time, Temperature and Mechanically Dewatered Residuals.

Reaction/Holding Time (Mins)	Temperature (ºC)	Mechanically Dewatered Residuals (%)
15	180	30.56
30	180	25.23
45	180	20.74
15	200	22.72
30	200	20.54
45	200	18.6
15	220	20.89
30	220	18.72
45	220	16.32

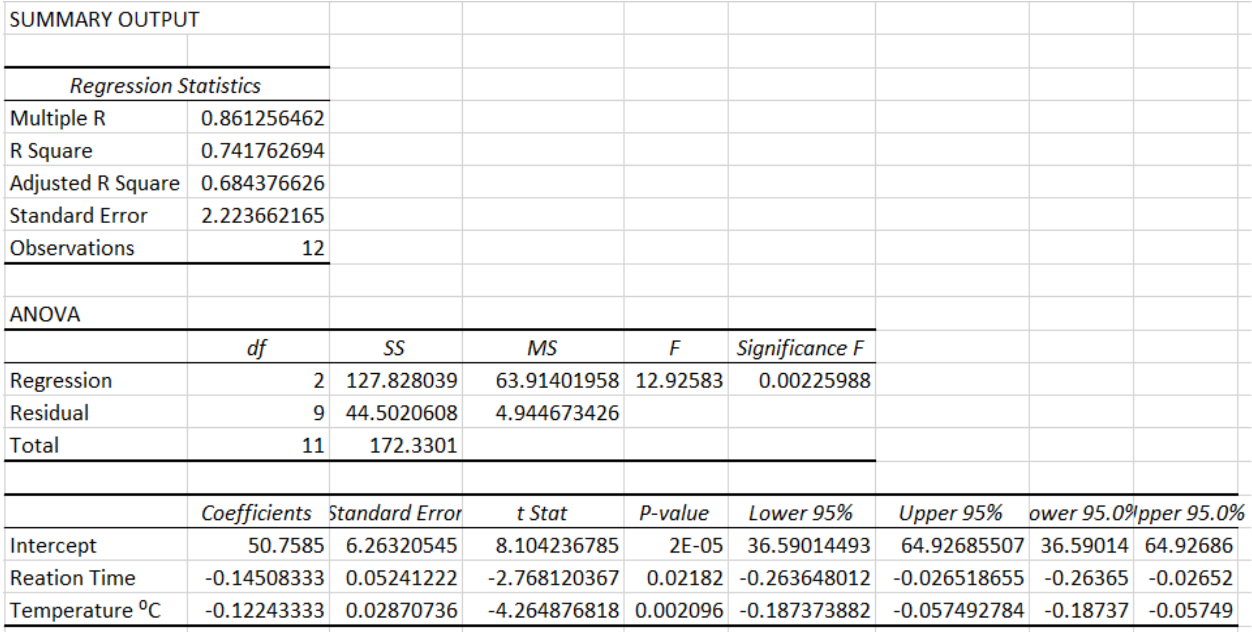
15	240	17.15
30	240	18.62
45	240	18.25



	Mechanical Dewatered Residuals %	*Reation Time*	*Temperature ^0C*
Mechanical Dewatered Residuals %	1		
Reation Time	-0.468892415	1	
Temperature ^0C	-0.722428264	0	1

Figure 21. Excel Correlation Analysis output for Mechanically Dewatered Residuals, Reaction Time & Temperature.

Fig 21 above displays the result of the correlation analysis performed among the input variables, temperature and reaction or holding time, and the mechanical dewatered residuals (response variable). The result expresses a very strong negative linear correlation coefficient between the operating temperature and the dewatered residuals and an averagely strong negative linear correlation between holding time and the mechanically dewatered residuals.



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.861256462
R Square	0.741762694
Adjusted R Square	0.684376626
Standard Error	2.223662165
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	127.828039	63.91401958	12.92583	0.00225988
Residual	9	44.5020608	4.944673426		
Total	11	172.3301			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	50.7585	6.26320545	8.104236785	2E-05	36.59014493	64.92685507	36.59014	64.92686
Reation Time	-0.14508333	0.05241222	-2.768120367	0.02182	-0.263648012	-0.026518655	-0.26365	-0.02652
Temperature ^{0}C	-0.12243333	0.02870736	-4.264876818	0.002096	-0.187373882	-0.057492784	-0.18737	-0.05749

Figure 22. Excel Software Regression Output for Mechanically Dewatered Residuals Vs. Temperature and Reaction Time.

4.2.5. Validity of the regression model for material/mass balance around the mechanical dewatering device.

Under the Anova section of figure 22, the significance of the regression analysis (significance F) was calculated by the software (excel) to have a magnitude of 2.25988 * 10^{-3}, which is far less than 0.05 and 0.01 significance level (α). This establishes the fact that the resulting regression model is valid or highly significant and as such, can be reasonably applied.

Summary output section from fig 22 presents the Adjusted R^2 (coefficient of variation with respect to multiple input variables), Multiple R (regression coefficient) and the Standard Error (precision) to be 0.684376626, 0.861256462, and 2.223662165 respectively. From the results presented it can be explained that ~68% (Adjusted R^2) of the variations in the % dewatered residuals is attributed to variations or changes in the operating temperature (^{0}C) and reaction holding time (minutes) of each run. It can also be interpreted that there is a strong linear relationship (Multiple R ~1) between the response variable (% dewatered residuals) and the input variables (operating temperature and reaction time). The standard error (~2.22) expresses the precision of the regression model.

From the regression result presented in fig 22 above and its interpretation, it becomes apparent that the regression model is valid and can be applied within the data points to make estimates of any variable among the constituent variables based on manipulations to suit available resources or planned objectives. The model is thus presented below

$Y = 50.7585 - 0.12243333X_1 - 0.14508333X_2$ (15)

Where X_1 = Temperature variable in ^0C (Degree Celsius)

X_2 = Reactor Holding Time in Min (minutes)

Y = % Dewatered residuals

Applying the chosen operating conditions, $X_1 = 210^0C$ and X_2 = 30Mins, to equation 4.6 above in other to find/calculate Y, we have;

$Y = 50.7585 - (0.12243333 * 210) - (0.14508333 * 30)$

Y = 20.695 %

Taking into consideration the regression model’s standard error (~2.22), Y becomes;

$Y = 20.695 \pm 2.22$ % of F (HTC reactor feed)

Where F = 3178 Kg. Therefore,

$Y = 657.69 \pm 70.5$ Kg of dewatered residuals

For the second component Y_2 (removed water), we have;

$Y_2 = 3104.8 - 657.69 = 2447.1$ Kg

Therefore, at operating conditions of temperature ***210^{0}C*** and ***30 Mins*** reaction/holding time, the magnitude of the dewatered residue and removed water are ***642.53 ± 68.9 Kg*** and ***2447.1 Kg*** respectively from the mechanical dewatering device.

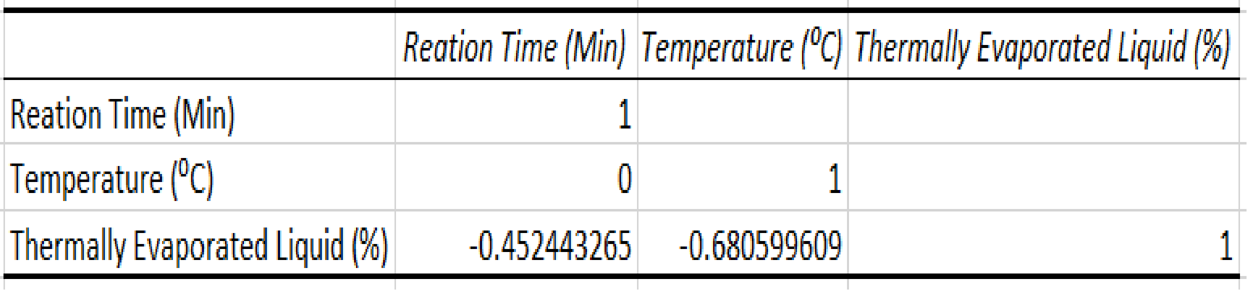
4.2.6. Material/mass around the thermal dryer

For the material/mass balance around the Thermal Dryer, different statistical analysis were used to understand and explain the relationship among pertinent variables (both input and response variables) and to model a material balance equation. Table 7 below, a subset of data from fig 11, was used for the different statistical analysis. Imperative is the fact that modelling a mathematical equation based on the dried solid fuel % from the thermal drying unit will be like the material balance of the entire process in the subsequent section of this research. In other to avoid duplicating the analysis and being professional, the material balance of the thermal drying unit of this section focused on the % thermally evaporated liquid. The output or products from the thermal dryer comprises of only the solid fuel (hydro-char) and the evaporated liquids and they are expressed as a percentage of the total input (hydro-char + liquids) into the thermal dryer.

Table 7. HTC Experimental Data for Reaction Time, Temperature and Thermally Evaporated Liquid.

Reaction Time (Min)	Temperature (ºC)	Thermally Evaporated Liquid (%)
15	180	21.48
30	180	16.45
45	180	12.26
15	200	14
30	200	11.99
45	200	10.31
15	220	12.38
30	220	10.6

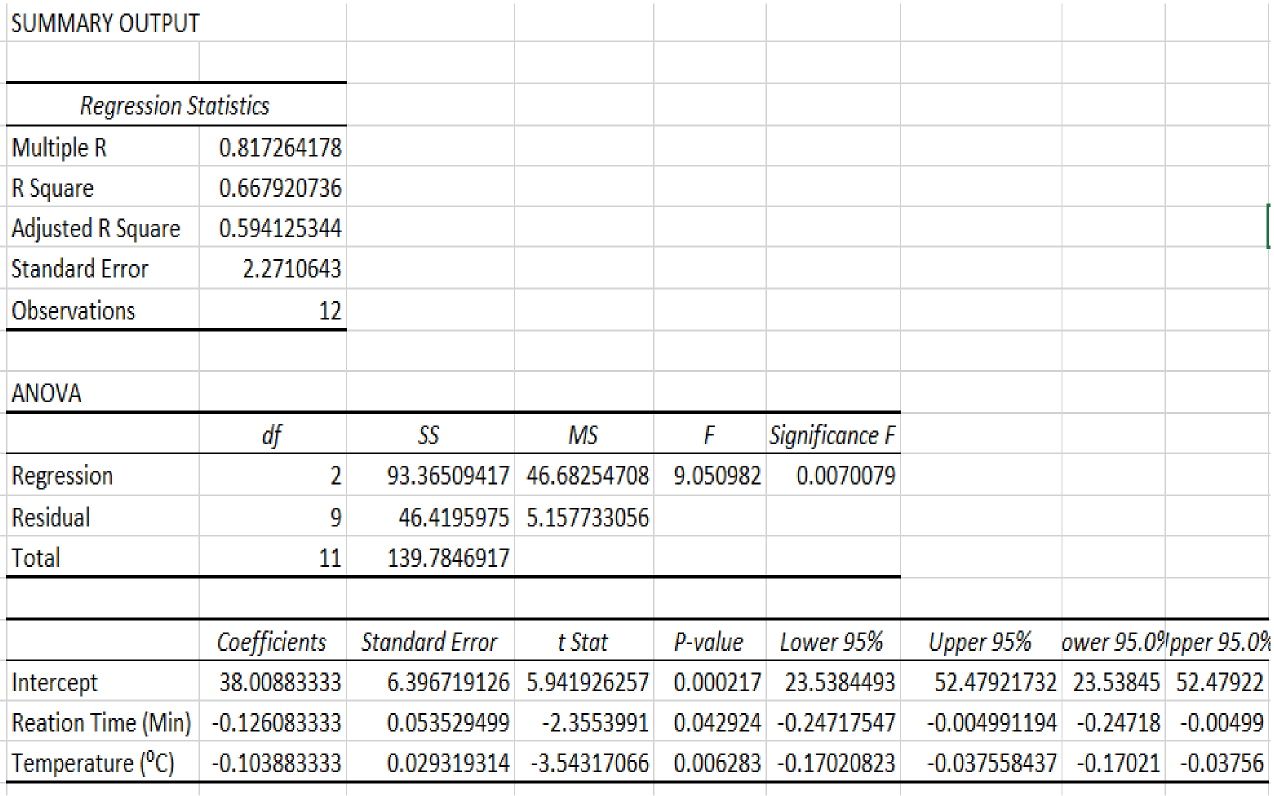
45	220	8.41
15	240	9.18
30	240	10.94



	Reation Time (Min)	*Temperature (^0C)*	*Thermally Evaporated Liquid (%)*
Reation Time (Min)	1		
Temperature (^0C)	0	1	
Thermally Evaporated Liquid (%)	-0.452443265	-0.680599609	1

Figure 23. Excel Correlation Analysis output for Thermally Evaporated Liquid, Reaction Time & Temperature.

