Techno-Economic Assessment for Valorisation of Waste Sawdust Biomass to Biochar Based Capsules

S. D. Maramba
Department of Chemical and Process Systems Engineering,
School of Engineering and Technology, Harare Institute of Technology,
Zimbabwe
sdmaramba@hit.ac.zw

I.Mutadza
Department of Chemical and Process Systems Engineering,
School of Engineering and Technology, Harare Institute of Technology,
Zimbabwe
imutadza@hit.ac.zw

M. M. Manyuchi
Department of Operations and Quality Management,
Faculty of Engineering and the Built Environment,
University of Johannesburg,
South Africa
mercy.manyuchi@gmail.com

N. Sukdeo
Department of Operations and Quality Management,
Faculty of Engineering and the Built Environment,
University of Johannesburg,
South Africa
nsukdeo@uj.ac.za

Abstract

In this study, the production of activated biochar capsules from sawdust for multipurpose medicinal use was investigated as a value addition strategy. The sawdust was chemically activated using phosphoric acid at a temperature of 450 °C in the absence of oxygen to give a 52.2% of activated biochar from the sawdust. The activated biochar's ash content was 4.0%, moisture content 2.0% and the iodine number 431 mg/g. A process was designed for the production of activated biochar capsules for multipurpose medicinal use. An environmental analysis was done taking for proper site selection and plant layout. An economic analysis carried out indicated a return on investment of 44% and a payback period of 2.3 years. Saw dust can be economically value added to activated biochar capsules as a waste management initiative.

Keywords:
Activation, biochar, economic assessment, saw dust, techno-assessment, waste valorisation

1. Introduction

Health care in the developing countries is expensive and a few people can afford it leading to high mortality rates (Bloom et al. 2004; (Odesola and Owoseni 2010)). Usually health aspects as dental care, skin care and digestive system care in the developing countries are overlooked since more emphasis is put on major diseases such as malaria and cholera due to the high cost of the medication (Bloom et al. 2004; (Noor et al. 2015). On the other hand, the timber industry in Zimbabwe produces close to 10 000 metric tonnes of saw dust per year of which 10% of it is used as an energy source and the rest is dumped in the areas close to the sawmills (Makonese 2016). The underutilisation of this sawdust in the past years has led to land pollution and veld fires as local people have tried to burn them and it led to uncontrollable fires ((Mohan et al. 2015; Xu et al. 2021). This waste saw dust has potential to generate greenhouse gases such as carbon dioxide and carbon monoxide that can destroy the environment through contribution to climate change (Abdullah and Wu 2009; Zhang et al.2019). The sawdust can however be useful in production of activated biochar capsules for multipurpose medicinal uses as a waste valorisation strategy.

1.1 Characteristics of sawdust found in Zimbabwe

Sawdust is a by-product of cutting and grinding of saw dust and is composed of fine particles of wood. Sawdust in Zimbabwe is scattered all over and is from various sawmills. The sawdust is sold at a very cheap price of roughly a dollar for a 50 kgs bag (Makonese 2016). Sawdust is made up of three major components which are cellulose, hemicellulose and lignin. Lignin protects the cellulose and hemicellulose from enzymatic attack by some microorganisms (Abdullah and Wu 2009; Liu and Han 2015).). Cellulose is the most abundant in sawdust as it contains carbon which activate to form activated biochar for multipurpose medicinal uses.

1.2 Activated bio char characteristics

Activated biochar is a fine black odourless and tasteless powder made from biomass that have been exposed to very high temperatures in an airless environment ((Jahirul et al. 2012; Ahmad et al. 2014). Biochar is a porous carbon with an increased surface area available for adsorption. Activated biochar has millions of tiny pores between the carbon atoms so as to improve its adsorption properties (Birzer et al.2014; He et al. 2019). The activated biochar has a large surface area of about 2000- 3000 m^2/g making it highly effective at adsorbing pathogens and poisons. Activated biochar has a modified graphite-like structure due to the presence of micro crystallites, formed during carbonization (Brassard et al.2016; (Ghani et al.2019)). During activation the biochar has their regular bonding interrupted causing free valences which are reactive. Furthermore, the presence of impurities and process conditions influence the formation of interior vacancies in the microcrystalline structure.

1.3 Types of Activated biochar capsules and their uses

Activated biochar capsules are a natural treatment used to trap toxins in the body allowing them to be flushed out so the body does not reabsorb them. Activated biochar works by trapping toxins through its pores since it is very porous (Downie et al. 2009; Chen et al. 2019). The principle of operation of the activated biochar is a chemical process called adsorption whereby the toxins will bind to the surface of the biochar. The activated biochar surface is negatively charged so it causes the positively charged toxins to bond with it leaving the human body free of toxins. The types of biochar capsules include: soft capsules and hard capsules (Claoston et al. 2014; Dewayanto et al. 2014). Biochgar capsukes can be used for teeth whitening, gas alleviation, mold cleanimg, water filtration, emergemcy toxins removal and as an anti-aging ingredient (Duan et al. 2019; Fisher et al. 2019; Ouyang et al. 2023).

1.4 Activating the Carbon in Sawdust

The sawdust is activated using the physical and chemical methods. Physical activation involves carbonization of a carbonaceous material using steam followed by the activation of the resulting biochar at temperatures between 600-1200 ^{0}C in the presence of oxidizing gases such as carbon dioxide or steam (Rahman et al. 2014). In the steam activation volatile compounds are removed and the layer of carbon atoms is peeled off and this enlarges the pores. In chemical activation the sawdust is mixed with a chemical agent and then pyrolyzed between 450-900 ^{0}C in the absence of air. After the pyrolysis, process phosphoric acid is added to activate the biochar under high temperatures (Rezaee et al. 2021). The activated biochar is then washed to remove the acid and then thoroughly dried afterwards. Chemical activation has advantages in that it is carried out in a single step combining carbonization and activation, performed at lower temperatures resulting in the development of a better porous structure. Since less energy is required for the chemical activation then it becomes more affordable as compared to the physical activation. Since the chemical method requires lower temperature, it is the most favourable process that will be adopted in this work.

1.5 Pyrolysis

Pyrolysis is the thermal decomposition of organic matter in a limited supply of air, leading to the release of volatiles and formation of biochar (Safari et al. 2019). Pyrolysis in wood is typically initiated at 200-500 ^{o}C, depending on the species of wood.

1.6 Composition of sawdust

The major constituents of wood are cellulose, hemicellulose and lignin (Suliman et al., 2016). Cellulose is taken to be 50% and the other two 25% each by dry weight. Cellulose is a glucon polymer consisting of linear chains of d-glucopyranose units. Cellulose component constitutes 45-50% of the dry wood (Uçar and Karagöz 2009). At temperatures less than 300 ºC, the dominant process is the reduction in degree of polymerisation. In the second step, at temperatures above 300 ºC, there is formation of biochar, tar and gaseous products. Hemicellulose is a mixture of polysaccharides mainly composed of glucose, mannose, galactose, xylose, arabinose and galacturonic acid residues (Verma et al., 2012). Hemicellulose content varies from 20-40%. Hemicellulose decomposes in the temperature range 200-260ºC and as compared to cellulose, hemicellulose gives rise to more volatiles, less tar and biochar. Lignin is the main binder for agglomeration of fibrous components. The lignin component in biomass such as saw dust varies between 17-30% (Tu et al. 2019). Lignin decomposes when heated between 280-500ºC. Biochar is the abundant constituent in the products of lignin pyrolysis with a yield of 55%.

1.7 Scope of study

This study is of producing activated biochar capsules from sawdust for multipurpose medicinal use thereby cutting costs of production and making the medicine very affordable at the same time promoting biomass waste management to mitigate climate change. The activated biochar capsules are used for various purposes that include alleviation of gas and bloating, treating alcohol poisoning, body health and teeth whitening. In each case the activated biochar capsules works with the principle of adsorption where by it binds with the positively charged toxins.

2. Materials and Methods

Four experiments were carried out and these are: activation of carbon in the sawdust, characterisation of the activated carbon, varying the temperatures for carbon activation and varying the activation time for the biochar.

2.1 Activation of carbon in sawdust

Firstly, the sawdust, which was obtained from a local saw milling plant in Mutare Zimbabwe, was sieved with a 0.5-1.0 mm sieve to achieve uniform size. The sawdust was then weighed and the initial weight was recorded then it was washed with distilled water to remove dust and ash and left to dry in the oven at temperatures of 110 ^{0}C (Wang et al. 2015). The drying is done to reduce moisture in the sawdust at least by 3%. The sawdust was then weighed again and then mixed with 90 mLs of phosphoric acid to make a paste of the activator and the sawdust. The paste was then wrapped in a foil paper to ensure absence of oxygen in the activation of the carbon. The sawdust was put in a muffle furnace at temperature of 450 ^{0}C for an hour and a half. The activated biochar produced was then rinsed with distilled water to wash away the activation agent which was phosphoric acid and dried at low temperatures of 110 ^{0}C. The final step was the weighing of the activated biochar to determine yield the of activated biochar. The yield of the activated biochar was calculated as indicated in Equation 1.

Percentage $Y_{\text{activated biochar}} = 100*(M_{\text{activated biochar}}/M_{\text{raw material}})$…………………………..(1)

Where: $M_{\text{activated biochar}}$ is the mass of the activated biochar produces and $M_{\text{raw material}}$ is the initial mass of sawdust before activation

2.2 Characterisation of activated biochar

The characterisation of activated biochar was done using five tests which are the moisture content, ash content, iodine number, test on decolourising properties of activated biochar, the test for deodorisation property of activated biochar and determination of ash content (Xu et al. 2021).

