The carbon abatement potential of pyrolysis biochar and its relationship with the processing conditions of pyrolysis

# Abstract

Pyrolysis biochar is the solid residue of a pyrolysis process. It received significant academic attention because of its ability to be a soil conditioner and sequestrating carbon. The carbon sequestration ability of pyrolysis biochar is closely related to its physiochemical properties, while the productivity is another parameter affecting the overall carbon sequestration potential of pyrolysis biochar. Both the physiochemical properties and productivity are affected by the processing conditions of pyrolysis. This project identifies the relationships between the productivity and physiochemical properties of pyrolysis biochar through a systematic literature review. The impacts of biochar properties on its carbon stability were modelled in terms of different processing conditions. A sensitivity study was conducted to figure out the most effective parameter for biochar stability management. An India-based case study was proposed with the consideration of the application of the pyrolysis system and life cycle assessment is used to predict the carbon abatement potential of pyrolysis biochar. Finally, the yield improvement analysis was conducted to identify the advantages using biochar as the soil amendment and its indirect effects to the carbon reduction.

Keywords: Pyrolysis; Biochar; Climate change; Economics; Life cycle assessment;

Aims/Objectives of project

The aim of this research is to acquire a greater depth of understanding of the pyrolysis biochar and how the pyrolysis technology can contribute to the carbon abatement with a possible mathematical model.

Objectives

* Learn about the pyrolysis biochar and its applications
* Understand the processing conditions of pyrolysis to product biochar
* Determine the satbility of biochar and its effects to carbon storage
* Analyze the carbon abatement potential in these applications
* Create a model based on the data collected
* Described the possible future application of the model

The use of biochar is considered to be the ideal tool to tackle the global warming. It is one of the carbon sequestration methods which can store the carbon in the soil carbon pool and gain the renewable energy sources replacing fossil fuel with its oil and gas byproducts in the production.

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# Introduction

So far, environmental issues became a prominent problem such as desertification, sea level rising, storm surge intensifying and other extreme weather occurring with increasing frequency, as the increases in CO2 emissions and other greenhouse gases caused by human activities have been a huge challenge for the whole world. The methods to reduce the concentration of carbon dioxide in atmospheric attracted global concern. Not only optimizing energy performance and cleaning up the fossil fuels to reduce the CO2 emissions from the source, but also improving the carbon capture and storage (CCS) technology to achieve carbon negative.

Biochar is a special charcoal used as a soil amendment with 2 thousands years’ history. With the thermal decomposition of organic material in the absence of oxygen. It produces biochar, bio-oil and syngas in the pyrolysis process. (Lehmann and Joseph, 2009) In the countries which economies grounded in agriculture and forestry, Biomass sources utilization in energy production is more and more attention. Efficient use of the biomass potential in these countries helps to reduce the dependence on imported energy sources and reduce the use of fossil fuel. Although almost all the biomass with organic carbon material can be converted into biochar by pyrolysis technology, agricultural waste is a cheap and available biomass in the countries from the point of view of circumstance and economy,

Due to the highly porous structure, biochar can improve soil structure, soil water holding, which increased soil fertility and crop yield, cut down the amount of chemical fertilizer and form a potential carbon sequestration. (Jeffery *et al.*, 2011) The main application of biochar is the long-term carbon storage in soil.(Mašek *et al.*, 2013)

Many researches show that biochar application to soil can significantly increase total DOC(dissolved organic carbon) and total MBC (microbial biomass), enhance the soil carbon storage. (Yin *et al.*, 2014) It can also improve the water holding capacity and neutralizes the pHfory its highly porous structure and pH value.(Sohi *et al.*, 2010) The microbial decomposition and chemical transformation reaction of biochar is slow so that it can be storage for thousands of years(Spokas, 2010)(Forbes, Raison and Skjemstad, 2006), much longer than agricultural waste and compost, which slows down the rate fixed carbon returned to the atmosphere and reduce the methane and nitric oxides emission from the decomposition process of biomass, which is 20 times more potent greenhouse effect than carbon dioxide. (Al-Wabel *et al.*, 2013)

Through photosynthesis, the plants absorb carbon dioxide and release oxygen, and fixed carbon dioxide into biomass and soil. The biochar improved the property of soil, increased plant growth, providing a positive feedback. In addition, energy generated in the processing of pyrolysis can replace parts of the fossil fuel.