Fig 23 above displays the result of the correlation analysis performed among the input variables, temperature and reaction or holding time, and the thermally evaporated liquid (response variable). The result expresses a strong negative linear correlation coefficient between the operating temperature and the thermally evaporated liquids and an averagely strong negative linear correlation between holding time and the thermally evaporated liquid.



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.817264178
R Square	0.667920736
Adjusted R Square	0.594125344
Standard Error	2.2710643
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	2	93.36509417	46.68254708	9.050982	0.0070079
Residual	9	46.4195975	5.157733056		
Total	11	139.7846917			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	pper 95.0%
Intercept	38.00883333	6.396719126	5.941926257	0.000217	23.5384493	52.47921732	23.53845	52.47922
Reation Time (Min)	-0.126083333	0.053529499	-2.3553991	0.042924	-0.24717547	-0.004991194	-0.24718	-0.00499
Temperature (^{0}C)	-0.103883333	0.029319314	-3.54317066	0.006283	-0.17020823	-0.037558437	-0.17021	-0.03756

Figure 24. Excel Software Regression Output for Thermally Evaporated Liquid Vs. Temperature and Reaction Time.

4.2.7. Validity of the regression model for material/mass balance around the thermal dryer

Under the Anova section of figure 24, the significance of the regression analysis (significance F) was calculated by the software (excel) to have a magnitude of 7.0079 * 10^{-3}, which is far less than 0.05 and 0.01 significance level (α). This establishes the fact that the resulting regression model is valid or highly significant and as such, can be reasonably applied.

Summary output section from fig 24 presents the Adjusted R^2 (coefficient of variation with respect to multiple input variables), Multiple R (regression coefficient) and the Standard Error (precision) to be 0.594125344, 0.817264178, and 2.2710643 respectively. From the results presented it can be explained that ~60% (Adjusted R^2) of the variations in the % thermally evaporated liquid is attributed to variations or changes in the operating temperature (^{0}C) and reaction holding time (minutes) of each run. It can also be interpreted that there is a strong linear relationship (Multiple R ~0.8) between the response variable (% thermally evaporated liquids) and the input variables (operating temperature and reaction time). The standard error (~2.27) expresses the precision of the regression model.

From the regression result presented in fig 24 above and its interpretation, it becomes apparent that the regression model is valid and can be applied within the data points to make estimates of any variable among the constituent variables based on manipulations to suit available resources or planned objectives. The model is thus presented below

$Y = 38.00883333 - 0.103883333X_1 - 0.126083333X_2$ (16)

Where X_1 = Temperature variable in ^0C (Degree Celsius)

X_2 = Reactor Holding Time in Min (minutes)

Y = % Thermally Evaporated Liquid

Applying the chosen operating conditions, $X_1 = 210^0C$ and $X_2 = 30$Mins, to equation 16 above in other to find/calculate Y, we have;

$Y = 38.00883333 - (0.103883333 * 210) - (0.126083333 * 30) = 20.695\ \%$

Taking into consideration the regression model's standard error (~2.27), Y becomes;

$Y = 12.41 \pm 2.27$ % of F_1 (HTC reactor feed). Therefore,

$Y = 394.39 \pm 72.14$ Kg of evaporated liquid

For the second component from the thermal dryer, Y_2(produced solid fuel or dried hydro-char)

$Y_2 = 657.69 - 394.39 = 263.3$ Kg of dry hydro-char.

Therefore, at operating conditions of temperature ***210⁰C*** and ***30 Mins*** reaction/holding time, the magnitude of the evaporated liquids and dry hydro-char or solid fuel are ***394.39 ± 72.14 Kg*** and ***263.3 Kg*** respectively from the thermal dryer.

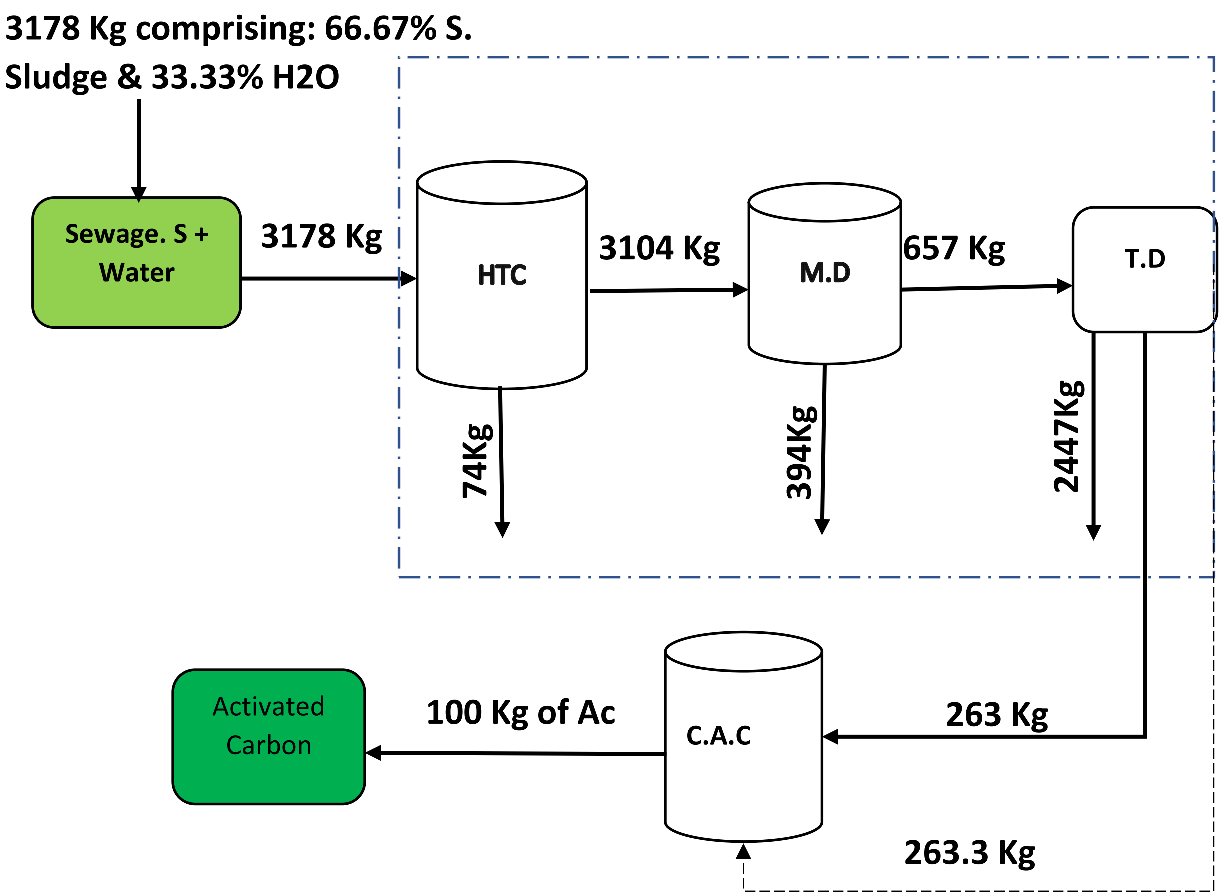
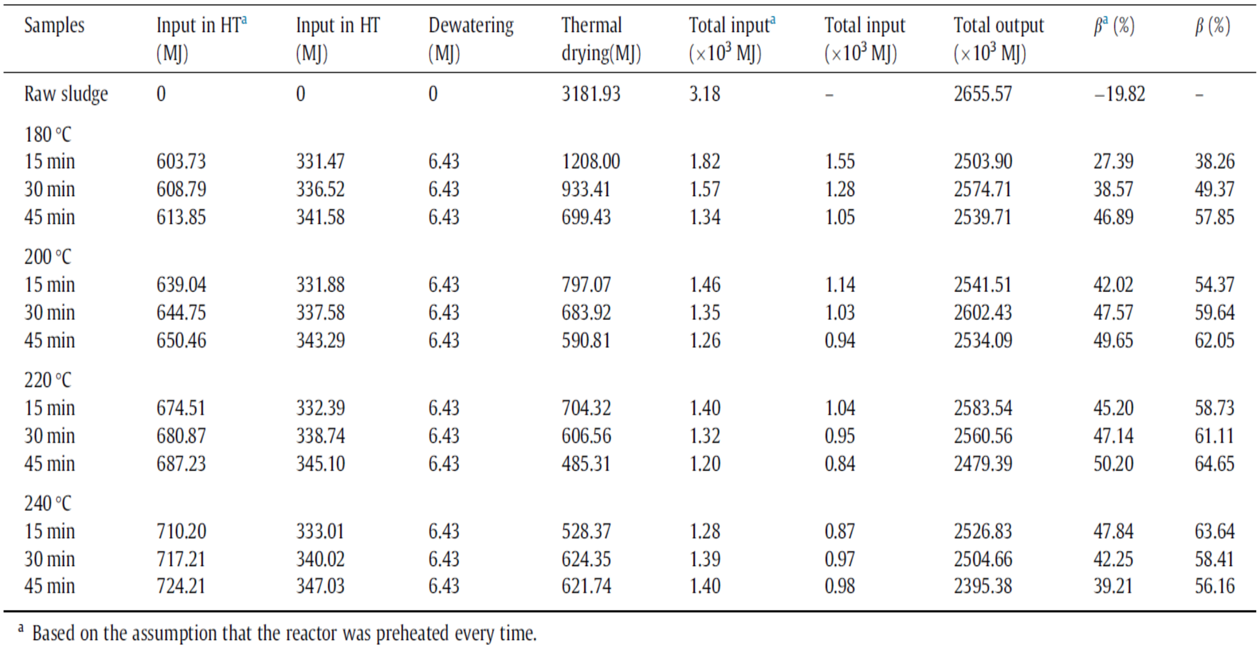


Figure 25. Flow Chart of the Entire Process Integrated with Material Balance.

4.3.0. Energy Balance of the entire Process.

Like the material balance of this process, in its entirety, the energy balance utilized a statistical model developed with a secondary data from Zhao et al (2014). Figure 26 is a screen shot of the energy balance data of the HTC experiment conducted by Zhao et al (2014) while table 8 is a subset of the data presented in figure 26. Table 8 was used directly for modelling the statistical equation which was in turn used for the energy balance of the entire process and for analyzing the relationship among energy requirements at each stage (Hydrothermal carbonization reactor and Thermal drying stage) and the operating parameters (Operating Temperature and Holding Time).



Samples	Input in HT[a] (MJ)	Input in HT (MJ)	Dewatering (MJ)	Thermal drying(MJ)	Total input[a] ($\times 10^3$ MJ)	Total input ($\times 10^3$ MJ)	Total output ($\times 10^3$ MJ)	β^a (%)	β (%)
Raw sludge	0	0	0	3181.93	3.18	–	2655.57	−19.82	–
180 °C									
15 min	603.73	331.47	6.43	1208.00	1.82	1.55	2503.90	27.39	38.26
30 min	608.79	336.52	6.43	933.41	1.57	1.28	2574.71	38.57	49.37
45 min	613.85	341.58	6.43	699.43	1.34	1.05	2539.71	46.89	57.85
200 °C									
15 min	639.04	331.88	6.43	797.07	1.46	1.14	2541.51	42.02	54.37
30 min	644.75	337.58	6.43	683.92	1.35	1.03	2602.43	47.57	59.64
45 min	650.46	343.29	6.43	590.81	1.26	0.94	2534.09	49.65	62.05
220 °C									
15 min	674.51	332.39	6.43	704.32	1.40	1.04	2583.54	45.20	58.73
30 min	680.87	338.74	6.43	606.56	1.32	0.95	2560.56	47.14	61.11
45 min	687.23	345.10	6.43	485.31	1.20	0.84	2479.39	50.20	64.65
240 °C									
15 min	710.20	333.01	6.43	528.37	1.28	0.87	2526.83	47.84	63.64
30 min	717.21	340.02	6.43	624.35	1.39	0.97	2504.66	42.25	58.41
45 min	724.21	347.03	6.43	621.74	1.40	0.98	2395.38	39.21	56.16

[a] Based on the assumption that the reactor was preheated every time.

Figure 26. Energy consumption data from the experiment (Zhao et al, 2014).