2.2.1 Determination of moisture content

Moisture content determines the amount of water content in the biochar (Xu et al., 2021). Storage and transportation conditions of the activated biochar is likely to alter the moisture content of the activated biochar. The moisture content analyses were done using an HC103 moisture analyser, a balance and a stop watch. A sample of activated biochar of 20g was made put in the oven at a temperature of 110 ^{0}C for 10 minutes. The initial mass of the activated biochar was measured and recorded then after heating in the oven the final mass of the activated biochar was also recorded. The same sample was put back in the oven for another 10 minutes and this was done continuously until the difference between initial and final mass was ±0.1 grams. Three replica experiments for moisture content were carried out with the same initial mass and their final masses were recorded. The moisture content is calculated using Equation 2.

$$\text{Moisture content (\%)} = \frac{\text{Initial sample weight} - \text{Final sample weight}}{\text{Initial sample weight}} \times 100 \ldots\ldots(2)$$

2.2.2 Test on decolourising properties of activated biochar

Water was placed in a beaker and a drop of food colouring was added into the beaker. A funnel with a filter paper was placed on a test tube. The funnel was then about quarter filled with activated biochar. The coloured water was then slowly poured in the filter paper containing activated biochar. The water was then collected in the test tube and the colour changes were observed and compared with the initial colour (Yu et al. 2019).

2.2.3 Test for deodorising property of activated biochar

A funnel with a filter paper quarter filled with activated biochar was placed on a test tube which was in a test tube rake (Zhang et al. 2019). Some malt vinegar was then placed in the funnel and it was allowed to pass through the activated biochar and it entered the test tube. The vinegar was then smelled and compared to the initial smell before passing through the activated biochar. The smell of the vinegar was then noted for analysis.

2.2.4 Determination of ash content in the activated biochar

A sample of activated biochar of 50g was put in an open crucible and placed in the oven at temperatures of 575-625 ^{0}C (Abdullah and Wu 2009). The temperature was kept constant and the biochar remained in the oven for at least three hours. Some ash remained in the crucible and then it was weighed and the mass was recorded and calculated as indicated in Equation 3.

Percentage $\text{biochar}_{\text{ash}} = 100*(M_{\text{ash}}/M_{\text{biochar}})$……………………………………….…………..(3)

Where: M_{ash} is the mass of the ash remaining in the crucible and M_{biochar} is the mass of biochar initially placed in the crucible.

2.2.5 Determination of iodine number of activated biochar

The iodine number gives an indication of the internal surface area of activated biochar (Ahmad et al., 2014) and is defined as the number of milligrams of iodine adsorbed from an aqueous solution by 1g of activated carbon when the iodine concentration of the residual filtrate is 0.02N. Two drops of starch solution were added to a conical flask containing 10 cc of 0.1N Iodine solution. The pale yellow colour of iodine solution then immediately turned blue. This solution was then titrated with 0.05N Sodium Thiosulphate until it became colourless. The burette reading was then recorded (B). Then 0.2 gm. of activated carbon were weighed accurately and introduced into a completely dry iodine flask.40 cc of 0.1N Iodine solution were added and into the flask and it was vigorously shaken for 4 minutes and filtered. The filtrate was collected in a dry flask and 10cc of the filtrated was titrated against a standard Sodium Thiosulphate solution using starch as an indicator. The burette readings were taken and they corresponded to (A). Lastly the iodine number was calculated which is represented in Equations 4 and 5.

Iodine number equal = C x Concentration factor; mg/gm as indicated ……………………..(4)
Factor = (Molecular weight of iodine (127) x normality of iodine x 40/Wt. of carbon)…….(5)

Where C is equal to B minus A.

2.3 Effect of temperature on biochar yield

The effect of temperature on biochar yield was investigated. This experiment was done to determine the temperature with the highest yield of activated biochar (Birzer et al., 2014). Temperatures were varied from 450–600 ^{0}C. The sawdust was activated within the same period of time but just varying temperature with 50 ^{0}C and noting the yield of activated biochar which was achieved.

2.4 Effect of varying the activation time

The effect of the activation time was also investigated. In this experiment the ideal temperature for the production of activated biochar was used and the temperature was held constant whilst varying the activation time of the sawdust. The time was varied from an hour up to three hours with each batch having an increase of 30 minutes in time. The yield of activated biochar obtained were noted for comparison and analysis. All experiments were replicated thrice and an average used.

3. Results and Analyses

A detailed analysis was carried out on the results obtained from the experiments and these gave rise to conclusions.

3.1 Activation of carbon in sawdust and biochar yield

The saw dust was activated using phosphoric acid. A black substance which is biochar was formed and had a yield of 52% of biochar from the sawdust that was loaded.

3.2 Moisture content analysis

In this case the moisture content was calculated using the average final masses recorded for a set of experiments recorded. The average moisture content was 2.0%.

3.3 Decolourising properties of activated biochar

During the test of decolourization, some green food colouring were added into water and the water was slowly poured in a funnel containing activated biochar. The water changed its colour after passing through activated biochar. A pale pink colour which was almost colourless was observed and this confirmed the decolourising property of the activated biochar.

3.4 Deodorising properties of activated biochar

The deodorisation properties of biochar was tested using malt vinegar. Malt vinegar has a strong smell and it was passed through activated biochar in a filter paper. The smell of the malt vinegar became very mild and it lost its original very strong properties. This shows that the activated biochar has deodorising properties.

3.5 Determination of ash content in activated biochar

The average ash content was found to be 4.02%. The average ash content according to literature for activated char varies from 2-5% so 4.0% is in the correct range showing that the results were successful.

3.6 Determination of iodine number analysis

The iodine number analysis showed that the activated biochar has a high internal surface area of 431 mg/g making it a good adsorbing agent for pathogens. This high internal surface area is achieved by the production of the activated biochar at the optimum conditions which ensure optimum performance.

3.7 Effect of varying the temperature for activation analysis

A range of temperatures from 450 -600 ^{0}C was used in this experiment (see Figure 1). This was to determine the experiment with the highest yield of activated biochar. The high temperatures of 450-600 ^{0}C allow the degradation of the hemicellulose and cellulose and also allows the formation of a carbon structure. There is a very small difference in the yield of the activated biochar within that range of temperatures. The differences in yield show that as temperature increases the yield of activated biochar decreases and this is due to the thermal decomposition of the lignin. The temperature with the highest yield is 450 ^{0}C and at that temperature the carbon structure would have been formed, thus it is the most ideal temperature for the activation of carbon as it is economic whilst achieving the best results as well.

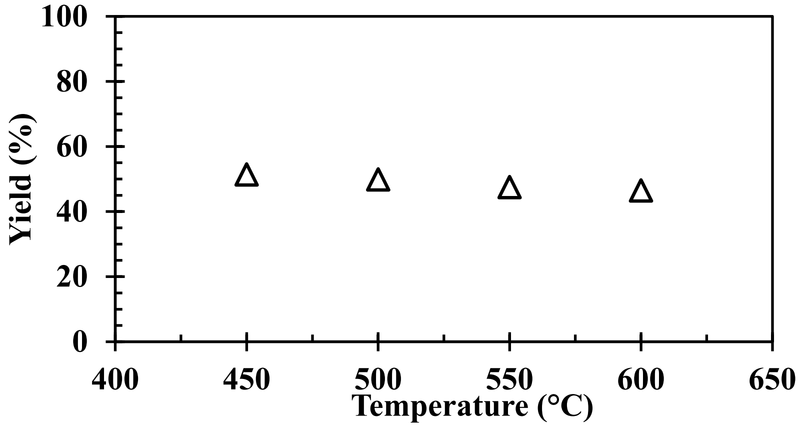

Figure 1. Effect of temperature on yield of activated biochar

3.8 Effect of varying activation time analysis

This experiment was done to determine the best time for the production of the activated biochar. This is to achieve the best activated biochar whilst considering energy costs thus the adequate time should be used for the activation of biochar. The temperature was held constant at the optimum temperature of 450 ^{0}C. There is a very high yield of 62.3% of biochar at an hour of pyrolysis because within an hour the degradation of the hemicellulose and the cellulose would not have taken place. However, at an hour and a half the degradation of the cellulose would have taken place leading to the yield decreasing to 52.2% and at this stage the surface area of the biochar would have increased making it highly efficient for adsorption. As the residence time increased the yield continued to decrease but at a very low rate showing that degradation of hemicellulose and cellulose at occurred. This led to a conclusion that the optimum time for activation of carbon is 1 hour 30 minutes has it is energy saving whilst achieving the best structure of the activated biochar. In Figure 2 it can be noted that the yield becomes almost constant at 1.5 hours to 3 hours showing that the optimum time is 1.5 hours.

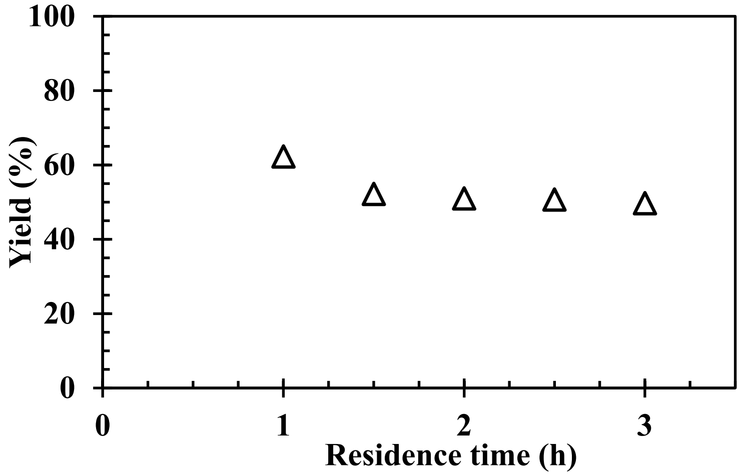

Figure *2*. Effect of residence time on biochar yield

4. Process Design

The process design makes use of the experimental results so as to come up with basic assumptions design for block flow diagram, material and energy balances for the entire process for biochar based capsules from saw dust.