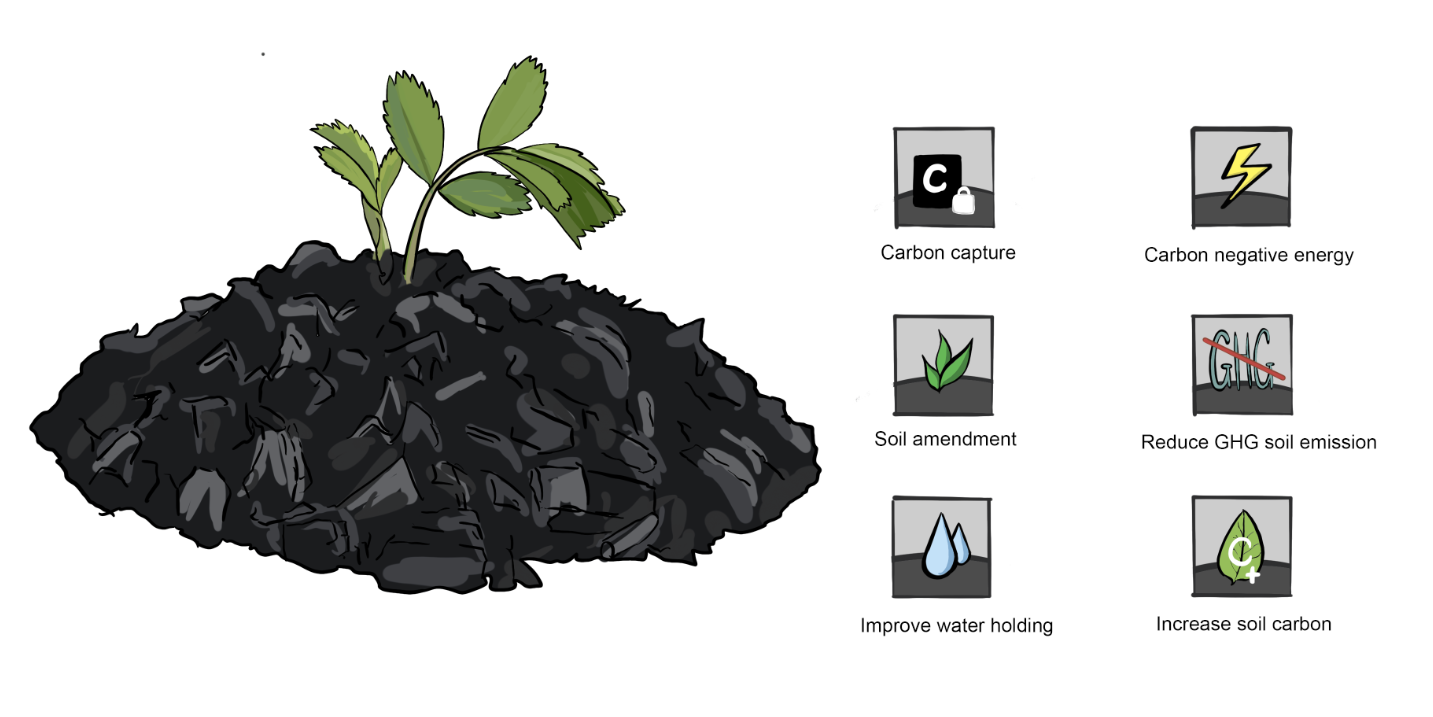


Figure 1 Benefits of biochar utilization

The original method to produce biochar is long time flameless combustion of biomass in the absence of oxygen covered the soil, the old and polluting methods such as mound kilns(American Chemical Society. *et al.*, 1987). But it releases CO2, black carbon and other greenhouse gas even toxins into the air and the ground, not suitable for sustainable biochar production.