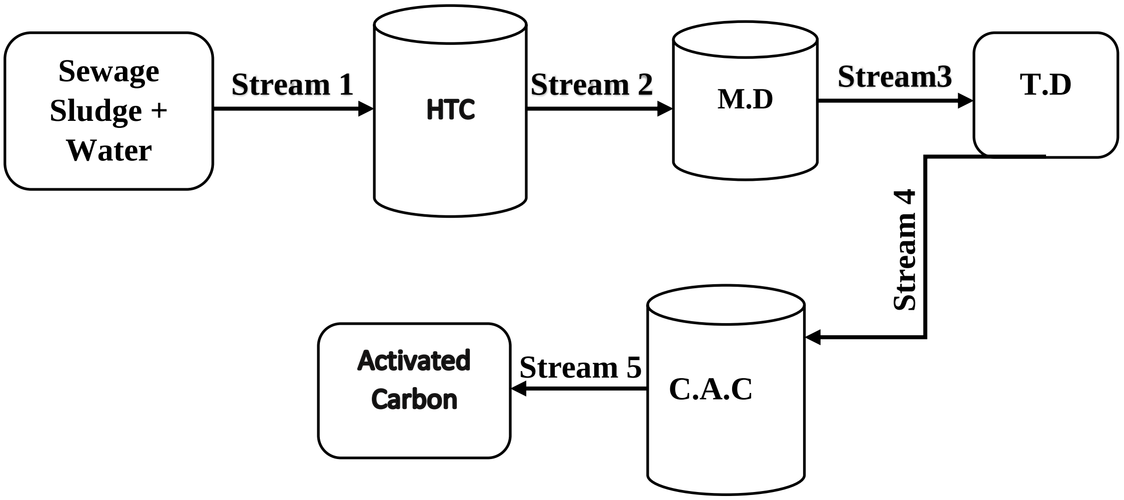
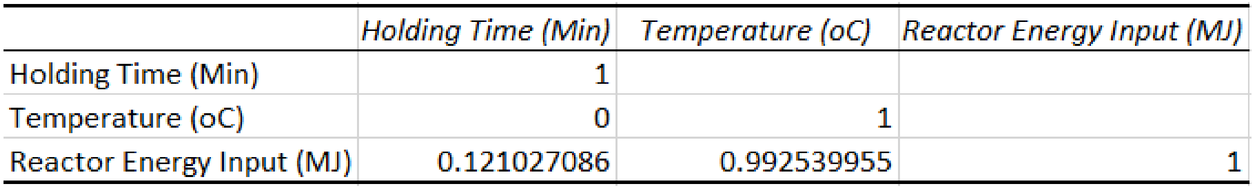


Table 8. Carbonization Experiment Energy Consumption Data.

Temperature (^{0}C)	Holding Time (Min)	Reactor Energy Input (MJ)	Mechanical Dewatering (MJ)	Thermal Drying (MJ)	Total Energy Input (*10^{3} MJ)
180	15	603.73	6.43	1208	1.82
180	30	608.79	6.43	933.41	1.57
180	45	613.85	6.43	699.43	1.34
200	15	639.04	6.43	797.07	1.46
200	30	644.75	6.43	683.92	1.35
200	45	650.46	6.43	590.81	1.26
220	15	674.51	6.43	704.32	1.4
220	30	680.87	6.43	606.56	1.32
220	45	687.23	6.43	485.31	1.2
240	15	710.2	6.43	528.37	1.28
240	30	717.21	6.43	624.35	1.39
240	45	724.21	6.43	621.74	1.4

4.3.1. Hydrothermal Carbonization Reactor Energy Balance

For the energy balance in the HTC reactor, different statistical analysis were used to understand and explain the relationship among pertinent variables (both input and response variables) and to model an energy balance equation.



	Holding Time (Min)	*Temperature (oC)*	*Reactor Energy Input (MJ)*
Holding Time (Min)	1		
Temperature (oC)	0	1	
Reactor Energy Input (MJ)	0.121027086	0.992539955	1

Figure 27. Excel Correlation Analysis output for Reactor Energy Input, Reaction Time & Temperature

Fig 27 above displays the result of the correlation analysis performed among the input variables, temperature and holding time, and reactor energy output (response variable). The result expresses a very strong positive linear correlation coefficient between the operating temperature and the energy requirement/consumption of the HTC reactor and a very weak positive linear correlation for holding time and reactor energy input.

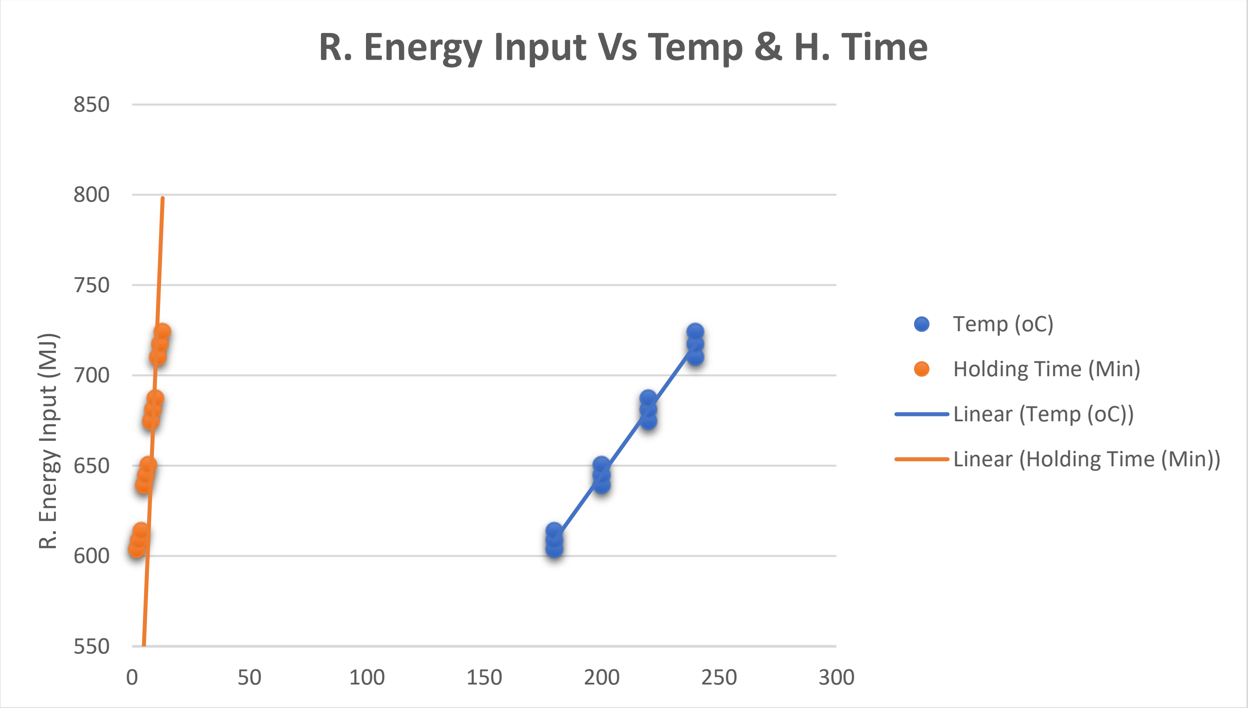
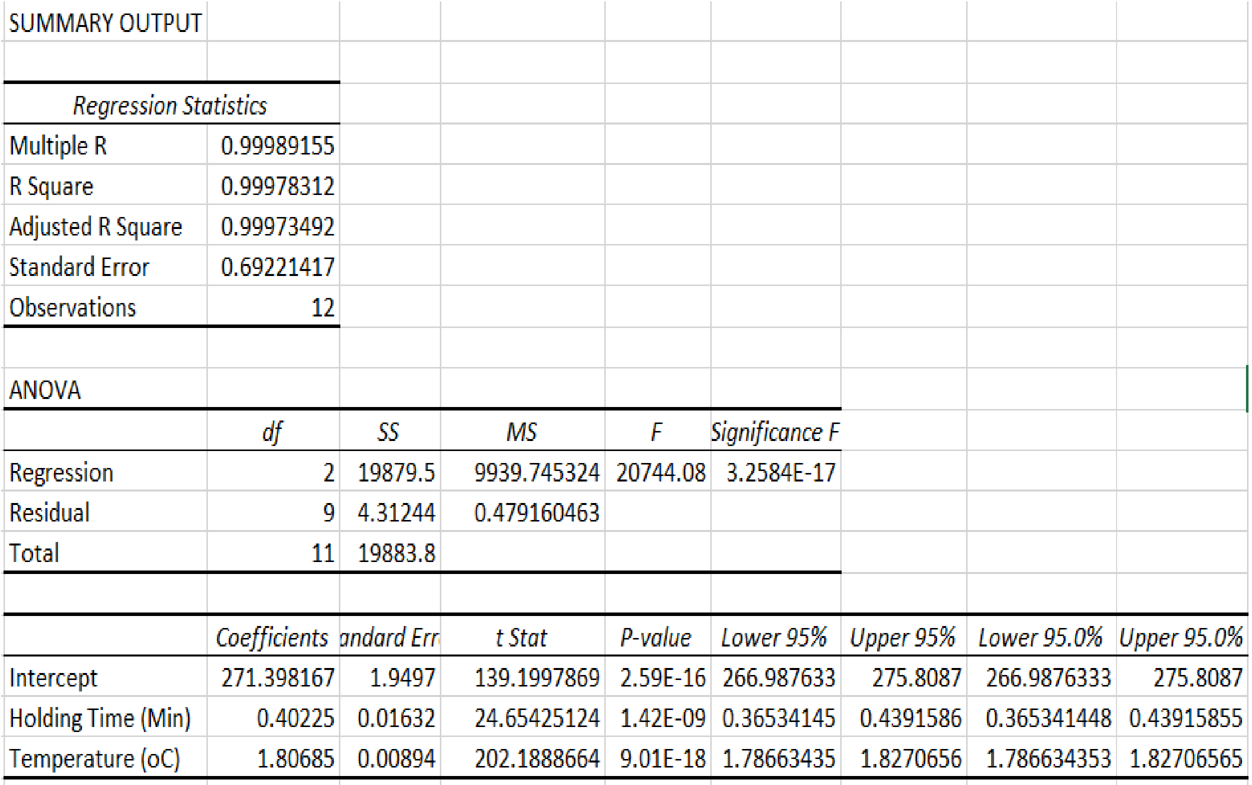


Figure 28. Scatter plot of R. Energy Input Vs. Temperature & Holding time.

The scatter plot of fig 28 above further buttresses the result of the correlation analysis presented in fig 27. From the above scatter plot it is evident that changes in temperature variable is almost equivalent to changes in the reactor energy input in terms of numerical value. The scatter plot trend line or line of best fit is almost inclined at 45^0 which speaks volume to the fact that changes in the *Temperature* variable sways more influence over changes in the response variable, *R. Energy input*, so much more than that of *Holding Time* which is seen to almost be inclined at 90^0.

Regression analysis was carried out on pertinent data presented in table 8 in other to model the energy balance of the HTC reactor. The result is presented in fig 29 below



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99989155
R Square	0.99978312
Adjusted R Square	0.99973492
Standard Error	0.69221417
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	19879.5	9939.745324	20744.08	3.2584E-17
Residual	9	4.31244	0.479160463		
Total	11	19883.8			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	271.398167	1.9497	139.1997869	2.59E-16	266.987633	275.8087	266.9876333	275.8087
Holding Time (Min)	0.40225	0.01632	24.65425124	1.42E-09	0.36534145	0.4391586	0.365341448	0.43915855
Temperature (oC)	1.80685	0.00894	202.1888664	9.01E-18	1.78663435	1.8270656	1.786634353	1.82706565

Figure 29. Regression analysis output for R. Energy Input (MJ) Vs. Temp (^{0}C) & Holding Time (Min).

4.3.2. Validity of the HTC reactor regression model

Under the Anova section of figure 29, the significance of the regression analysis (significance F) was calculated by the software (excel) to have a magnitude of 3.26*10^ (-17), which is far less than (or almost negligible in comparison with) 0.05 and 0.01 significance level (α), this establishes the fact the regression analysis/equation is valid or highly significant and as such, can be reasonably applied.

Summary output section from fig 29 presents the Adjusted R^2 (coefficient of variation with respect to multiple input variables), Multiple R (regression coefficient) and the Standard Error (precision) to be 0.99973492, 0.99989155, and 0.69221417 respectively. From the results presented it can be explained that ~100% (Adjusted R^2) of the variations in the hydrothermal reactor energy consumption (MJ) is attributed to variations or changes in the operating temperature (^{0}C) and reaction holding time (minutes) of each run. It can also be interpreted that there is a very strong positive linear relationship (Multiple R ~1) between the response variable (Hydro-char yield) and the input variables (operating temperature and reaction time). The standard error (~0.69) expresses the precision of the regression model.