4.1 Process description

Activated biochar is usually produced using two methods which are the steam and chemical activation. Since steam activation requires very high temperatures than chemical activation the, chemical activation is used in this process since it requires lower energy and has a shorter production time.

4.1.1 Sawdust sieving, washing, drying and activation

The first stage is the sieving of the sawdust to remove unwanted matter that include stones, leaves and sand. This is done to ensure that the final product is of high quality. The sawdust is washed to remove small particles of dirt that would not have been removed using the sieve so as to make sure that it is in its pure form. Soon after washing the sawdust is then put in a rotary dryer then dried at temperatures of about 110 ^{0}C so as to remove excess moisture from the washing of the sawdust. The sawdust is impregnated with phosphoric acid and a paste is made. The sawdust and phosphoric acid are mixed in a ratio of 1:0.5 respectively and they are thoroughly mixed to make a homogenous mixture.

4.1.2 Pyrolysis of saw dust

The sawdust paste is put in a foil paper and then tightly packed in a crucible to ensure absence of oxygen during the pyrolysis reaction. Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. Pyrolysis involves the simultaneous change of chemical composition and physical phase, and is irreversible. Pyrolysis was done at temperatures of 450 ^{0}C for an hour and a half which is the reaction time needed. The non-carbon elements which include hydrogen, oxygen, traces of sulphur and nitrogen are first removed in a gaseous form by pyrolytic decomposition.

4.1.3 Water wash and acid recovery

The activated biochar is washed to remove the phosphoric acid that would have been used for the activation process. The filtrate is recycled back to the process for acid recovery. This phosphoric acid is then reused in the activation of another batch of activation of biochar.

4.1.4 Drying and crushing

The washed activated biochar is then dried up using a spray dryer at temperature of 110 ^{0}C so as to remove all the moisture. The moisture is removed to avoid the agglomeration of the activated biochar and so as to store it at best conditions at which it is best preserved. After drying the activated biochar is then crushed to achieve a smaller size with a surface area ranging from 400-2000m^2.After activation the biochar will be having large particles as those of sawdust but after crushing the activated biochar becomes a fine powder.

4.1.5 Preparation of biochar capsules and encapsulation

The activated biochar is measured to prepare it for encapsulation. One capsule has a mass of 260mg so the activated biochar is measured into 260 mg sachets. The capsules are supplied as closed units which means the top and bottom part of the capsule will be closed. Before use, the two halves are separated, usually the upper half has a greater diameter than the lower half. So the capsules are arranged in preparation for the encapsulation. The encapsulation process is when the measured activated biochar is put in hard gelatine capsules. The capsule is filled with powdered activated biochar. One half of the capsule is filled with the activated biochar and the other half of the capsule is pressed on. The lower half with a smaller diameter is filled with biochar and the upper half is then pressed on and it thereby closes the capsule. A summary of the biochar based capsules production process is shown in Figure 3.

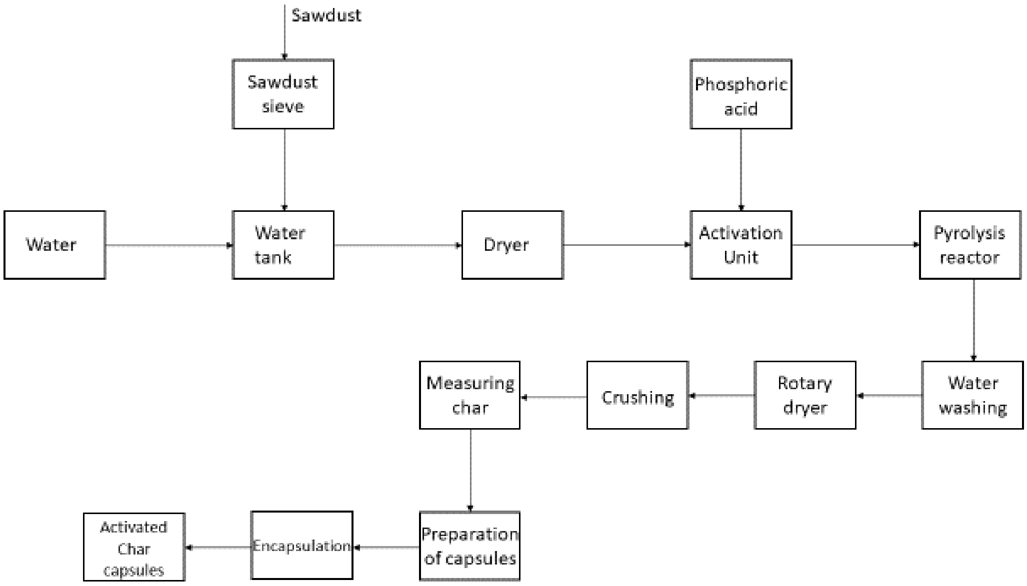

Figure *3*. Block flow diagram for the production of activated biochar capsules

4.2 Mass balances for the process

Mass balances are done to account for the amount of material used in the process and to also know the yield and see if the process is viable. The mass balances were done using the black board approach and also taking into consideration the law of conservation of mass which states that mass is neither created nor destroyed but just changed from one form to another.

4.2.1 Planned production

The planned plant produces 36.4 tonnes of activated biochar per year and it operates for 240 days per year thus an average of 150 kgs of activated biochar is produced per day. The activated biochar produced per day is then 3600 kg divided by 240 days to give 150 kgs per day. All the mass balances will be carried out using the conservation of mass which states that mass in less mass out plus generation less consumption is equal to accumulation. Assuming that the plant operates for 240 days per year and that a single batch per day is being processed. For industrial scale the basis was 150kgs of activated char produced per day for encapsulating.

4.2.2 Scale up factor and calculations of the raw materials required

If 0.18kg/day of sawdust produced 0.094 kg/day of activated biochar thus the required raw material will be calculated as 150 kg per day divided by 0.094 kg to get 1596. Sawdust required will be equal to the mass of sawdust in experiment multiplied by the scale up factor to get 287 kg per day. After washing the sawdust and rinsing the biochar some losses occurred of about 4% of the sawdust so to obtain 150kg/day the feed must be increased by 4.0% and a mass of feed of 299 kg/day. Amount of water required is equal to mass of water in experiment multiplied by the scale up factor to get 383 kg per day. Amount of phosphoric acid required for activation is equal to mass of phosphoric acid in experiment multiplied by the scale up factor to get 144 kg/day.

4.3 Component mass balances

4.3.1 Mass balance for the washing tank

The assumptions made was mass in is equal to mass out in kgs per day as indicated in Table 1. There are 2% losses of the initial sawdust mass in washing.

Table 1. Mass balance for the washing tank

Component	**Mass in**	**Mass out**
Dry dirty sawdust	299	
Water	383	
Dust and water	-	369
Wet sawdust	-	313
Total	682	682

4.3.2 Mass balance for the dryer

The assumptions made was using mass in equal to mass out in kgs per day as indicated in Table 2. The dryer is 100% efficient. The water vapour is equal to mass of wet sawdust input -mass of dry sawdust.

Table *2*. Component mass balance for the dryer

Component	**Mass in**	**Mass out**
Wet sawdust	313	-
Water vapour	-	20
Dry sawdust	-	293
Total	313	313

4.3.3 Mass balance of the activation unit

The assumptions made was the mixer is 100% efficient and mass in equals to mass out in kgs per day as indicated in Table 3. The sawdust is completely dry**.** Mass of paste is equal to mass of dry sawdust and the mass of phosphoric acid.

Table *3*. Mass balance for the activation unit

Component	**Mass in**	**Mass out**
Dry sawdust	293	-
Phosphoric acid	144	-
Paste	-	437
Total	437	437

4.3.4 Mass balance for the pyrolysis reactor

The assumption made was mass in is equal to mass out in kgs per day as indicated in Table 4. The reactor is 100 % efficient. There is 52.2% yield of activated biochar. The mass of volatile matter is equal to mass of dry sawdust and mass of phosphoric acid) less making up the paste less mass of activated biochar (52.2% of the mass of the dry sawdust).

Table 4. Mass balance for the pyrolysis reactor

Component	**Mass in**	**Mass out**
Dry sawdust	293	-
Phosphoric acid	144	-
Activated biochar	-	153
Volatile matter	-	284
Total	437	437

4.3.5 Mass balance for the washing tank 2

The assumptions made was mass in is equal to mass out in kgs per day as indicated in Table 5. In addition, 2.2% of the activated biochar is not recovered after washing.

Table 5. **Mass balance for the washing tank 2**

Component	**Mass in**	**Mass out**
Activated biochar	153	-
Water	200	180
Wet activated biochar	-	170
Activated char losses	-	3
Total	353	353

4.3.6 Mass balance for the spray dryer

The assumptions made was the dryer is 100% efficient. Mass in is equal to mass out in kgs per day as indicated in Table 6. Amount of activated biochar leaving the dryer for encapsulation is 150 kg/day

Table *6.* Mass balance for activated biochar

Component	**Mass in**	**Mass out**
Wet activated biochar	170	
Water vapour	-	20
Dry activated biochar	-	150
Total	170	170

4.4 Energy balances assumptions

Energy balance are essential in the plant as they give a balance between the energy input into the system and the energy output out of the system as according to the law of conservation of energy, energy is neither lost nor created but just converted from one form to another (Chen et al., 2019). There are basically three types of energy which are kinetic energy which is due to the translational motion of the system, potential energy which is due to the position of the system in a potential field and internal which is all energy possessed by the system other than kinetic or potential. The general law of conservation of energy shall be applied in this section which states that: Energy out is equal to energy in and generation less consumption is equal to Accumulation. According to the first law of thermodynamics which is represented in Equation 6:

$$U + KE + PE = Q - W \text{……………………………………………………………………}(6)$$

Where: U is internal energy, KE is kinetic energy, PE is potential energy, Q is heat added to the system and W is the work done by the system.