In modern pyrolysis processes, it is clean and economy that can also produce by-product such as bio-oil and syngas.(Lehmann and Joseph, 2009) The syngas and bio-oils are typically are of great value asfuel. Thee bio-oil is also a common chemical material. The product yields and the group compositions of the products are dependent on processing condition, the temperature. It is crucial to have some insight into the key factor of production and control the chemical and physical properties of biochar. Due to the various components of the feed stock and the different thermal reactions, the pyrolysis is a complex process with multiple input and output factors. At low to moderate temperatures, in the long time reaction process, slow pyrolysis can produce high yields of biochar. With the development of the technology, high temperature pyrolysis or gasification, requires very short reaction time produces mainly syngas and bio-oil with fewer biochar but has a significantly higher energy density. Both of the processes are self-sustaining as the syngas output 3 to 9 times the amount of energy required to maintain the process.(Xu *et al.*, 2011)

Biochar has been suggested as one possible mean against the increasing amount of carbon dioxide in the air. Based on the global estimates of impacts of biochar, the carbon abatement potential of the negative emission is 0.7 GtCeq per year (the maximum technical potential is 1.3 GtCeq per year)(Smith, 2016) Other researches also mentioned the abatement potential by different biomass between 2.6 and 16 t CO2e t−1 biochar.(Gaunt and Cowie, 2012)

Recently, there have already been carried on many researched about the characteristics of biochar and the influence of pyrolysis condition. Based on the plant type, plant part, soil condition, weather condition and the pyrolysis condition, the characteristics of biochar can vary considerably. It is significant to model the relationship with the processing conditions of pyrolysis and calculate the carbon abatement potential of biochar.

# Method

## Biochar production

Due to the large impact of the feed stock type, all the wastes were grouped into four main types.

By category of raw biomass, the feed stock is mainly classified into three parts, plant waste, animal waste and other waste. The wood based biomass was separately divided from the plant waste for the low ash content compared with other plant waste, which is shown in the ash content table below.The heating treatment temperature of these feed stocks ranged from 200 ℃ to 1000 ℃ and the heating rate were from 2 ℃ per min to 18000 ℃ per min, that covered slow pyrolysis to fast pyrolysis.

## Biochar properties

The main biochar properties discussed in the project were yield of the biochar, fix carbon, ash content, volatile matters, carbon content, higher heating value, BET specific surface, pH value, H: C ratio and O: C ratio.