From the regression result presented in fig 29 above and its interpretation, it becomes apparent that the regression model is valid and can be applied within the data points to make estimates of any variable among the constituent variables based on manipulations to suit available resources or planned objectives. The model is thus presented below

$Y = 271.398167 + 1.80685X_1 + 0.40225X_2$ (17)

Where X_1 = Temperature variable in ^{0}C (Degree Celsius)

X_2 = Reactor Holding Time in Min (minutes)

Applying the chosen operating conditions, $X_1 = 210^0$C and X_2 = 30Mins, to equation 17 above in other to find/calculate Y, we have;

$Y = 271.398167 + (1.80685 * 210) + (0.40225 * 30)$

$Y = 662.90$ MJ

Taking into consideration the regression model precision/standard error (~0.69), Y becomes;

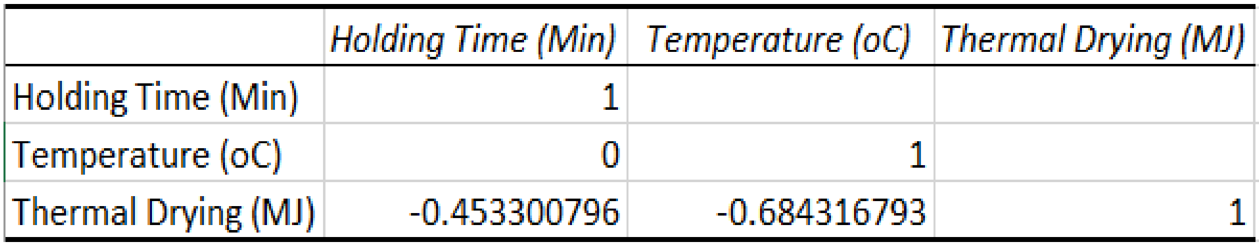
$Y = 662.90 \pm 0.69$ MJ

Therefore, at operating conditions of temperature ***210^{0}C*** and ***30 Mins*** reaction/holding time, the magnitude of the required energy or consumed energy by the hydrothermal carbonization reactor is ***662.90 ± 0.69 MJ.***

4.3.3. Thermal drying (Forced Convective Drier) energy balance

From table 8 the energy requirement or energy consumption of the thermal dryer was found to vary as the operating conditions (180 – 240 ^{0}C & 15 – 45 Mins) changes. The forced convective dryer was operated at an air temperature of 30.4 ± 0.4 ^{0}C and velocity of 1.34 ± 0.004 m/s.

For the energy balance in the thermal drying unit, different statistical analysis were used to understand and explain the relationship among pertinent variables (both input and response variables) and to model an energy balance equation.



	Holding Time (Min)	*Temperature (oC)*	*Thermal Drying (MJ)*
Holding Time (Min)	1		
Temperature (oC)	0	1	
Thermal Drying (MJ)	-0.453300796	-0.684316793	1

Figure 30. Excel Correlation Analysis output for Thermal Drying, Reaction/Holding Time & Temperature.

Fig 30 above displays the result of the excel correlation analysis performed among the input variables, temperature and holding time, and thermal drying unit energy requirement/consumption (response variable). The result expressed a strong negative linear correlation coefficient between the operating temperature and the energy requirement/consumption of the thermal drying unit and an averagely strong negative linear correlation for holding time and energy requirement/consumption of the thermal drying unit.

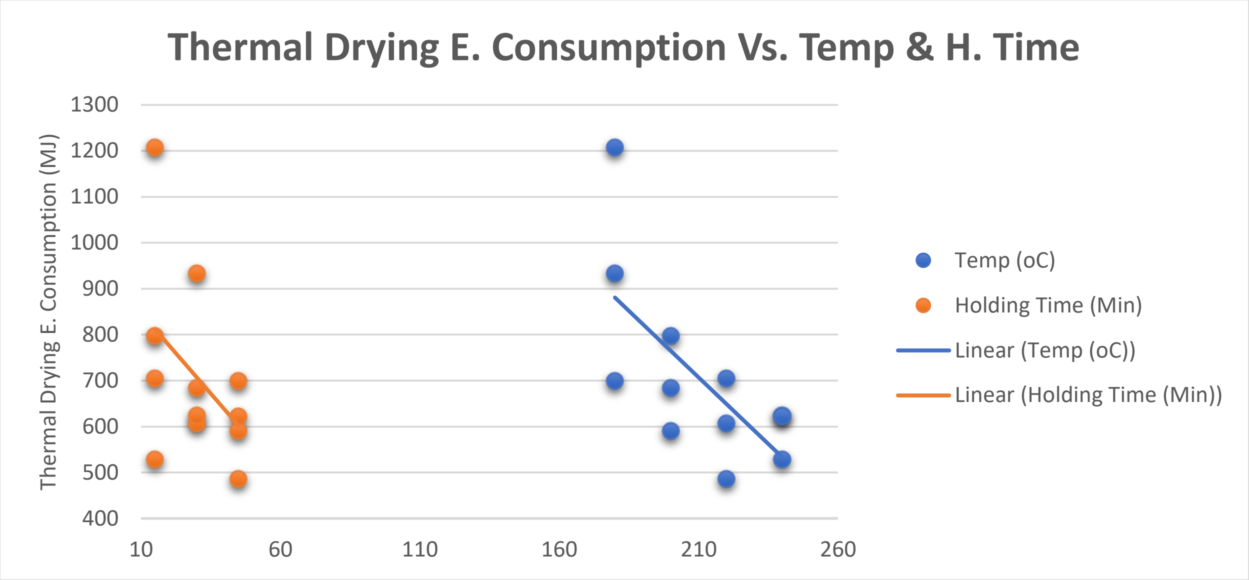
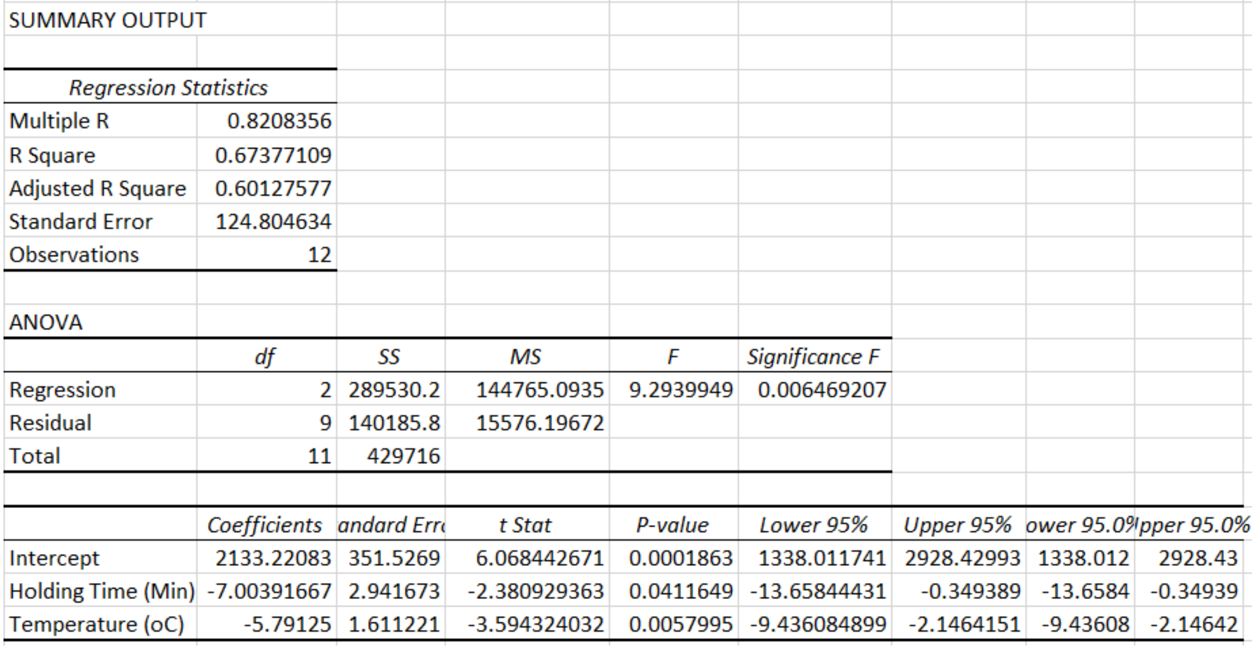


Figure 31. Scatter plot of Thermal Drying Unit E. Consumption Vs. Temperature & Holding time.

The scatter plot of fig 31 above further buttresses the result of the correlation analysis presented in fig 30. From the above scatter plot it is evident that changes in temperature and holding time input variables determines the magnitude or quantity of energy consumed by the thermal drying unit. The scatter plot trend line or line of best fit is almost inclined at some angle which also speaks volume to the fact that as the input variables, *Temperature* and *Holding Time*, increases the response variable, *Thermal Drying Unit Energy Consumption*, decreases. The negative line of best fit makes sense, in that, as the operating temperature and holding time increases, the production of hydro-char decreases and gives way to the production of more liquids and gases. Ying et al (2012), in their research on ‘characterization of products from hydrothermal treatment of cellulose’ discovered that above an operating temperature of 200 ^{0}C, due to improved decomposition by fragmentation of large molecules, solid products of cellulose decreases giving way to increased production of other components which includes liquids and incondensable low molecular gas. Sevilla et al (2009) also recorded a decrease in the O/C and H/C atomic ratios as the HTC temperature increased from 230 – 250 ^{0}C.

Regression analysis was carried out on pertinent data presented in table 8 in other to model the energy balance of the thermal drying unit. The result is presented in fig 32 below



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8208356
R Square	0.67377109
Adjusted R Square	0.60127577
Standard Error	124.804634
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	2	289530.2	144765.0935	9.2939949	0.006469207
Residual	9	140185.8	15576.19672		
Total	11	429716			

	Coefficients	andard Err	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	pper 95.0%
Intercept	2133.22083	351.5269	6.068442671	0.0001863	1338.011741	2928.42993	1338.012	2928.43
Holding Time (Min)	-7.00391667	2.941673	-2.380929363	0.0411649	-13.65844431	-0.349389	-13.6584	-0.34939
Temperature (oC)	-5.79125	1.611221	-3.594324032	0.0057995	-9.436084899	-2.1464151	-9.43608	-2.14642

Figure 32. Regression analysis Output for Thermal Drying Unit Energy Consumption Vs. Temp & Holding Time.

4.3.4. Validity of the regression model

Under the Anova section of figure 32, the significance of the regression analysis (significance F) was calculated by the software (excel) to have a magnitude of 0.006469207, which is far less than 0.05 and 0.01 significance level (α), this establishes the fact the regression analysis/equation is valid or highly significant and as such, can be reasonably applied.

Summary output section from fig 32 presents the Adjusted R^2 (coefficient of variation with respect to multiple input variables), Multiple R (regression coefficient) and the Standard Error (precision) to be 0.60127577, 0.8208356, and 124.804634 respectively. From the results presented it can be explained that 60% (Adjusted R^2) of the variations in the thermal unit energy consumption (MJ) is attributed to variations or changes in the operating temperature (^{0}C) and reaction holding time (minutes) of each run. It can also be interpreted that there is a very strong linear relationship (Multiple R 0.8) between the response variable thermal unit energy consumption and the input variables (operating temperature and reaction time). The standard error (124), although quite high, expresses the precision of the regression model.

From the regression result presented in fig 32 above and its interpretation, it becomes apparent that the regression model is valid and can be applied within the data points to make estimates of any variable among the constituent variables based on manipulations to suit available resources or planned objectives. The model is thus presented below

$Y = 2133.22083 – 5.79125X_1 – 7.00391667X_2$ (18)

Where X_1 = Temperature variable in ^{0}C (Degree Celsius)

X_2 = Reactor Holding Time in Min (minutes)

Applying the chosen operating conditions, $X_1 = 210^0$C and X_2 = 30Mins, to equation 18 above in other to find/calculate Y, we have;

$Y = 2133.22083 – (5.79125 * 210) – (7.00391667 * 30) = 706.9$ MJ

Taking into consideration the regression model precision/standard error (124), Y becomes;

$Y = 706.9 \pm 124$ MJ

Therefore, at operating conditions of temperature ***210^{0}C*** and ***30 Mins*** reaction/holding time, the magnitude of the required energy or consumed energy by the hydrothermal carbonization reactor is ***706.9 ± 124 MJ.***

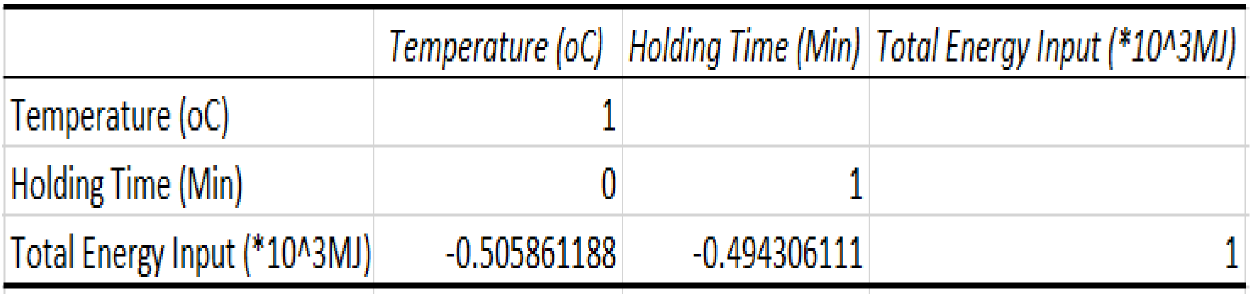
4.3.5. Mechanical dewatering (Press Filter) energy balance

From table 8, the energy requirement or energy consumption of the thermal dryer was found to be ***6.43 MJ*** regardless of the operating condition. The forced convective dryer was operated at an air temperature of 30.4 ± 0.4 ^{0}C and velocity of 1.34 ± 0.004 m/s.