Initial temperature is at room temperature which is 25 ^{0}C. There is no heat loss due to radiation. The parameters being considered were: specific heat capacity (C_{PW}) of water is 4.187 kJ/kg°C. Specific heat capacity (C_{Ps}) of sawdust is 0.9 $J.g^{-1}K^{-1}$. Latent heat of vaporization of water is 2250 J/kg. The feed rate of the process is 299kg/day. Heat loss from the dryer (shell radiation) is 10% of the inlet heat energy

4.5 Energy balance for the rotary dryer

The first energy consuming process in the process is the drying of the sawdust after washing it. This is done to remove the moisture from washing so that it is dry before the pyrolysis process. The dryer operates at temperatures of 110 ^{0}C and heat is used as a driving force for evaporation as indicated in Table 7.

Table *7.* Thermal properties of a biochar spray dryer

Parameter	**Value**
Datum temperature	0°C = 273K
Inlet stream temperature	25°C = 298K
Temperature within the dryer	110°C = 383K
Outlet temperature	110°C = 383K
Specific heat capacity of vapor	4184 J/kg/K
Specific heat capacity of sawdust	900 J/kg/K

Inlet stream

Heat in sawdust $= \mathrm{mCp\Delta T}$ = 299Kg/day x (900J/kg/K) x (298-273) K =6 727 500 J/day =77.8 J/s =7.8 x 10^1 Watts……………………………..…….(7)

Inlet stream enthalpy $= \mathrm{Q} + 7.8 \times 10^1\mathrm{W}$

Outlet stream

Heat in sawdust $= \mathrm{mCp\Delta T}$ =299kg/day x (900J/kg/K) x (383-298) K =22 873 500 J/day =246.74 J/s =2.467 x 10^2 Watts…………………………………….……..(8)

Heat in vapour $= \mathrm{mCp\Delta T}$ $= 293\mathrm{kg/day} \times 4184\ \mathrm{J/KgK}(383 - 273)\mathrm{K}$ =1560.77 J/day =1.5607 x 10^3 J/s = 1.5607 x 10^3 Watts…………………...…………(9)

Outlet streams =2.467 x 10^2 Watts +1.5607 x 10^3 Watts = 1807.47 Watts=1.80747 x 10^3 Watts ………………………………………….…………………………………..(10)

Overall balance

$(\mathrm{mC_p\Delta T})_{\mathrm{in}} + \mathrm{Q} = (\mathrm{mC_p\Delta T})_{\mathrm{out}} + (\mathrm{mC_p\Delta T})_{\mathrm{v}}$.

Q = 2.5 x 10^2 Watts +1.6 x 10^3 Watts-7.8 x 10^1 Watts =1.7 x 10^3 Watts………………………………………………………..…………..…(11)

Steam evaporation enthalpy is 2056 kJ/kg/K (From steam tables). Therefore : Amount of drying steam required:

$= \frac{\mathrm{Q}}{\text{Steam evaporation enthalpy}} = \frac{1.7\times 10^3\mathrm{J/s}}{2056\mathrm{kJ/kgK}}$ = 0.8 kg/s…………………..…………...…..(12)

4.6 Energy balance for the pyrolysis reactor

Q = mCpΔT……………………………………………………………………..(13)

The pyrolysis reactor operates at temperatures of 450 ^{0}C.

Q = 293 kg/day x 900 J/kg/K x 723.2K =190 694 655J =1.9 x 10^9 J…………………(14)

This is a coal fuelled reactor and energy gained by sawdust is equal to energy supplied by the coal. The calorific value of coal is 30 MJ/tonne.

Mass of coal = Energy gained/ calorific value. = 1.9 x 10^9J / 30x 10^6J.Kg^{-1} = 63.6 Kg…………………………………………………………………………………(15)

4.7 Energy balance for the spray dryer

The thermal properties of the drier are shown in Table 8.

Table 8. Thermal properties of the drier

Parameter	Value
Datum temperature	0°C = 273K
Inlet stream temperature	25°C = 298K
Temperature within the dryer	110°C = 383K
Outlet temperature	110°C = 383K
Specific heat capacity of vapor	4184J/kg/K
Specific heat capacity of activated char	768 J /kg/ K

Inlet stream

Heat in sawdust $= \mathrm{mCp\Delta T}$ = 150 kg/day x (768J/kg/K) x (298-273) K =2 880 000J/day =33.3 J/s =3.3 x 10^1Watts…………..……..(16)

Inlet stream enthalpy $= \mathrm{Q} + 3.3 \times 10^1\mathrm{W}$……………………………………..……(17)

Outlet stream

Heat in sawdust $= \mathrm{mCp\Delta T}$ =150 kg/day x (768 J/kg/K) x (383-298) K = 9 792 000 J/day =113.3J/s =1.13 x 10^2 Watts……………………………………………………………………………..(18)

Heat in vapour $= \mathrm{mCp\Delta T}$ $=150\ \mathrm{kg/day} \times 4184\ \mathrm{J/KgK}(383 - 273)\mathrm{K}$ =69 036 000 J/day =799.0J/s = 799.0Watts = 8.0 x 10^2Watts………………………………………………………………………….……..(19)

Outlet streams =1.1 x 10^2 Watts + 8.0 x 10^2Watts = 912.0 Watts =9.1 x 10^2 Watts ……………………………………………………………………………………..(20)

Overall balance

$(mC_p\Delta T)_{in} + Q = (mC_p\Delta T)_{out} + (mC_p\Delta T)_v$……………………………………………..(21)

$Q = 1.1 \times 10^2$ Watts + 8.0×10^2Watts-3.3×10^1Watts
 =878.7 Watts =8.8×10^2 Watts…………………………………………..………...…(22)

Steam evaporation enthalpy is 2056kJ/kgK (From steam tables). Therefore : Amount of drying steam required: $= \frac{Q}{\text{Steam evaporation enthalpy}} = \frac{8.7873 \times 10^2 \text{J/s}}{2056\text{kJ/kgK}}$ = 0.427 kg/s……………….…(23)

4.8 Energy balance for the sieve

The assumptions made were that energy in is equal to energy out. The motor requires 1hp per day. The total energy required by the sieve was 735.5 Watts (735.5J/s).

4.9 Energy balance for the crusher

Average size reduction of activated biochar from 106μm to 75μm requires effective energy of 2 KW (kg/s). Now for size reduction from 150 μm to 106 μm. Assuming Rittinger's law applies.

$E = K_P F_C [(1\backslash L_2) - (1\backslash L_1)]$, Therefore $2 = K_P F_C [(1\backslash 0.08) - (1/0.1)]$……………….……..….(24)
$K_P F_{C\,=}\, 2/ [(1\backslash 0.08) - (1/0.1)] = 0.5$………………..…………………………..……(25)
$E = K_P F_C [(1\backslash L_2) - (1\backslash L_1)] = 0.513\ [(1\backslash 0.1) - (1\backslash 0.2)] = 1.4$ KJ/s = 1419.6 J/s…………….(26)

4.10 Energy balance on a pump balance on the pump

The general balance equation is represented by Equation 28.

$\Delta H + \Delta E + \Delta P = Q + W$……………………………………………………………..…(28)

Where: ΔH = Change in enthalpy, ΔE = Change in kinetic energy, ΔP = Change in potential energy, Q = Heat transferred and W = Work done.
Phosphoric acid is being pumped at velocity of 10ms^{-1} and a height of 3m

Kinetic energy

$\Delta E = \frac{1}{2}mv^2 = \frac{1}{2} \times 144$ kg/day x $(10\text{ms}^{-1})^2$ = 0.08 kgm^2/s^3 =0.08 Watts……….………(29)

Potential energy

$\Delta P = mgh$ =144 kg/day x 9.8 $\text{ms}^2 \times -3\text{m}$ = -0.05 $\text{kgm}^2\text{s}^{-3}$ = - 0.05 Watts……………..….(30)
$\Delta Q = 0$…………………………………………………………………………………………(31)
The process is adiabatic therefore there is no heat loss or heat gain
$\Delta H = \Delta U + PV = C_v\Delta T + PV$………………………………………………………………(32)
$\Delta T = 0$ ………………………………………………………………………………..…(33)
It is because they are no change in temperature
$\Delta H = PV$……………………………………………………………………………………(34)
The pump operates at a pressure of 1atm.
1atm = 101325Pa = 101325 N/m^2…………………………………………………..……..(35)
Volume the fluid

$V = \frac{m}{\rho} = \frac{144\text{kg/day}}{1880\text{kg/m3}}$ = $7.7 \times 10^{-2}\ \text{m}^3$/day =$8.9 \times 10^{-7}\ \text{m}^3$/s………………....(36)

Enthalpy

$\Delta H = PV$= 101325 $\text{kgm}^{-1}\text{s}^{-2} \times 8.9 \times 10^{-7}\ \text{m}^3/\text{s}$= 0.09 Watts……………..…………………(37)
$\Delta H + \Delta E + \Delta P = Q - W$= 0.09 Watts +0.08 Watts - 0.05 Watts ………………..………...(38)
$-W$ = 0.1 Watts………………………………………………………………………….(39)

5. Selected Process Equipment Design

In this section a detailed design of the major equipment required in the process is done. The most important aspects of design to be considered are: functionality, must operate safely minimizing the risks of explosion, easy to maintain, minimum operating costs and must be able to work with varying capacity. The major equipment in the production of activated biochar capsules are the rotary dryer and the pyrolysis reactor.

5.1 Pyrolysis reactor

The pyrolysis reactor must have certain principle features to function at its optimum level and these include: the size of the reactor, dimensions of internal structures, the composition and physical condition of the products from the reactor (Table 9). The composition of the products must lie within limits set in the original specification of the process. The temperatures within the reactor must be made for heat transfer. There are several types of pyrolysis reactors and they are classified on the way the solids move through the reactor. There are four major types which are batch reactors, shaft furnaces, rotary kiln and fluidized bed. The most common and economic pyrolysis reactor for biochar is the batch reactor and s ince the sawdust is put in the reactor at once and removed when the biochar is produced it is the most suitable type of pyrolysis reactor. The most critical step in designing a pyrolysis reactor is to obtain kinetic data that describes the system.

Table 9. Pyrolysis reactor design specification

Parameter	**Description**
Number required	1
Function	Pyrolysis of sawdust to produce biochar
Type	Batch
Operation	Batch pyrolysis reactor
Temperature	450 ºC
Reactor volume	3.8 m^3
Residence time	1.5 hours
Cross-sectional area	10.3 m^2
Reactor diameter	1.5 m
Height of reactor	2.7 m
Area	18.8 m^2
H/D	1.5
Material of construction	Mild steel

5.2 Design of a dryer

There are various factors to be considered when designing a dryer which are material of construction, drying requirements, production requirements and product quality among others as indicated in Table 10.

Table 10. Decision matrix for the dryer selection

Criteria	**Requirement**	**Rotary dryer**	**Spray dryer**	**Fluidised bed dryer**
Particle size	-	4	5	4
Temperature	110ºC	3	4	4
Space	Moderation	5	4	4
Final and initial moisture	2-8%	3	4	3
Cost	Low	2	4	2
Mode of operation	Batch	3	5	1
Total		**20**	**26**	**18**

The spray dryer is the most suitable dryer for the process according to the decision matrix in Table 10. The spray dryer produces powders of controllable sizes and overall quality. Other characteristics that are considered include: the bulk density, degree of crystallinity and solvent levels. The spray dyer is assumed to be 70% efficient. The washed activated biochar is to be dried from 1.5 wt.% to 0.3 wt.%. The spray drier selection criterion is shown in Table 11.

Table 11. Spray dryer material selection

Process condition	**Selection factor**
Fairly high temperature	110 ºC
Moist feed	Rust resistant material
Attrition forces on tower wall	Abrasion resistant to avoid easy wear

Pressure build up	High tensile strength
Process Economics	Selection factor
Fabrication	Affordable since product is sold at middle range price
Cost	Material should be affordable

The best material for the above considerations which include best performance and cost effective is mild steel. The design parameters of the spray drier are shown in Table 12.

Table *12*. Chemical engineering design parameters of the spray dyer

Parameter	**Description**
Settling velocity (V_s)	0.08 m/s
Operating velocity(V_a)	0.2 m/s
Column diameter	1.4 m
Column area	1.1 m^2
Residence time	24.5 s
Droplet moisture evaporation time	0.05s
Chamber dimensions	
Cylindrical height (H_{cyl})	2.7m
Height of bottom cone (H_{bcon})	1.2 m
Height of top cone (H_{tcon})	0.5 m
Total volume of chamber	4.4 m^3
Volume of bottom cone (V_{bcon})	0.6 m^3
Volume of top cone (V_{tcon})	0.3 m^3
Top cone angle (A)	110.3°
Bottom cone angle (B)	59.5°
Mechanical design	
Working pressure	0.1013 N/m^2
Design pressure	0.152 N/m^2
Permissible stress of material	124 N/m^2
Material of construction	Mild steel
Length of dryer	5.91m

6. Process Control and HAZOP Analysis

This section focuses on the hazard and operability study (HAZOP) of the process equipment designed. The detailed HAZOP was performed on the major equipment which are the pyrolysis reactor and the rotary dryer. The main objective of the process control is to maintain the process at optimum conditions safely and efficiently.

6.1 Process control for a pyrolysis reactor

The major control variables and parameters that have to be measured and controlled in a pyrolysis reactor are as follows: temperature-the temperature in the pyrolysis reactor should range from 450-500°C so that the pyrolysis of sawdust occurs at an optimum temperature with a maximum yield. Pressure-the pressure in the pyrolysis reactor should be controlled to avoid the bursting of the reactor due to pressure build up from the vapours and the gases that are released in the in the process. The process control diagram for a pyrolysis reactor is shown in Figure 4.

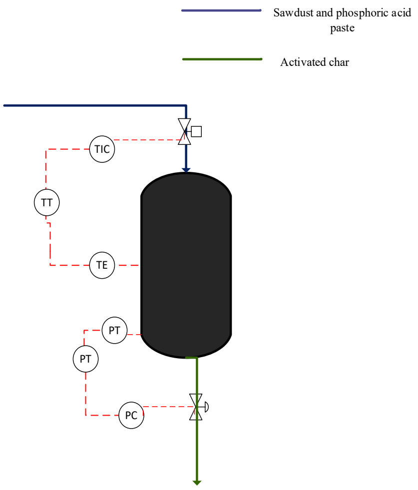

Figure *4*. Process control diagram for a pyrolysis reactor for biochar production

A temperature for the pyrolysis of sawdust is going to be maintained at 450°C. The temperature of the feed fuel will be controlled using the temperature transmitter which measures the temperature using a thermocouple then transmits it to the temperature control for monitoring. The transmitter converts the temperature to current signals proportional to the temperature measured. From the temperature control the temperature is then monitored and assessed .If there is a temperature ±10°C from the required temperature then the temperature is regulated by a temperature regulator.

The pressure for the reaction is the atmospheric pressure which is held constant for the reaction. In the pyrolysis reaction various gases and volatile matter is released which may subsequently lead to pressure increase in the reactor. The reactor has a control loop composed of the pressure sensor, a controller, alarm for notification and a safety relief valve. The pressure sensor is linked to the transmitter which will transmit the pressure to the fluid velocity. The safety relief valve will then open to release the pressure in the reactor so that it returns back to the optimum temperature by depressurizing.

6.2 Process control for a spray dryer

The resistance temperature detector is used to measure the temperature. Its resistance increases with increasing temperature and the opposite is true. The required spray drier temperature which is 110 °C with an allowance of ±10°C of temperature variance. If the temperature is lower or higher than the optimum temperature, then a signal is sent to the temperature transmitter which then converts the resistance to a measurement of temperature and is transmitted to the temperature indicator and controller. The temperature indicator and controller will then compare the output to control the temperature.

The pressure is controlled by a pressure controller which receives a signal from the transmitter. The pressure is controlled using by the closing and opening of the valve. If there is a pressure build up, then the relief valve will be opened to allow a decrease in pressure. The relief valve will open at a predetermined pressure to protect the spray dryer from being subjected to pressure exceeding its design limits. The flow controller will be monitoring the flow of the hot air into the spray dryer. The flow transit will ensure the flow and then transit it to the flow indicator and controller. This is very important because if flow of air is very low then it may lead to under drying of the activated biochar. If the flow is too much then a pressure build up may result leading to bursting of the spray dryer. The process control diagram for a spray dryer is show in Figure 5.

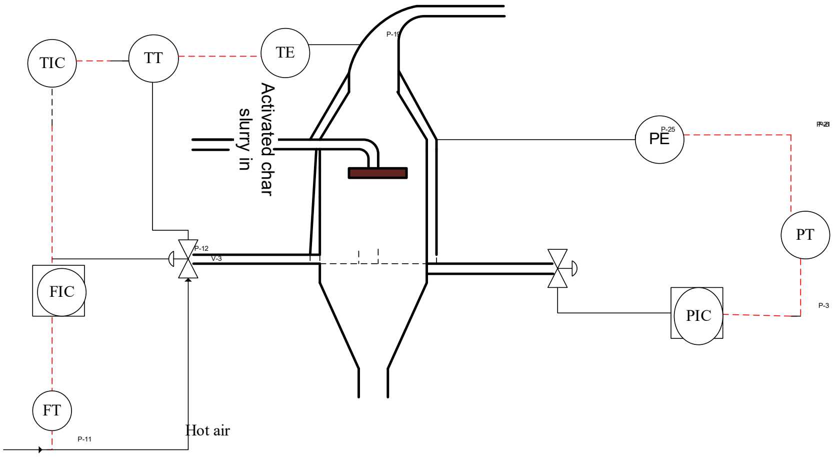

Figure *5*. Process control diagram for a spray dryer

6.3 HAZOP analysis

A hazard and operability study (HAZOP) is a systematic critical examination of a planned or an existing process in order to identify and evaluate problems that may represent risks to equipment or personnel or prevent efficiency operation.

Any operation inside the design envelope that would cause a shutdown that could lead to a violation of environmental, health or safety regulations or negatively impact profitability. The guide words are used for temperature, pressure, flow and level (Table 13). Any possible deviation of these variables from normal operation is considered and the possible causes and consequences of these deviations are noted as well. The consequences of these deviations on the process are then assessed. The measures needed to correct the implications of the deviations are then developed. The HAZOP analysis was done for the pyrolysis reactor and the spray drier as shown in Table 14 and Table 15.