4.3.6 Energy balance for HTC reactor, mechanical dewatering and thermal drying units considered as a single unit.

In order to eliminate or reduce to the barest minimum the cumulative error introduced by considering the HTC reactor, Mechanical dewatering and thermal drying as individual units in the statistical models presented in the previous sections, it is but paramount to consider these three stages as a single unit.

For the energy balance in the three integrated units, different statistical analysis were used to understand and explain the relationship among pertinent variables (both input and response variables) and to model an energy balance equation.



	Temperature (oC)	Holding Time (Min)	Total Energy Input (*10^3MJ)
Temperature (oC)	1		
Holding Time (Min)	0	1	
Total Energy Input (*10^3MJ)	-0.505861188	-0.494306111	1

Figure 33. Excel Correlation Analysis output for Total Energy Input, Reaction/Holding Time & Temperature.

Fig 33 above displays the result of the correlation analysis performed among the input variables, temperature and holding time, and total energy input (response variable). The total energy input represents the sum of the energy requirements or consumption by HTC reactor, thermal drying unit and mechanical dewatering unit. The result expresses an averagely strong negative linear correlation between the operating temperature and the energy requirement/consumption of the three integrated units and an averagely weak negative linear correlation/relationship between for holding time and total energy input.

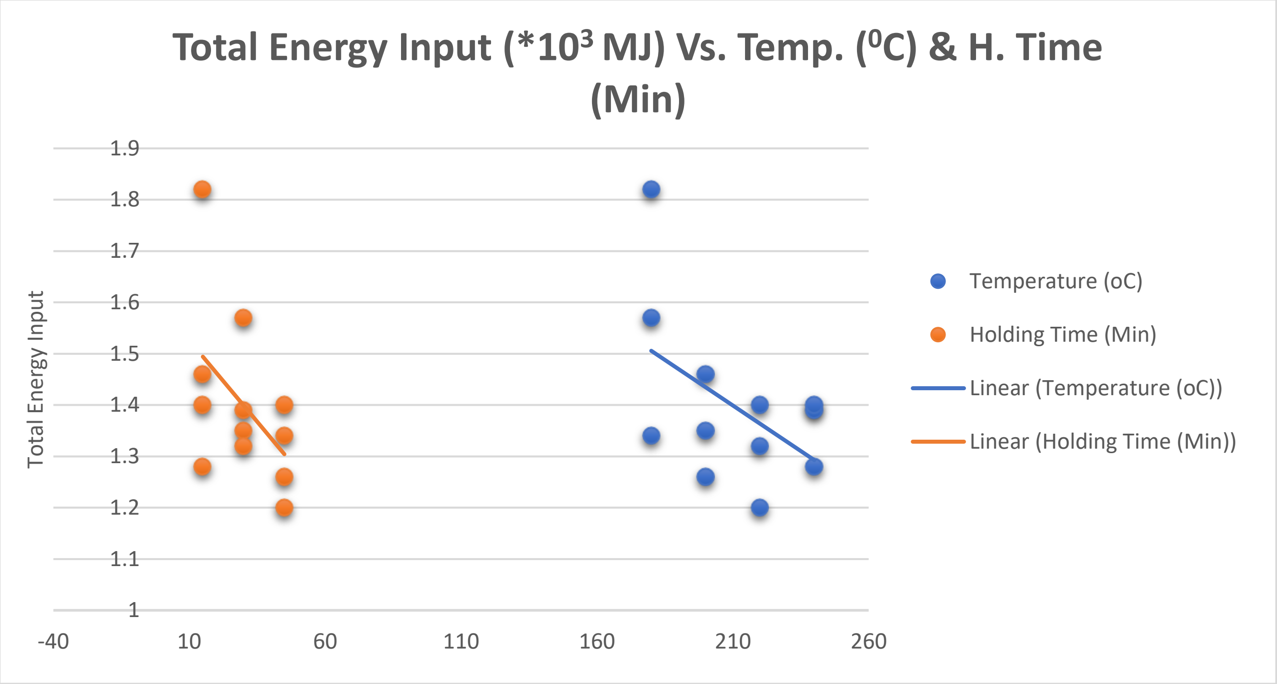
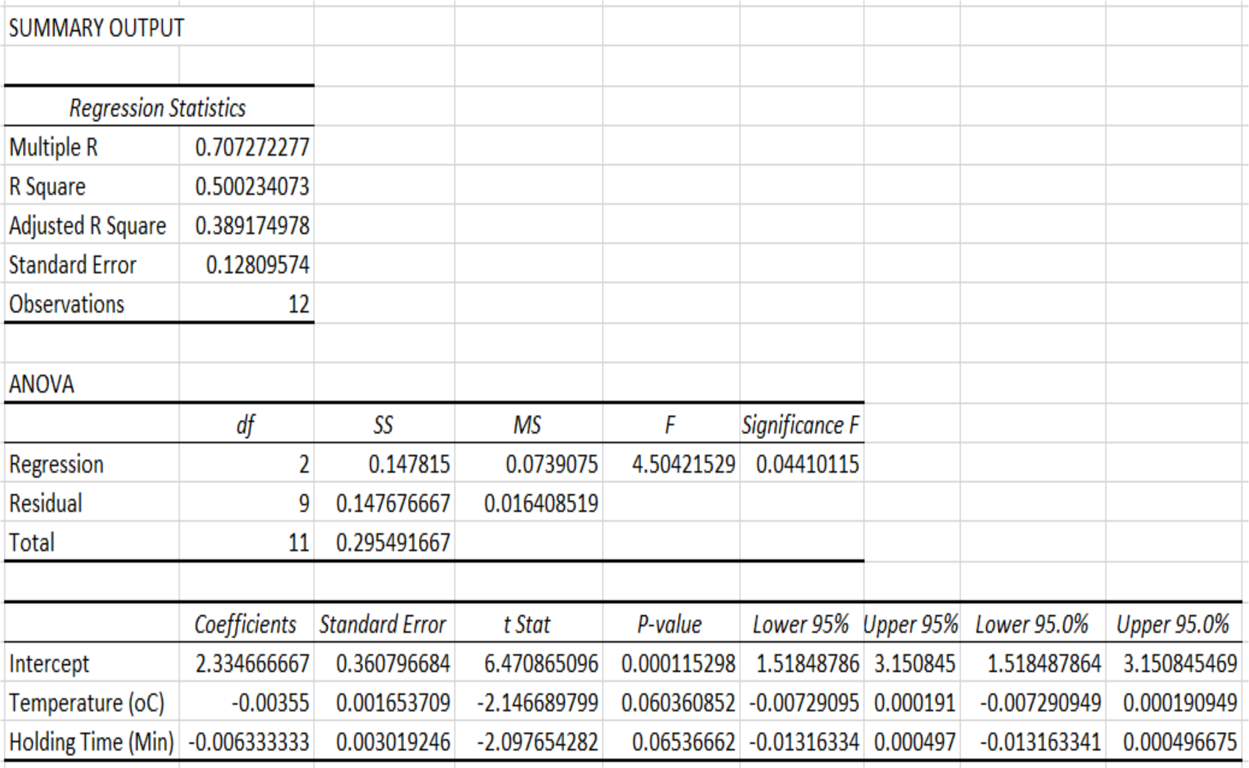


Figure 34. Scatter plot of Total Energy Input Vs. Temperature & Holding time.

The scatter plot of fig 34 above further buttresses the result of the correlation analysis presented in fig 33. From the above scatter plot it is obvious that as the operating temperature variable increases, the total energy input of the entire process (carbonization) decreases in terms of magnitude and similarly increases in holding time reflects decreases in the total energy input of the carbonization process due to the fact that literature concludes hydrothermal carbonization to be an exothermic process.

Regression analysis was carried out on pertinent data presented in table 8 in other to model the energy balance of the carbonization process. The result is presented in fig 35 below;



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.707272277
R Square	0.500234073
Adjusted R Square	0.389174978
Standard Error	0.12809574
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.147815	0.0739075	4.50421529	0.04410115
Residual	9	0.147676667	0.016408519		
Total	11	0.295491667			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.334666667	0.360796684	6.470865096	0.000115298	1.51848786	3.150845	1.518487864	3.150845469
Temperature (oC)	-0.00355	0.001653709	-2.146689799	0.060360852	-0.00729095	0.000191	-0.007290949	0.000190949
Holding Time (Min)	-0.006333333	0.003019246	-2.097654282	0.06536662	-0.01316334	0.000497	-0.013163341	0.000496675

Figure 35. Excel Regression analysis Output for Thermal Drying Unit Energy Consumption (MJ) Vs. Temp (^{0}C) & Holding Time (Min).

4.3.7. Validity of the regression model for the considered single unit

Under the Anova section of figure 35, the significance of the regression analysis (significance F) was calculated by the software (excel) to have a magnitude of 0.04410115, which is far less than 0.05 and 0.01 significance level (α), this establishes the fact the regression analysis/model is valid or highly significant and as such, can be reasonably applied.

Summary output section from fig 35 presents the Adjusted R^2 (coefficient of variation with respect to multiple input variables), Multiple R (regression coefficient) and the Standard Error (precision) to be 0.389174978, 0.707272277 and 0.12809574 respectively. From the results presented it can be explained that ~39% (Adjusted R^2) of the variations in the total energy input of the carbonization process (* 10^3 MJ) is attributed to variations or changes in the operating temperature (^{0}C) and reaction holding time (minutes) of each run. It can also be interpreted that there is a very strong linear relationship (Multiple R ~0.7) between the response variable, total energy input, and the input variables (operating temperature and reaction time). The standard error (0.12809574), although quite high, expresses the precision of the regression model.

From the regression result presented in fig 35 above and its interpretation, it becomes apparent that the regression model is valid and can be applied within the data points to make estimates of any variable among the constituent variables based on manipulations to suit available resources or planned objectives. The model is thus presented below

$Y = 2.334666667 – 0.00355X_1 – 0.006333333X_2$ (19)

Where X_1 = Temperature variable in ^{0}C (Degree Celsius)

X_2 = Reactor Holding Time in Min (minutes)

Y = Total Energy Input at X_1 and X_2

Applying the chosen operating conditions, $X_1 = 210\ ^0$C and $X_2 = 30$ Mins, to equation 19 above in other to find/calculate Y, we have;

$Y = 2.334666667 – (0.00355 * 210) – (0.006333333 * 30) = 1.399 * 10^3$ MJ

Taking into consideration the regression model precision/standard error (0.128), Y becomes;

$Y = (1.399 \pm 0.22) * 10^3$ MJ

Therefore, at operating conditions of temperature ***210^0C*** and ***30 Mins*** reaction/holding time, the magnitude of the required energy or consumed energy by the hydrothermal carbonization reactor is ***$(1.399 \pm 0.22) * 10^3$ MJ.***

4.3.8 Activation column (Furnace Carbolite TZF 15/610) energy balance

According to secondary data of analysis from Rio et al (2006), in their research on ‘preparation of adsorbents from sewage sludge by steam activation for industrial emission treatment’, the optimum activation temperature and activation time was found to be 760 ^{0}C and 30mins which corresponds to 38% yield and 226 m^2 g^{-1} BET surface area (porosity) of the activated carbon as the response variables of interest. Resources utilized includes;

- 700 KWh t-1
- Steam flow: 2.5 L/min = 0.075 m^3/min

700 kWh/t = 700 * 3.6 * 10^6 = 2.52 * 10^9 J = 2520 MJ

Steam Energy/seconds = (m_s * h_e)/3600 (Engineering toolbox, 2008)

h_e (Steam Enthalpy) = 2703.49 kJ/kg, $Density_{steam}$ = 0.880277 m^3/kg, (TLV, 2017)

Steam flowrate = 2.5 L/min, Activation Time = 30 mins = 0.5 hr. 2.5 L/min = 2.5 * 30 * 10^{-3} = 0.075 m^3/min

m_{steam} = Density * flowrate = 0.880277 * 0.075 = 0.066 kg/min = 3.96 kg/hr.