Table 13. The guide words for the HAZOP study

Guide Term	**Description**
More of	More of a parameter means that it will be above the standard requirements and should be lowered
Less of	Less of a parameter means that it will be below the standard requirements and should be increased
High	There will be a rise from the standard
Low	There will be a decrease from the standard
Reverse	This is usually wrong routing for example failure of a pump leading to a reverse flow
Other	This refers to what needs to happen other than normal operation and this includes start up, shutdown and maintenance

Table *14*. HAZOP Analysis for a pyrolysis reactor

Parameter	**Guide Term**	**Possible Cause of Disturbance**	**Consequence Of Disturbance**	**Correction Measure**
Temperature	More of	Malfunctioning or fault in the heating system	The ashing of the char due to very high temperatures	An automated temperature control
	Less of	Malfunctioning or fault in the heating system	The pyrolysis reaction will take a longer period of time and will not be effective	An automated temperature control
Pressure	High	Blockage in the line	Bursting of the pyrolysis reactor leading to injuries or fatalities and damage to the equipment and plant	Installation of pressure relief valves and highly sensitive pressure alarms
Flow	More of	Malfunction of the pump or the valve	Overflow and spillage could cause electric faults and compromise the quality of the char	Installation of flow alarms and pump and valve replacement
	None	Malfunction of the pump or the valve	Bursting of pipes and failure to activate the char	Always check valves and pumps

Table *15*. HAZOP Analysis for the spray dryer

Parameter	**Guide Term**	**Possible Cause of Disturbance**	**Consequence Of Disturbance**	**Correction Measure**
Temperature	More of	Malfunctioning in the heating system	Burning of the char being dried and run away reactions	An automated temperature control
	Less of	Malfunctioning in the heating system	Decreased rate of the moisture removal and inefficient drying	An automated temperature control
Pressure	High	Line blockage	Bursting of the dryer leading to damage of equipment and injuries or fatality of operators	Installation of a highly sensitive pressure alarm and a relief valve
	Low	Line blockage	Inefficient drying of the activated char	Installation of a highly sensitive pressure alarm
Flow	High	Malfunctioning of the valve that controls the flow of the hot air	Pressure build up due to very high amount of hot air in the dryer	Monitoring the valve so that the required amount of hot air enters

	Low	Malfunctioning of the valve that controls the flow of the hot air	Under drying of the activated char	Monitoring of the valve

7. Environmental Impact Assessment
This section assesses the environmental impacts that result from the process of the production of activated biochar capsules from sawdust. The aim of this is to come up with mitigation and prevention measures so as to keep the environment safe. The assessment covers the impact on land, water and living organisms caused by gaseous, liquid and solid pollutants produced from the process. The environmental assessment impacts are classified in five major categories which are: project planning, site clearance and preparation impacts, construction works impacts, operation, production impacts and decommissioning impacts.

7.1 Project Planning Impacts
Planning usually has no environmental impacts since it is mostly the paper work and meetings to discuss on how the project will be carried out.

7.2 Site clearance and preparation impacts

7.2.1 Soil erosion and proposed mitigation measures
Soil erosion is the removal of topsoil faster than the soil forming processes can replace due to natural, animals or human activities. Soil erosion is a result of vegetation clearance, excavation and construction works for the plant for production of activated biochar capsules leaving the ground bare. The soil erosion may then lead to siltation in nearby rivers. Site clearance should be done on only the portion to be used for construction to minimize the area exposed to erosion. The exposed soil should be temporarily bund to redirect flows from heavy runoff areas that threaten to erode or result in substantial surface runoff.

7.2.2 Dust and proposed mitigation measures
Large amounts of particulate matter mainly dust will be generated during the clearance of the land. This may be worsened during the dry season and when wind is most prevalent. Air borne particulates may pose a health hazards which include respiratory infections, bronchitis and asthma to workers as well as the residents in the vicinity downwind of the site being constructed. Keeping the access points as the driveway and areas around wet to prevent or minimise dust from rising. Stockpiles of fine materials the activated char should be wetted or covered with tarp during windy conditions.

7.2.3 Destruction of natural habitats and ecosystem and proposed mitigation measures
Some natural habitats of living organisms such as birds, mice and squirrels maybe destroyed during land clearance as the trees are removed which are natural habitats. Food for some organisms is also removed and this affects the ecosystem. Trees and grass are food for some browsers and herbivores. Clearance should only be limited to the area of development so as to destroy habitats of some living organisms. There should be no side tipping of excavated materials or cleared vegetation unto areas outside the footprint.

7.3 Construction works impact

7.3.1 Construction waste and proposed mitigation measures
Some construction waste is generated during construction and these include some rubbles, and broken bricks. If not correctly disposed of these may degrade the land and also injure human beings. A disposal place should be in place for the correct disposal of the construction matter. Vegetation may have to be burned elsewhere and that should be catered for. Unusable construction waste, such as damaged pipes, formwork and other construction material, must be disposed at an approved dumpsite.

7.3.2 Land degradation and proposed mitigation measures
The material for construction is obtained mostly from the quarry and the mining areas. Deliberate or unwitty purchase of these materials from unlicensed operations indirectly supports, encourages and promotes environmental degradation at the illegal quarry sites and causes long-term negative impacts on the land that it becomes unsuitable for use. Purchase the materials required for the construction from licensed sellers that legally mine the material and are conscious of the environment.

7.3.3 Material transportation and proposed mitigation measures

Sometimes transportation of material is done with open trucks that will not be covered. The trucks usually transport particulate matter and due to wind it then affects quality of air in the surrounding areas. All trucks carrying earth material must be covered to avoid dusting and spillage. In case of spillage of the construction material then a clean-up should be done within the first few hours to avoid road accidents

7.4 Operation and production impacts

7.4.1. Release of gases and proposed mitigation measures

The process of making activated bio char involves pyrolysis a process in which various gases and volatile matter are produced. Gases such as carbon dioxide and carbon monoxide are produced and these gases cause global warming when released in the atmosphere. Over and above they also affect the human health when inhaled as they cause respiratory infections and irritate the eyes. There is need to build very high chimneys and towers so that the plume rises to a higher level so that when it settles on the ground the concentration will be less. Facilitate for complete combustion during the pyrolysis reaction. Resort to the use of catalytic converters which converts all those noxious gases to harmless products. The use of scrubbers and electrostatic precipitators to treat exhaust gases before releasing them into the atmosphere

7.4.2 Phosphoric acid spillage and proposed mitigation measures

Phosphoric acid is used as an activation agent in the production of activated biochar from sawdust. Phosphoric acid is harmful if not stored or handled properly in the plant. If the phosphoric acid is spilled in water bodies, then it may also result in eutrophication and algae growth in the water bodies. Eutrophication is a situation in which a body of water receives an increased supply of plant nutrients which provide the conditions for the rapid growth Phosphoric acid is used for the activation of carbon so there is need to store it safely and prevent spillage. Clearly labelling the containers with the acid so that they are treated cautiously. There is need to treat the water used for washing the activated biochar when roving phosphoric acid so that it is disposed with acceptable amounts of phosphoric acid. There is need to recover a large amount of phosphoric acid so that it can be used in the recycle stream

7.5 Decommissioning impacts

Unemployment rate will be increased as many employees will be left jobless and this has negative impacts that include increase in crime rate and poverty. There is need to train workers for entrepreneurship so as to generate income in cases of losing their jobs. Ghost sites creation. Before the plant decommissioned the facilities should be used for other purposeful projects

8. Site Selection and Plant Layout

This section highlights the various reasons considered for selecting the location of the plant for production of activated biochar capsules from sawdust which is Mutare. It shows factors that will be considered when the plant will be set which include its operations. In addition, it gives a description of the plant layout and the setup as well as arrangement of various pieces of equipment within the plant.

8.1 Site selection

Site selection shows the practice of new facility location, for business, industry and government. Site selection involves analysing and measuring the needs of the project of producing activated char capsules against the advantages of potential locations. There should also be room for expansion when considering site location. There are various factors considered for site selection and these factors should lead to an economic production. The factors considered include these: availability of raw materials, transportation facilities, industrial infrastructure, availability of raw water, availability of power, availability of manpower, disaster preparedness in terms of safety and security, political strategic considerations, local community considerations, environmental impact and effluent disposal and climate.

8.1.1 Availability of raw material

The availability of raw material will affect the selection of site as the major raw material for production of biochar is sawdust and it is bulky therefore to reduce transport cost the plant must be located close mill plants. The other raw materials that are required are phosphoric acid and hard gelatine which are not bulky and are usually supplied by chemical companies as Cure-chem or can be imported from nearby countries as South Africa.

8.1.2 Transportation facilities

The final product is a 260mg capsule which can be easily transported even in very large quantities. Thus the plant can be located even far from the market but closest to the raw materials since they are the ones that are bulky.

However, for efficient transportation of the raw material there is need for good quality roads that will be used by trucks for transporting the capsules.

8.1.3 Availability of raw water

The plant must be situated close to a source of raw water which is very important in the production of activated biochar capsules. Water is firstly used for the initial washing of sawdust then it is later on used for removal of the phosphoric acid in the activated biochar thus a large amount of water is required. Site selection is therefore dependant on availability of water preferably close to a local river.

8.1.4 Availability of power

Power in the form of electricity is a very major requirement in the process since there is many major equipment that require large amounts of power. The pyrolysis reactor, the rotary dryer and spray dryer require power for them to function. Thus when selecting a site, the issue of power should be considered. the plant should be located where there is sufficient supply of electricity.

8.1.5 Availability of manpower

Manual labour will be required in the plant for several tasks like loading of the sawdust and other raw materials. Skilled personals will also be required in the plant and these can be outsourced and these will be responsible for maintenance, monitoring the process and for the management of the plant.

8.1.6 Disaster preparedness in terms of safety and security

During the operation of the plant so many accidents may occur which include bursting of acid storage tanks and the burning of equipment and employees by the pyrolysis reactor. There is need to then select a site that is very close to hospitals and clinics or roads that reach hospitals. There should also be training centres to inform the people of the possible dangers associated with staying close to the plant and how to deal with possible accidents.

8.1.7 Local community considerations

The activated biochar capsules plant should be acceptable by the community. The site of the plant should not affect the day to day lives of the people that live close by. The community should also be able to offer basic requirements like accommodations, shopping areas, schools and hospitals to the employees of the plant.

8.1.8 Environmental impact and effluent disposal

During the production of activated biochar there are gases released in the atmosphere such as carbon dioxide. These gases can be a nuisance and a health hazard to those residing close by thus when selecting a site such factors should be considered and the plant should be a reasonable distance away from the houses. In addition to that should be suitable places for the disposal of some waste material that are produced in the process. The disposal of toxic and harmful effluents will be covered by local regulations.

8.2 Suitable sites for biochar plant

The suitable areas for location of the activated biochar plant are Harare, Mutare and Chimanimani. These places will be logically analysed to determine the best site that will be most advantageous for the plant using the Kepner -Tregoe Situation Analysis (KT analysis). The KT analysis which is a practical way of decision making was used for site selection as indicated in Tables 16-19.

Table *16*. Harare (Mbudzi) Site

Selection factor	**Description**
Availability of raw materials	The raw material is fairly available but will not sustain a long period of time
Transportation facilities	The roads are well maintained and transport is readily available
Industrial infrastructure	There is no industrial infrastructure available in that area
Availability of raw water	Water can be supplied from Manyame river which is not very close
Availability of power	Power is readily available for use

Availability of manpower	Manpower from close by residential areas is available
Disaster preparedness in terms of safety and security	There are several hospitals and clinics that are available
Political strategic considerations	There are less benefits since it's a place with already existing industries
Local community considerations	Schools and accommodation are readily available since it is a developed place
Environmental impact and effluent disposal	It is strategically located a bit far from city center where waste can be safely discharged

Table *17*. Mutare site

Selection factor	**Description**
Availability of raw materials	The raw material is available very large quantities. Mutare has so many sawmills with the largest sawmill in Zimbabwe situated jus 65km from Mutare thus abundant raw material
Transportation facilities	The roads are well maintained and transport is readily available
Industrial infrastructure	There is industrial infrastructure available in that areas where sawmills are
Availability of raw water	Water can be supplied from several rivers that include Sakubva river, Odzi river rand Save river thus enough water is available
Availability of power	Power is readily available for use
Availability of manpower	Manpower from close by residential areas such as Chikanga and Sakubva where there is high rate of unemployment is available
Disaster preparedness in terms of safety and security	There are several hospitals and clinics that are available
Political strategic considerations	There are benefits since it's a place with high unemployment
Local community considerations	Schools and accommodation are readily available since it is a developed place
Environmental impact and effluent disposal	There may be difficulty in discharging waste and effluent since there are no designated places

Table *18*. Chimanimani Site

Selection factor	**Description**
Availability of raw materials	The raw material is available in fairly large quantities
Transportation facilities	There are poor roads therefore it will be difficult to transport the product to various locations
Industrial infrastructure	There is no industrial infrastructure available in that area
Availability of raw water	Water can be supplied from Save river
Availability of power	Power is not readily available since the area is mostly remote and underdeveloped
Availability of manpower	Manpower from close by residential areas is available since most people are unemployed

Disaster preparedness in terms of safety and security	There hospitals and clinics that are very few and at a distance
Political strategic considerations	There are benefits since it's a place with high rate of unemployment and is remote with no industries
Local community considerations	Schools and accommodation are limited and not readily available
Environmental impact and effluent disposal	There are no designated places for waste disposal

Table *19*. KT Decision Matrix Table

Criterion	**Rank**	**Site Performance (P)**			**Site Total Score**		
	Weight	Harare	Mutare	Chimanimani	Harare	Mutare	Chimanimani
Availability of raw materials	10	4	10	6	40	100	60
Transportation facilities	10	8	7	3	80	70	30
Industrial infrastructure	7	4	5	3	28	35	21
Availability of raw water	9	4	7	5	36	63	45
Availability of power	10	8	8	5	80	80	50
Availability of manpower	10	10	10	7	100	100	70
Disaster preparedness	8	6	5	4	48	40	32
Political strategic considerations	9	3	5	6	27	45	54
Local community considerations	8	6	6	3	48	48	24
Environmental impact and effluent discharge	9	5	7	4	45	63	36
Total	88	66	63	79	532	644	422

According to the KT decision matrix the highest total is 644 for Mutare making it the most suitable site for the location of the plant. The plant will be cost effective since it will be located very close to the raw materials which are bulky therefore reducing the cost of transportation.

8.3 Plant layout

A plant layout is used to analyze different physical outlines for a manufacturing plant and is also known as facilities planning and layout. A plant layout focuses on the physical arrangement of equipment, machinery, tools and furniture so that the flow of material is quickest and most efficient.

Proper and efficient utilization of available space, transportation of work from one point to the next without any delay. Easy supervision and control, reduce accidents and provide for employee safety and health. In addition, reduction of material handling cost and provide for volume and product specification.

9. Biochar Plant Utilities Requirements

This section shows the resources that are required to run the plant at an optimum level incorporating the quality, quantity and the source. Some of the major requirements of the plant include the power and water which are very critical in running the day to day proceedings of the plant. The utilities that are required by the activated biochar plant include raw materials, water, diesel steam and electricity.

9.1 Raw materials

The plant processes 72 tonnes/year of sawdust to produce 36 tonnes per year of biochar which in turn produce 48 979 591 (735mg capsules) activated biochar capsules per year. This implies that 299kgs per day of raw material yields about 150kgs and 204 081 capsules per day.144kg/day of phosphoric acid is required thus per year 34.560 tonnes of phosphoric acid are required.

9.2 Water

The plant requires some distilled water for cleaning the sawdust to remove some dust and unwanted matter that would not have been removed by the screen. The distilled water is also used to wash away phosphoric acid the biochar that is used to activate the biochar. There are other several uses of water that include the cleaning of the equipment and drinking. All the water that is used in the plant is recycled for later use. A total of 500 L/day is required on a daily basis.

9.3 Electricity

Electricity is used to run different equipment in the plant that include the major equipment which are the pyrolysis reactor, spray drier and the screen. A total of 0.1MW is required to run the plant.

9.4 Steam and diesel

The rotary dryer uses the steam from the spray dryer to dry the sawdust after washing it and roughly about 15kg/s of the steam is required for drying.

The diesel is used as an emergency source of fuel in cases of electricity load shedding. Diesel will be used for the spray dryer as well as the rotary dryer and about 1000litres/day will be required. Standard heat of combustion of diesel is 44.8MJ/kg (H) and it has a density of diesel is 0.832kg/L.

10. Economic Analyses

The economic analysis is the assessment of the economic feasibility of the project and its capital requirements. Several parameters such as the payback period, the rate of return on investment and breakeven point are considered.

10.1 Capital cost estimation

Capital cost is the total cost required to bring the project to an economically viable status. The capital cost estimation of the project was done using a factorial method for estimation of material cost from prices in the local market.

10.2 Working capital

Working capital is required for the day to day running of the biochar plant and it includes the cost of the raw materials required for the production of activated biochar capsules from sawdust.

10.3 Fixed capital cost

Fixed capital cost is the capital required to set up the equipment. The fixed capital costs are broken down into direct costs and indirect costs. Two equipment are going to be fabricated and these are the spray dryer and the pyrolysis reactor. The bill of quantities was prepared to determine the costs of the equipment as indicated in Table 20.

Table *20*. Cost of equipment for biochar based capsules

Quantity	Equipment	Unit cost (USD)	Total cost (USD)
1	Pyrolysis reactor	9 123.00	9 123.00
1	Spray dryer	36 374.55	36 374.55

1	Screen	800.00	800.00
2	Washing tank	4 500.00	9 000.00
2	Acid tank	9 000.00	18 000.00
1	Encapsulating machine	21 000.00	21 000.00
1	Rotary dryer	8 500.00	8500.00
2	Storage tank	5 000.00	10 000.00
2	Water tanks	2 000.00	4 000.00
1	Activation unit	7 900.00	7 900.00
1	Crusher	5 000.00	5 000.00
Grand total			129 697.55

10.4 The factorial method of cost estimation

Capital cost estimates for chemical process plants are often based on an estimate of the purchase cost and fabrication cost of the equipment items in the plant required for the process. The other costs are then estimated as factors of the equipment cost. The factorial method of cost estimation as represented by Equation 40.

$C_f = f_L Ce$……………………………………………………………………………(40)

Where: C_f is fixed capital cost, C_e is the total delivered cost of all major equipment items, F_L is the Lang factor which depends on the type of process, F_L =3.1 for predominantly solids processing plant, F_L =4.7 for predominantly fluids processing plant and F_L =3.6 for a mixed fluids solids processing plant. In this case it's a fluid-solid system so the factors to be used are for the fluid-solid system.

10.5 Direct costs

Direct costs consist all major processing equipment, installation material required for the equipment, labour and the supervision required for complete equipment installation. The cost of equipment was calculated from prices and quotations taken from local suppliers as shown in Table 21.