Steam Energy/seconds = (0.066 * 2703.49)/60 = 2.973 KW = 2973 J/s

Total Activation Energy = 2,520,000,000 + 2973 = 2,520.003 MJ ~2520 MJ

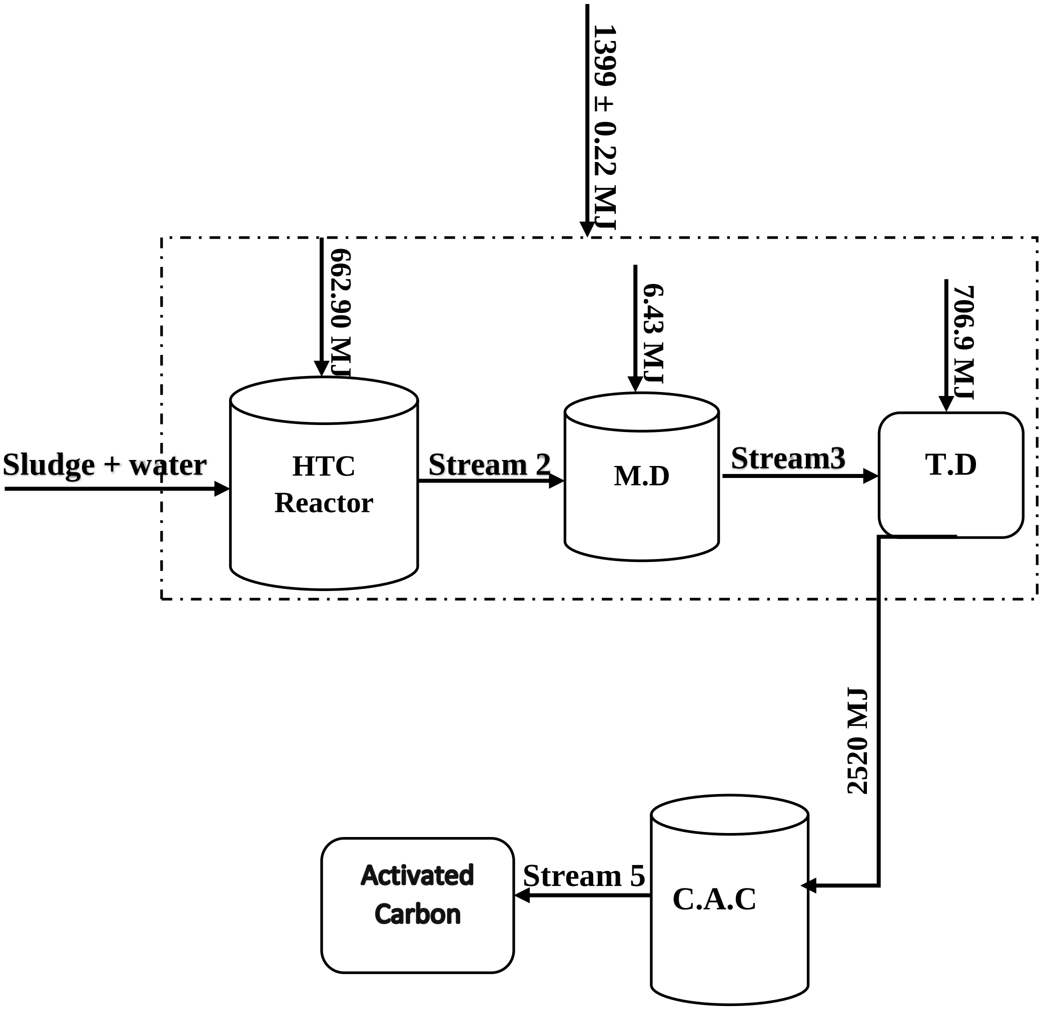


Figure 36. Process Flow Chart Integrated with Energy Balance.

The chemical properties of the carbonized hydro-char or produced activated carbon is displayed in the table below;

Operating Temperature (^{0}C)	Activation Time (Mins)	S_{BET}	V_{meso}	V_{micro}
780	65	217	0.269	0.072

760	30	226	0.295	0.083

4.4.0. Economic/financial implication result and discussion

Just as it was unequivocally stated in the methodology of this research, the economic or financial implications of this project incorporated project cost estimation, sensitivity analysis and annualized rate of return on investment. For these three financial analysis certain inevitable ***assumptions*** were made that affects them all, and they are listed below.

- Project life span of 3 years
- 365 work days per year
- 8 work hours per day

Data gotten from the material and energy balance calculations of this research include;

- 2118.77 kg of Sewage Sludge processed per 3 hrs. 12 min. (~4 hrs.)
- 100 kg of Activated Carbon produced per 4 hours
- 200 kg of Activated Carbon produced per day
- 73,000 kg of Activated Carbon produced per year

4.4.1. Project cost estimation

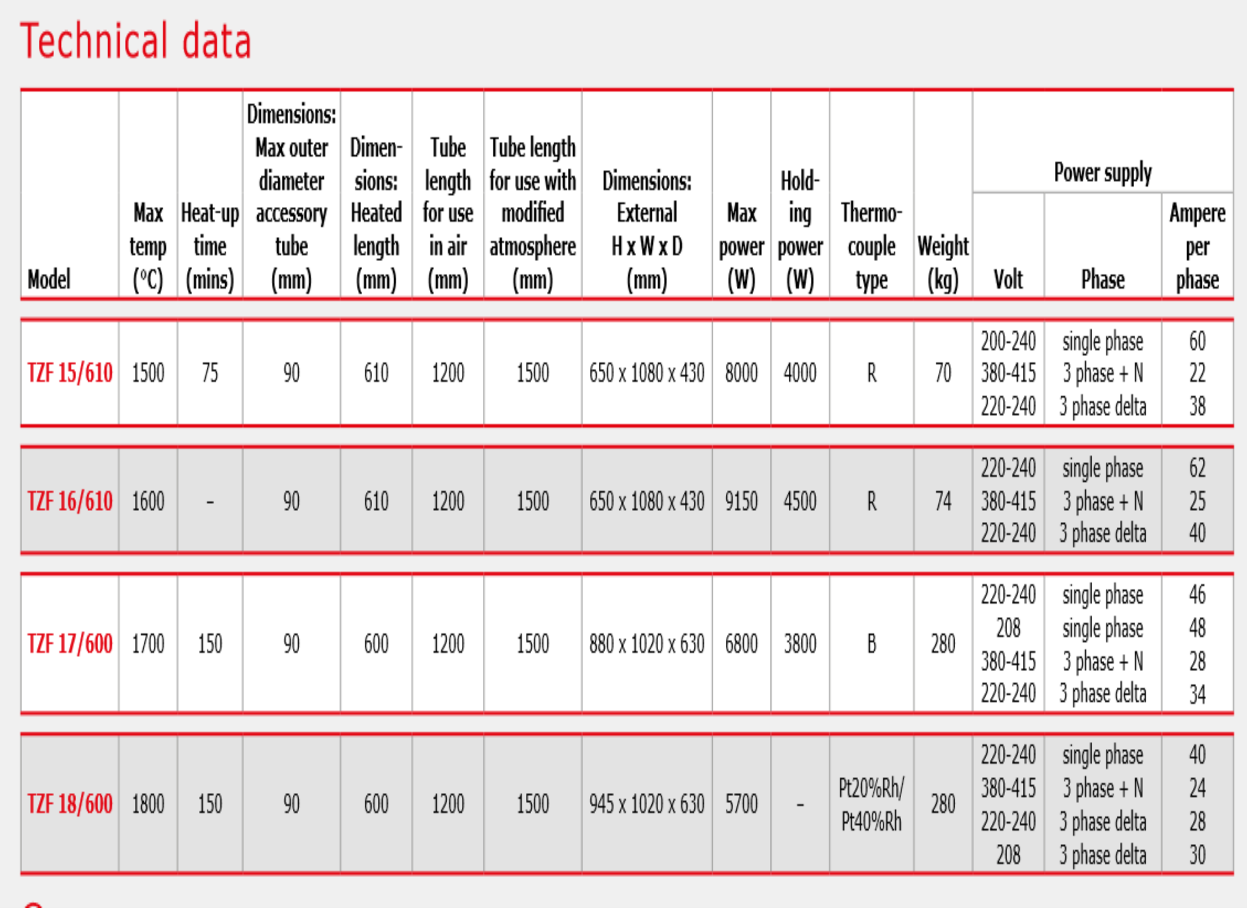
From the result of the first objective of this research*, 'the material balance of the entire process'*, it was proven/estimated that 2118.77 Kg of sewage sludge from waste water treatment plant (~2 tons of sewage sludge) and 1159.22 Kg of fresh water (~1 ton of H_2O) are required for the production of 100 Kg (or 0.1 ton) of activated carbon via hydrothermal carbonization. The total duration of the entire process being 3 hrs. 12 min. Based on an 8 hours/day working time, it is safe to assume a 200 Kg production of activated carbon or 4 tons of processed waste water sewage sludge per day. The details are presented in the table below. Starting consecutively as follows -:

- Cost estimation of carbon activation column/furnace (three heat zone furnace Carbolite TZF 15/610) and necessary accessories.
- Cost estimation of the Hydrothermal Carbonization batch reactor.
- Cost estimation of the filter press (Belt filter press) for Mechanical dewatering.
- Cost estimation of the thermal dryer (forced convective dryer).

Table 9. Cost of activation column and requisite accessories (Pricing source: Wolf-Lab, 2019).

Equipment (Carbolite furnace) & requisite accessories	**Cost (£)**
Three heat zone furnace Carbolite TZF 15/610	11111.06
Audible alarm carbolite with separate cancel button	212.93
Conduit Carbolite	182.97
Inert gas inlets or retorts flowmeter Carbolite	711.49
Remote setpoint input Carbolite for 3508 controller	327.97
Separate control Carbolite with horizontal base	549.98
Temperature alarm relay	139.68
Temperature indicator	413.75
Time switch	403.66
Tube support	227.17
Work tube package for inert atmosphere	4117.35
Work tube package for steam	4167.81

Steam gas inlets flowmeter Carbolite	711.49
Total Cost price	**23,277.31**



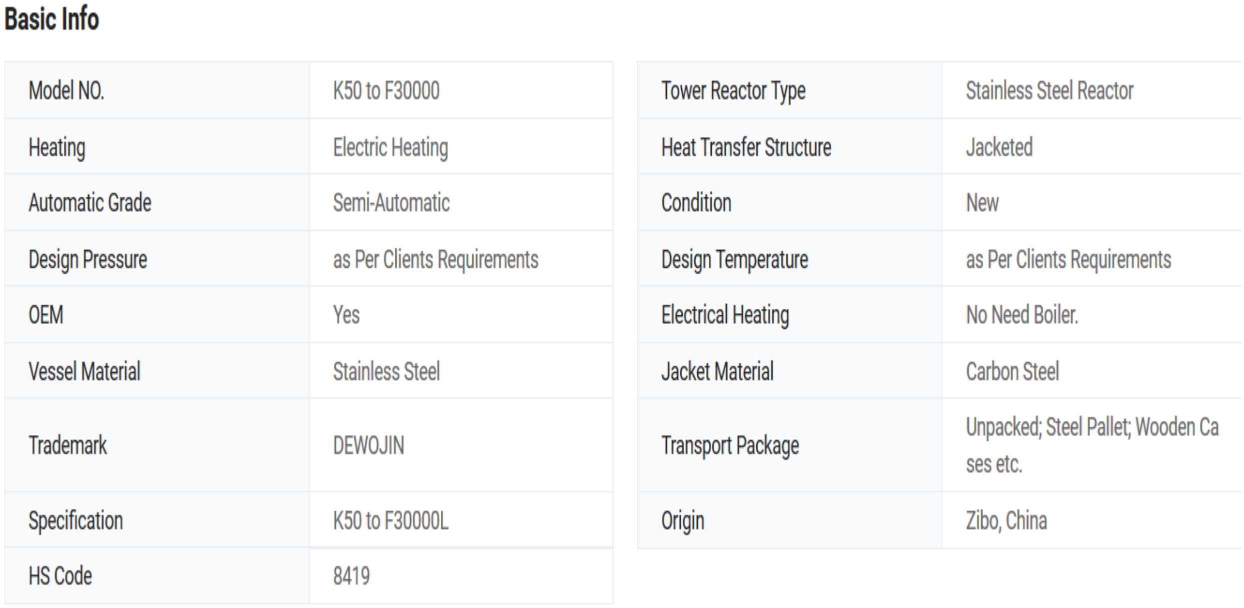
Technical data

Model	Max temp (°C)	Heat-up time (mins)	Dimensions: Max outer diameter accessory tube (mm)	Dimensions: Heated length (mm)	Tube length for use in air (mm)	Tube length for use with modified atmosphere (mm)	Dimensions: External H x W x D (mm)	Max power (W)	Holding power (W)	Thermocouple type	Weight (kg)	Power supply		
												Volt	Phase	Ampere per phase
TZF 15/610	1500	75	90	610	1200	1500	650 x 1080 x 430	8000	4000	R	70	200-240 380-415 220-240	single phase 3 phase + N 3 phase delta	60 22 38
TZF 16/610	1600	-	90	610	1200	1500	650 x 1080 x 430	9150	4500	R	74	220-240 380-415 220-240	single phase 3 phase + N 3 phase delta	62 25 40
TZF 17/600	1700	150	90	600	1200	1500	880 x 1020 x 630	6800	3800	B	280	220-240 208 380-415 220-240	single phase single phase 3 phase + N 3 phase delta	46 48 28 34
TZF 18/600	1800	150	90	600	1200	1500	945 x 1020 x 630	5700	-	Pt20%Rh/ Pt40%Rh	280	220-240 380-415 220-240 208	single phase 3 phase + N 3 phase delta 3 phase delta	40 24 28 30

Figure 37. Basic information of the priced tube furnace (Carbolite TZF 15/610).