Table 21. Direct costs

Lang factor	**Item**	**Percentage of equipment**	**Cost (USD)**
Major equipment	Plant equipment cost	-	129 697.55
f_1	Equipment erection	0.45	58 363.90
f_2	Piping	0.45	58 363.90
f_3	Instrumentation	0.15	19 454.63
f_4	Electrical	0.10	12 969.76
f_5	Buildings process	0.10	12 969.76
f_6	Utilities	0.45	58 363.90
f_7	Storage	0.20	25 939.51
f_8	Site development	0.05	6484.88
f_9	Ancillary buildings	0.20	25 939.51
Total			408 547.30

Total physical plant cost = PCE $(1+f_{1+}f_{2......}f_9)$ =129 697.55 (3.15) =USD408 547.28……(41)
The indirect costs are shown in Table 22.

Table *22.* Indirect costs

Lang factor	**Item**	**Percentage of direct costs**	**Cost (USD)**
F_{10}	Design and engineering	0.25	102 136.82
F_{11}	Contractor 's fee	0.05	20 427.36
F_{12}	Contingency	0.10	40 854.73
Total			163 418.91

Fixed capital investment= PPC $(1+f_{10}+f_{11}+f_{12})$ = USD408 547.28 (1.4) = USD571 966.19………………………………………………………………………………..(42)

This can also be calculated by using the known fact that fixed capital investment is the sum of direct cost and indirect cost which is equal to USD571 966.19. It was assumed that the working capital was 10% of fixed capital investment. Working capital is 10% of the working capital (USD 571 966.19) which is USD57 196.62.

10.6 Total capital investment

This is the total capital required for both plant set up and the day to day running of the plant. Total capital investment consists of the fixed capital and the working capital and the total is USD626 162.81.

10.7 Total direct product cost

The total direct product cost is shown in Table 23.

Table 23. Estimation of direct product cost

Raw material	**Amount required**	**Cost (USD)**
Phosphoric acid	34 560 kg	27 420.00
Sawdust	71 760kg	1435.20
Total		28 855.20

10.7.1 Utilities cost

An assumption was made that cost of utilities are 20% of raw material cost. This gave a total utilities cost of USD5 771.04.

10.7.2 Maintenance and repair cost

The cost was assumed as 10% of Fixed Capital investment. Therefore, the maintenance cost was USD57 196.62.

10.7.3 Operating labour and supervision costs

The cost was assumed as 10% of raw material cost. This gave a total operating labour and supervision costs of USD2 885.52.

10.7.4 Laboratory and other service costs

It was assumed to be 1% of raw material cost. The total laboratory and other service cost was USD288.55.

10.7.5 Total direct production costs

the total direct production cost was determined by adding the raw material cost, utilities costs, maintenance and repair costs, operating labour, supervision and laboratory costs. the total direct production cost was usd94 996.93.

10.8 Fixed costs

Fixed costs are expenses that do not vary in total when the level of output by the business varies. These include costs for depreciation, local property taxes, insurance and rent. Expenses of this type are a direct function of the total capital investment. These charges amount to roughly about 10-20% of the total product cost.

10.8.1 Depreciation

Depreciation is the reduction in asset value over time due to wear and tear. The depreciation was assumed to have a value of 10% of the fixed capital investment to get USD57 196.62.

10.8.2 Insurance costs

Insurance costs were assumed to be 3% of fixed capital investment. This gave a value of USD17 158.99.

10.8.3 Local taxes

The local taxes were calculated as 2% of fixed capital investment. This resulted in a value of USD11 439.32.

10.8.4 Total fixed cost

The total fixed cost was calculated as the total sum of the depreciation cost, insurance cost and the local taxes. This gave a total fixed cost of USD85 794.93.

10.9 Plant overhead costs

Plant overheads are also referred to as manufacturing overheads, is the total cost involved in operating all production facilities of a manufacturing business. Plant overheads applies to indirect labour and indirect costs, all costs involved in manufacturing except the cost of direct labour and raw materials. The plant overhead costs were determined as 10% of the total production cost to give USD9 499.96.

10.10 Total manufacturing costs

The total manufacturing costs is the sum of direct production costs, total fixed costs and plant overhead costs. For this study, the total manufacturing cost was USD190 291.82.

10.11 Total production costs

Total production costs are the sum of the total manufacturing costs and total general expenses. The general expenses include administrative costs, distribution and marketing costs. The administrative cost is 1% of total manufacturing cost to give USD1902.92. The distribution and marketing costs are 2% of total manufacturing costs to give USD3 805.84. The total general expenses are a sum of administrative cost, distribution and marketing costs to get USD5 708.76. The total production costs are therefore total general expenses plus total manufacturing cost to get USD196 000.58.

10.12 Net profit

The process the production of activated biochar capsules from sawdust for multipurpose medicinal uses runs 8 hours a day for 240 days a year The activated biochar capsules are sold per 100 at a cost of USD1.05 /dozen. The profitability analysis for biochar based capsules is shown in Table 3.

Table 24: Profitability analysis for biochar based capsules production

Item	Calculation	Value
Amount of biochar produced per day		150 Kg
Number of capsules produced per day	150/0.000735kg	204 081 capsules
The number of pack from capsules made	204 081capsules/100	2040.81 packs
Annual income from sales	USD1.05 ×2040.81 ×240	USD514 284.12
Gross income	Total income from sales – Total production cost	USD 324 283.54
Tax	Tax rate is 15% of gross income	USD48 642.53
Net profit	Gross Income – Tax	USD275 641.01

10.13 Rate of return on investment

The rate of return on investment refers to the loss or gain of an investment over a specific period. The rate of return is calculated as indicated in Equation 43.

Rate of return = Net profit per year/ Total capital investment= 44%... ....(43)

10.14 Payback period

Payback period is the time needed to cancel all debts acquired in setting up the plant and start making profits. For a sustainable project the payback period should be at most 5 years. Payback period is the inverse of the rate of return on investments (See Equation 44). The amount of time to be taken to payback is 2.3 years which is below 5 years hence this is a bankable project.

Payback period = (Total capital investment)/ (Net profit per year) = 2.3 years…………(44)

10.15 Net present value

The net present value (NPV) is the variance between the present value of cash inflows and the present value of cash outflows and is represented by Equation 45. NPV is used to analyse the profitability of a projected investment through usage of present value factors. The present value factors for this study are shown in Table 25 with the cash flow forecast shown in Table 26.

NPV = Total present value of cash flows – Initial investment

$$=\left[\frac{R_1}{(1+i)}+\frac{R_2}{(1+i)^2}+\frac{R_3}{(1+i)^3}+\cdots\right] \text{ - Initial investment}\ldots\ldots\ldots\ldots\ldots(45)$$

Where: i is the target rate of return per period; R_1 is the net cash inflow during the first period; R_2 is the net cash inflow during the second period and R_3 is the net cash inflow during the third period.

Table *25*. Present value factors for biochar based capsules

Year	**Calculation**	**PV Factor**
1	$\frac{1}{(1+0.44)^1}$	0.69
2	$\frac{1}{(1+0.44)^2}$	0.48
3	$\frac{1}{(1+0.44)^3}$	0.33
4	$\frac{1}{(1+0.44)^4}$	0.23
5	$\frac{1}{(1+0.44)^5}$	0.16
6	$\frac{1}{(1+0.44)^6}$	0.11
7	$\frac{1}{(1+0.44)^7}$	0.08
8	$\frac{1}{(1+0.44)^8}$	0.05

Table *26*. Cash flow forecast for biochar based capsules production

Year	**Cash flow (USD)**	**Present value factor**	**Present value (USD)**	**Cumulative cash flow (USD)**
1	324 283.54	0.69	223 755.64	223 755.64
2	324 283.54	0.48	155 656.10	68 099.54
3	324 283.54	0.33	107 013.57	(38 914.03)
4	324 283.54	0.23	74 585.21	(113 499.24)
5	324 283.54	0.16	51 885.36	(165 384.60)
6	324 283.54	0.11	35 671.19	(201 055.79)
7	324 283.54	0.08	25 942.68	(226 998.47)
8	324 284.54	0.05	16 214.23	(243 212.70)

The Net present value is equal to total present values of cash flows less Initial investment to get USD64 561.17.

10.16 Break-even analysis

Breakeven analysis is the identification of the point where the company revenue begins to exceed its total cost. The break-even packs and price where calculated in terms of Equations 46 and 47 respectively.

Breakeven point $= \frac{\text{Total fixed cost}}{\text{Price per unit}-\text{variable cost per unit}} = \frac{USD85\ 794.93}{USD3.25/pack-USD1.05/pack}$ =38 997.70 packs……………………………………………………………………………………(46)

Breakeven point in terms of the price = $\frac{USD85\ 794.93}{\frac{USD3.25-USD1.05}{3.25}}$ =USD126 742.51……….(47)

11. Conclusion

The assessment for the production of activated biochar capsules from sawdust as a climate change and waste management strategy was found to be technically and economically feasible. Preliminary cost estimation for the plant was found to have a rate of return of 44% and a payback period of 2.3 years. Measures to protect the environment were put in consideration with analysis of every possible environmental pollution and its mitigation measure. Site selection and plant layout were done to locate the plant at the most economical location. From this study, it is recommended that the pyrolysis of sawdust to produce activated biochar releases heat; hence it is suggested that heat integration is done so that the heat from the furnace can be reused for another pyrolysis reaction. Pyrolysis gas can be condensed to produce bio oil which is a fuel. This fuel can then be used for operating the pyrolysis reactor and other equipment as the spray and rotary driers and minimise their emission to the environment. Waste valorisation of saw dust to biochar based capsules for potential medicinal uses is essential in combatting climate change.

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