Table 10. Cost of Hydrothermal Carbonization Batch reactor and requisite accessories (Dewojin, 2019 & Head, 2019).

Equipment (Semi/low carbon Stainless Steel electrical heating batch reactor)	Unit Price ($)
Semi/low carbon stainless-steel batch reactor	6,000 – **65,000**
Stainless steel condenser	**2,000**
Total cost price	**67,000**

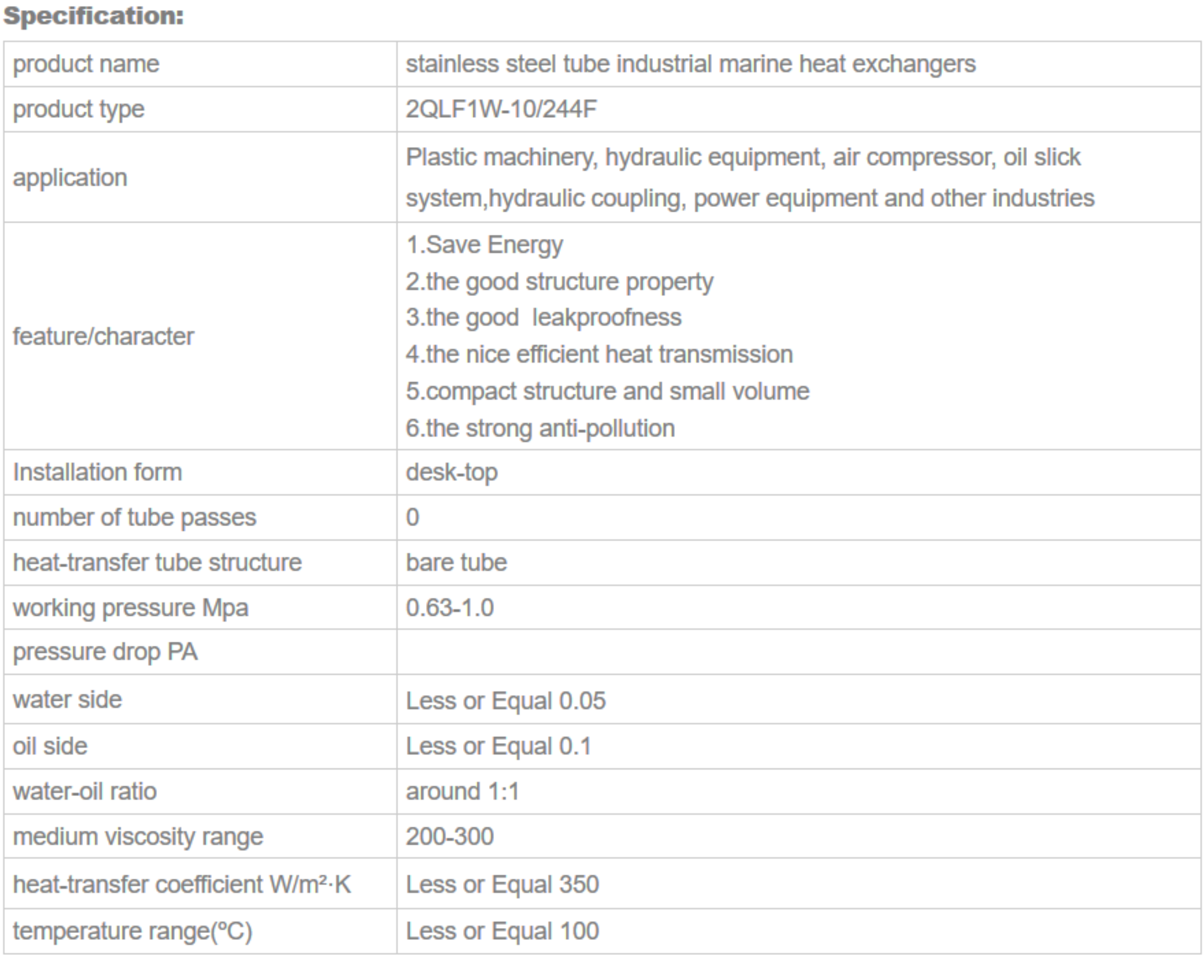


Basic Info

Model NO.	K50 to F30000
Heating	Electric Heating
Automatic Grade	Semi-Automatic
Design Pressure	as Per Clients Requirements
OEM	Yes
Vessel Material	Stainless Steel
Trademark	DEWOJIN
Specification	K50 to F30000L
HS Code	8419

Tower Reactor Type	Stainless Steel Reactor
Heat Transfer Structure	Jacketed
Condition	New
Design Temperature	as Per Clients Requirements
Electrical Heating	No Need Boiler.
Jacket Material	Carbon Steel
Transport Package	Unpacked; Steel Pallet; Wooden Cases etc.
Origin	Zibo, China

Figure 38. Basic information of the priced reactor (Dewojin, 2019).



Specification:

product name	stainless steel tube industrial marine heat exchangers
product type	2QLF1W-10/244F
application	Plastic machinery, hydraulic equipment, air compressor, oil slick system,hydraulic coupling, power equipment and other industries
feature/character	1.Save Energy 2.the good structure property 3.the good leakproofness 4.the nice efficient heat transmission 5.compact structure and small volume 6.the strong anti-pollution
Installation form	desk-top
number of tube passes	0
heat-transfer tube structure	bare tube
working pressure Mpa	0.63-1.0
pressure drop PA	
water side	Less or Equal 0.05
oil side	Less or Equal 0.1
water-oil ratio	around 1:1
medium viscosity range	200-300
heat-transfer coefficient W/m²·K	Less or Equal 350
temperature range(°C)	Less or Equal 100

Figure 39. Basic Information of the priced condenser (Head, 2019).

Table 11. Cost estimate of belt filter press (Mechanical dewatering device). DZ, (2019).

Equipment	Cost ($)
Sludge dewatering belt filter press	1600
Total	**1600**

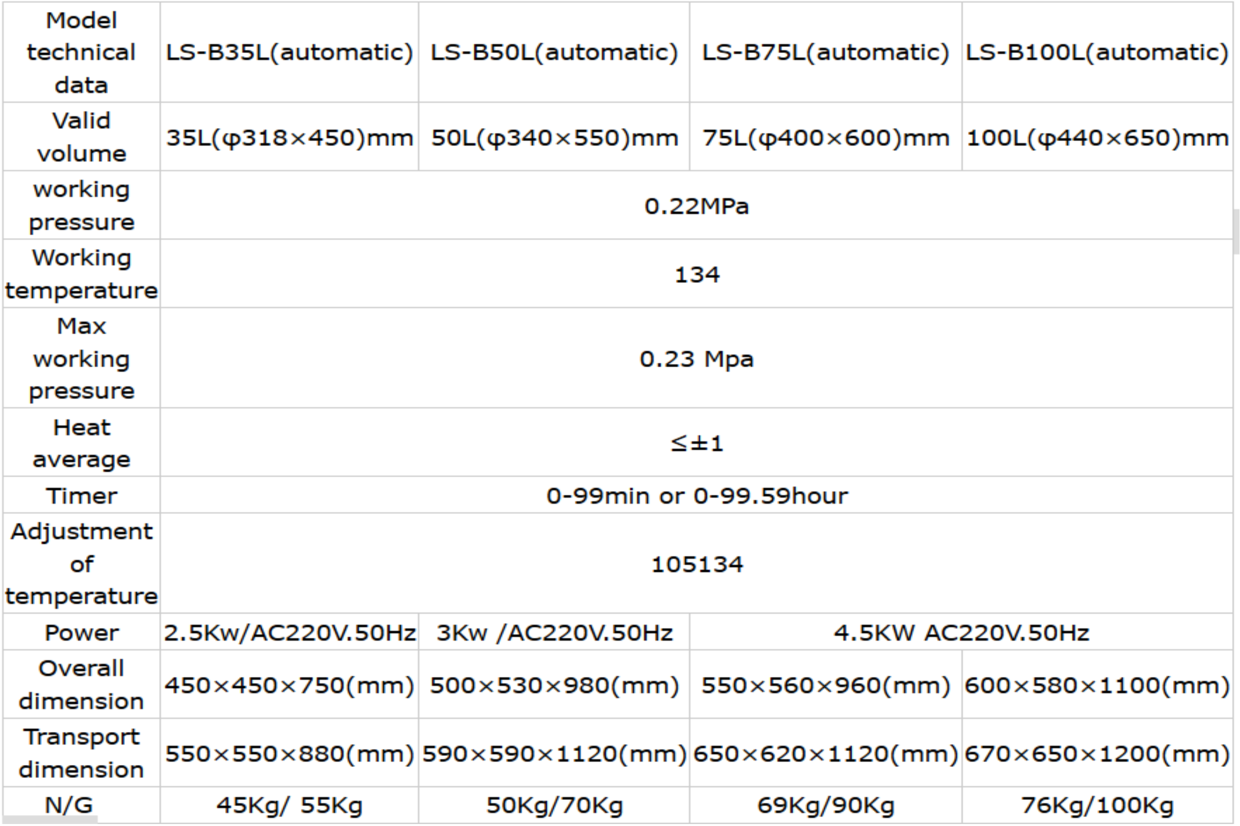
Quick Details

Condition:	New	Automatic Grade:	Automatic
Production Capacity:	High Efficiency	Place of Origin:	Henan, China (Mainland)
Brand Name:	DZ	Model Number:	XMY4/450-30U
Voltage:	Customer Requirement	Power(W):	2.2kw
Weight:	860kg	Dimension(L*W*H):	1950*700*900mm
Certification:	ISO9001	Name:	DZ Sludge dewatering belt filter press for sale in china
Type:	Automatice Filter Press	Application:	Sewage Dewatering
Material:	Carbon Steel	Color:	Blue
Description:	Hydraulic Press Filter Machine	Function:	Liquid Solid Separation
Filter area:	10-1000 Square Meters	Keywords:	Automatic Pressing Machine
Product name:	Filter press malaysia for sale	After-sales Service ...	Engineers available to service machinery overseas
Warranty:	1 Year		

Figure 40. Basic Information of the priced belt filter press (DZ, 2019).

Table 12. Cost estimation of the thermal drying device (Forced convective dryer), Binjiang, (2019).

Equipment	Cost ($)
Forced convection vacuum machine drying oven	1800
Total	**1800**



Model technical data	LS-B35L(automatic)	LS-B50L(automatic)	LS-B75L(automatic)	LS-B100L(automatic)
Valid volume	35L(φ318×450)mm	50L(φ340×550)mm	75L(φ400×600)mm	100L(φ440×650)mm
working pressure	0.22MPa			
Working temperature	134			
Max working pressure	0.23 Mpa			
Heat average	≤±1			
Timer	0-99min or 0-99.59hour			
Adjustment of temperature	105134			
Power	2.5Kw/AC220V.50Hz	3Kw /AC220V.50Hz	4.5KW AC220V.50Hz	
Overall dimension	450×450×750(mm)	500×530×980(mm)	550×560×960(mm)	600×580×1100(mm)
Transport dimension	550×550×880(mm)	590×590×1120(mm)	650×620×1120(mm)	670×650×1200(mm)
N/G	45Kg/ 55Kg	50Kg/70Kg	69Kg/90Kg	76Kg/100Kg

Figure 41. Basic Information of the priced forced convective dryer (Binjiang, 2019).

Based on the data available for/in this research, indirect costs (administrative cost, labor costs, insurance fees etc.) will not be considered in the economic evaluation and the economic evaluation will be based on the annual cost of the process per ton of sewage sludge.

4.4.1.1. Cost estimate of energy consumption per ton of processed sludge per year

- **For hydro-char produced (HTC + Mechanical Dewatering + Thermal drying process);**

Total quantity of sewage sludge processed per day = 4237.54 Kg (4.23754 tons)

Total energy consumed per 2118.77 Kg (2.11877 tons) = 1399 MJ

Total energy consumed per day (per 4.23754 tons) = 2789 MJ

From elementary Physics or Calc, (2019).

1 MJ = 1000 kJ / 3600 secs = 0.27777 kW; 0.27777 * 1 hour = 0.27777 kWh

Therefore: 2789 MJ = 0.27777 * 2789 = 774.72 kWh/day

Or

For every processed 4.23754 tons, energy consumed = 2789 MJ

For 1 ton, energy consumed = 658.16 MJ

658.16 MJ = 0.27777 * 658.16 = 182.81 kWh/ton

Based on 4.23754 tons of processed sewage sludge per day, we have;

182.81 * 4.23754 = 774.7 kWh/day

On a 365 days/year basis, we have;

774.7 * 365 = 282,765.5 kWh/year

Therefore, energy consumed to produce hydro-char per year of operation is 282 765.5 kWh.

According to EU Energy Portal, (2019), 1 kWh electricity for medium scale companies costs €0.0912 in Finland as at 1st of January 2019. That is, €0.0912/kWh of electricity.

Energy cost per year to produce hydro-char = 282 765.5 * 0.0912 = €25,788.21

- **For HTC process;**

Energy consumed per 2.11877 tons of SS = 662.90 MJ

For 1 ton of SS, Energy consumed = 312.87 MJ

312.87 MJ = 0.27777 * 312.87 = 86.906 kWh/ton

For 4.23754 tons, we have;

86.906 * 4.23754 = 368.267 kWh/day

On a 365 days/year basis,

Energy consumed = 368.267 * 365 = 134,417.45 kWh/yr.

At €0.0912/kWh,

Energy cost for the HTC process = 134,417.45 * 0.0912 = €12,258.87

- **For Mechanical Dewatering process**

Energy consumed per 2.11877 tons of SS = 6.43 MJ

For 1 ton of SS, Energy consumed = 2.939 MJ

2.939 MJ = 0.27777 * 2.939 = 0.816 kWh/ton

For 4.23754 tons, we have;

0.816 * 4.23754 = 3.459 kWh/day

On a 365 days/year basis,

Energy consumed = 3.459 * 365 = 1,262.53 kWh/yr.

At €0.0912/kWh,

Energy cost for the HTC process = 1,262.53 * 0.0912 = €115.143

- **For Thermal Drying process**

Energy consumed per 2.11877 tons of SS = 706.9 MJ

For 1 ton of SS, Energy consumed = 333.63 MJ

333.63 MJ = 0.27777 * 333.63 = 92.67 kWh/ton

For 4.23754 tons, we have;

92.67 * 4.23754 = 392.70 kWh/day

On a 365 days/year basis,

Energy consumed = 392.70 * 365 = 143,336.60 kWh/yr.

At €0.0912/kWh,

Energy cost for the HTC process = 143,336.60 * 0.0912 = €13,072.29

- **For Carbon Activation process**

For every processed 1 ton of sewage sludge (1000 kg.) energy balance for carbon activation reckons 700 kWh

Therefore, 2.11877 tons (2118.77 Kg) will require 143.139 kWh

4.23754 tons/day of sewage sludge will require 286.278 kWh

∴ Energy consumption per year = 104,491.47 kWh

Energy cost = 104,491.47 * 0.0912 = € 9,529.62

Activation steam flow rate = 3.96 kg/hr. = 3.96 * 8 = 31.68 kg/day

∴ Steam flowrate per year = 31.68 * 365 = 11,563.2 kg

Cost of steam = € 17.80/ton (Rio et al, 2006)

Cost of steam for carbon activation = 438,000/1000 * 17.80 = € 7,796.4/yr.

4.4.1.2. Calculations on linear depreciation

- **Linear Depreciation of HTC equipment**

Using double-declining balance depreciation method; based on a 3 years life span.

Linear depreciation = 2 * 100%/3 = 66.66%

Yearly linear depreciation will be taken as the average of the linear depreciation throughout the HTC equipment lifespan.

1st year = 66.66% * Total cost/value of the HTC equipment ($67,000.00 = €58,960.00 at the rate of $1 = €0.88) = 66.66/100 * 58,960 = €38,913.6

2nd year = 66.66% * present HTC equipment value (58,960 – 38,913.6) = 66.66/100 * 20,046.4 = €13,362.9

3rd year = 66.66% * (20,046.4 – 13,362.9) = €4,455.22

Therefore, Yearly linear depreciation = (38,913.6 + 13,362.9 + 4,455.22)/3 = €18,910.57 yr^{-1}

- **Linear Depreciation of Filter Press mechanical dewatering device**

Linear depreciation = 2 * 100%/3 = 66.66%

Cost of Filter press = $1600 = €1,408

1st year = 66.66% * (1600 * 0.88) = 66.66% * €1408 = €938.57

2nd year = 66.66% * (1408 – 938.57) = €312.92

3rd year = 66.66% * (469.43 – 312.92) = €104.32

∴ Yearly linear depreciation = (938.57 + 312.92 + 104.32)/3 = €677.90

- **Linear Depreciation for Convective thermal dryer**

Linear depreciation = 2 * 100%/3 = 66.66%

Cost of the thermal dryer = $1800 = 1800 * 0.88 = €1,584

1st year = 66.66% * €15848 = €1055.89

2nd year = 66.66% * (1584 – 1055.89) = €352.03

3rd year = 66.66% * (528.11 – 352.03) = €176.08

∴ Yearly linear depreciation = (1055.89 + 352.03 + 176.08)/3 = €528

- **Linear Depreciation of Activation column (Carbolite furnace and its accessories)**

Linear depreciation = 2 * 100%/3 = 66.66%

Total cost of Carbolite furnace and requisite accessories = £ 23,277.31 = 23,277.31 * 1.16 = €27,001.67

1st year = 66.66% * €27,001.67 = €17,999.31

2nd year = 66.66% * (27,001.67 – 17,999.31) = €6,000.9

3rd year = 66.66% * (9002.35 – 6,000.9) = €2000.72

∴ Yearly linear depreciation = (17,999.31 + 6,000.9 + 2000.72)/3 = €8,666.97

4.4.1.3. Equipment maintenance cost for the entire process

Maintenance cost is taken as 1% of the investment cost (in this case it is the cost of purchasing the equipment).

The table below summarizes the result of the economic analysis.

Table 13. Synopsis of the Economic/Financial Implication of the Project.

Production Stage / Economic Quantity	**Hydrothermal Carbonization**	**Mechanical Dewatering**	**Thermal Drying**	**Carbon Activation by Steam**
Equipment cost	€ 58,960.00	€ 1,408	€ 1,584	€ 27,001.67
Equipment Linear depreciation over 3 years	€ 18,910.57	€ 677.90	€ 528	€ 8,666.97
Maintenance cost	€ 589.6	€ 14.08	€ 15.84	€ 270.01
Energy consumption	134,417.45 kWh/yr.	1,262.53 kWh/yr.	143,336.60 kWh/yr.	104,491.47 kWh/yr.
Energy Cost (€0.0912/kWh)	€ 12,258.87/yr.	€ 115.143/yr.	€ 13,072.29/yr.	€ 9,529.62/yr.
Steam flow/consumption	-	-	-	3.96 kg/hr. or
Cost of consumed steam per year	-	-	-	€ 205.82
Total cost per year	€ 31,759.04	€ 807.123	€ 15,200.13	€ 18,672
Total cost per 100 kg of produced activated carbon (or per 2.11877 tons of processed waste	€ 43.50	€ 1.10	€ 20.82	€ 25.58

water sewage sludge)				

∴ Total cost of producing 100 kg of activated carbon = 43.50 + 1.10 + 20.82 + 25.58

= **€ 91**

Total cost per year (or of producing 73 tons of AC) = 31,759.04 + 807.123 + 15,200.13 + 18,672

= **€ 66,438.29**

4.4.2. Sensitivity analysis

This analysis studies how changes in the assumed ***selling price*** of a unit of produced activated carbon (A.C) and units of A.C produced or ***sold*** per annum influence the ***estimated profit*** with respect to their individual magnitude of influence.

Data from research;

1 unit = 100 kg of produced Activated Carbon
200 kg of produced A.C per day = 2 units sold or produced per day
73,000 kg of produced A.C per year = 730 units sold or produced per year
A.C production cost per unit = € 91
Production cost per year or for producing 730 units of A.C = € 66,430 (~66,438.29 due to roundoff error)

Assumptions:

1. ***Unit Price of A.C = € 120*** (reasonable assumption judging by general online cost price A.C from biomass)
2. The entire 730 units or 73,000 kg of A.C produced yearly are sold.

3. 10% change in the selling price variable (120 euros/unit or 100 kg) and Units of A.C sold per year (730 units/year) for calculating the variables (selling price and units produced) influence on estimated profit

Account Statement

Revenue = units of A.C produced per year * Unit Price of A.C = 120 * 730 = **€ 87,600**

Yearly Cost of Sales or Project cost estimation for a year = 91 * 730 = **€ 66,430**

∴ **Estimated Profit** = 87,600 – 66,430 = **€ 21,170**.

Table below presents it comprehensively.

	Assumptions (Expected)	Estimated Profit
Selling Price/unit of A.C	€ 120	+ € 87,600
Production cost/unit of A.C	€ 91	- € 66,430
Units sales of A.C/year	730	
		€ **21,170**

	Assumptions (10% worse)
Selling Price/unit of A.C	€ 108
Units sales of A.C/year	657

When selling price is € 108;

Estimated profit = (108 * 730) – (91 * 730) = € 12,410

When Unit sales of A.C/year is 657;

Estimated profit = (120 * 657) – (91 * 657) = € 19,053

Estimated profit variation due to changes in selling price = (21,170 – 12,410) / 21,170 = 0.4137 * 100% = 41.37%

Estimated profit variation due to changes in unit sales per year = (21,170 – 19,053) / 21,170 = 0.1 * 100% = 10%

The table below presents the result

	Assumption (10% worse)	Estimated Profit (€)	Variation (compared to € 21,170)
Selling Price/unit of A.C	€ 108	12,410	- 41.37%
Units sales of A.C/year	657	19,053	- 10%

From the result of the sensitivity analysis, it is obvious that between the selling price/unit of A.C produced variable and the yearly unit sales of A.C variable, changes in the selling price of A.C per unit produced sway more influence (- 41.37%) over the estimated profit of the project in a year than the annual unit sales of A.C (- 10%). For a 10% decrease in selling price from 120 euros to 108 euros, there is consequent 41.37% reduction in annual estimated profit from 21,170 euros to 12,410 euros.

4.4.3. Annualized rate of return

Rate of Return = [(Ending value of investment/Beginning value of investment) $^{1/\text{years}}$ – 1] * 100

Ending Value of Investment = Annual estimated profit

= 120 * 730 = € **87,600**

Beginning value of Investment = Annual estimated cost of production

= 91 * 730 = **€ 66,430**

Project lifespan = 3 years

∴ Rate of Return = [(87,600 / 66,430) $^{1/3}$ – 1] * 100 = **9.66 %**

The 9.66 % of the rate of return calculation implies that at the end of the business year after pertinent accounts are balanced, 9.66% of the initial investment will be recouped. It also implies that in the long haul or throughout the project's life (3 years), 28.98% of the investment will be recouped, provided conditions remain the same or at least as estimated.

5. CONCLUSION

With respect to the production of activated carbon with wet biomass as a feed, hydrothermal carbonization serves as an auspicious tool to prepare or produce hydro-char with suitable physical (required pore size and volume) and chemical (adequate oxygenated functional groups) structure for carbon activation.

This research in its absoluteness responded specifically to the '*economic implication, material and energy balance of the production of 100 kg of activated carbon via hydrothermal carbonization process'* questions extended by the case company (Woima Coorporation) within the boundary or scope or delimitation of the research. Scatter plot, correlation and regression analysis tools were applied with excel software for data analysis.

From the result of the analysis and subsequent calculations, approximately 2.12 tons of waste water sewage sludge (~2120 kg) and 0.70666 tons (~706.66 kg) of fresh water both at room temperature (25 ^{0}C) and pressure (1 bar) going through the carbonization stage (HTC reactor, mechanical dewatering, and thermal drying) and carbon activation stage at carbonization operating temperatures and holding time of 210 ^{0}C and 30 mins and carbon activation temperature and holding/activation time of 760 ^{0}C and 30 mins respectively are required to produce 100 kg of activated carbon in approximately four hours (4 hr.). The energy balance results and also subsequent calculation estimated 1339 MJ as total required energy for the sewage sludge carbonization sub-stages (HTC reactor, mechanical dewatering, and thermal drying) and a 2520 MJ of energy required (including the energy of steam with volume flowrate of 2.5 Lmin^{-1}) for the carbon activation stage both stages operated at the choice operating conditions.

The economic implication of the entire project which integrated assets linear depreciation, maintenance costs, energy and equipment costs, sensitivity analysis and annualized rate of return, estimated a € 91 cost of producing 100 kg of activated carbon with a BET surface area of 226 within approximately four (4) hours at a 9.66 % rate of return on investment with selling price variable being the most influencial variable with respect to estimated yearly profit. This estimated cost which falls below market value of activated carbon and the calculated rate of return implies that the production of activated carbon within the boundaries or delimitations of this research is economically favorable.

In future, research within this context should consider the integration of aspects such as the logistics and specifics on the availability, treatment revenue, and indirect costs associated with the carbonization and subsequent carbon activation of sewage sludge or any other biomass under consideration.

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