Table 1 Classification According to Feedstock Type

|  |  |  |
| --- | --- | --- |
| Feed stock type | Biomass | Reference |
| General Plant Waste | Bagasse | (Sun et al., 2014) |
|  | Chlorella | (Zhao et al., 2013) |
|  | Conocarpus wastes | (Al-Wabel et al., 2013) |
|  | Cottonseed hull chars | (Uchimiya et al., 2011) |
|  | Date palm | (Usman et al., 2015) |
|  | Date palm waste | (Usman et al., 2015) |
|  | Dry algae | (Ronsse et al., 2013) |
|  | E. Saligna leaves | (Singh, Cowie and Smernik, 2012) |
|  | Geodae-uksae 1 | (Lee et al., 2013) |
|  | Grass | (Zhao et al., 2013) |
|  | Green waste | (Ronsse et al., 2013) |
|  | Lignosulfonate | (Zhang, Liu and Liu, 2015) |
|  | Peanut shell | (Zhao et al., 2013) |
|  | Pecan shells | (Uchimiya et al., 2011) |
|  | Rhodes grass | (Jouiad et al., 2015) |
|  | Rice straw | (Fu et al., 2012) |
|  | Rice straw | (Park et al., 2014) |
|  | Safflower seed press cake | (Angin, 2013) |
|  | Straw | (Zhang, Liu and Liu, 2015) |
|  | Straw-Stalk of Rapeseed Plant | (Angin, 2013) |
|  | Sugar cane straw | (Melo et al., 2013) |
|  | Timothy grass | (Mohanty et al., 2013) |
|  | Waterweeds | (Zhao et al., 2013) |
|  | Wheat straw | (Mohanty et al., 2013) |
|  | Wheat straw | (Bruun et al., 2011) |
|  | Wheat straw | (Zhao et al., 2013) |
|  | Wheat straw | (Ronsse et al., 2013) |
| Wood (Low-ash) | Bamboo | (Sun et al., 2014) |
|  | Beech trunkbark | (Demirbas, 2004) |
|  | Douglas Fir bark | (Suliman et al., 2016) |
|  | Douglas Fir wood | (Suliman et al., 2016) |
|  | Eucalyptus saligna wood | (Singh, Cowie and Smernik, 2012) |
|  | Hickory wood | (Sun et al., 2014) |
|  | Hybrid poplar wood | (Suliman et al., 2016) |
|  | Moso bamboo | (Chen et al., 2016) |
|  | Pine wood | (Ronsse et al., 2013) |
|  | Pinewood | (Mohanty et al., 2013) |
|  | Pitch pine (Pinus rigida) | (Kim et al., 2012) |
| Animal Waste | Bone dregs | (Zhao et al., 2013) |
|  | Broiler litter | (Uchimiya et al., 2011) |
|  | Cow manure | (Singh, Cowie and Smernik, 2012) |
|  | Cow manure | (Zhao et al., 2013) |
|  | Dairy (MD) | (Cantrell et al., 2012) |
|  | Paved-feedlot (FL) | (Cantrell et al., 2012) |
|  | Pig manure | (Zhao et al., 2013) |
|  | Poultry litter | (Singh, Cowie and Smernik, 2012) |
|  | Poultry litter (PL) | (Cantrell et al., 2012) |
|  | Shrimp hull | (Zhao et al., 2013) |
|  | Swine solids (SW) | (Cantrell et al., 2012) |
|  | Turkey litter (TL) | (Cantrell et al., 2012) |
| Other Waste | Sawdust | (Zhao et al., 2013) |
|  | Sewage sludge | (Song et al., 2014) |
|  | Sewage sludge | (Chen et al., 2014) |
|  | Sewage sludge | (Yuan et al., 2015) |
|  | Waste paper | (Zhao et al., 2013) |
|  | Wastewater sludge | (Zhao et al., 2013) |

Table 2 Characteristics of the raw biomass

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Fixed carbon (%) | Volatile matter (%) | Ash content (%) | Carbon (%) | heating value | Specific surface m2/g | pH | H/C ratio | O/C ratio |
| Straw-stalk of rapeseed plant | 18.58 | 75.55 | 5.87 | 45.15 | 17.64 |  |  | 1.37 | 0.71 |
| Rapeseed | 15.80 | 70.00 | 5.80 | 41.10 | 19.40 |  |  | 1.75 | 0.87 |
| Hickory wood |  |  |  | 45.51 |  | 0.10 | 5.80 | 0.14 | 1.05 |
| Bagasse |  |  |  | 45.82 |  | 0.40 | 6.00 | 0.14 | 1.03 |
| Bamboo |  |  |  | 46.52 |  |  | 6.60 | 0.13 | 1.01 |
| Rice straw | 13.50 | 66.71 | 14.11 | 47.50 | 14.97 | 1.51 |  | 1.47 | 0.67 |
| Douglas fir wood |  |  | 51.30 | 51.30 |  |  |  | 1.92 | 0.58 |
| Douglas fir bark |  |  | 53.40 | 53.40 |  |  |  | 1.71 | 0.50 |
| Hybrid poplar wood |  |  | 50.40 | 50.40 |  |  |  | 1.86 | 0.59 |
| Straw | 29.86 | 59.33 | 10.81 | 35.17 |  |  | 6.57 | 2.24 | 1.05 |
| Lignosulfonate | 25.18 | 41.84 | 32.98 | 25.74 |  |  | 4.89 | 2.33 | 1.35 |
| Beech trunk bark |  | 68.50 | 7.40 | 50.40 | 21.70 |  |  |  |  |
| Pine | 21.60 | 73.20 | 2.00 | 49.50 |  |  |  | 1.43 | 0.68 |
| Rice husk | 15.00 | 59.40 | 21.30 | 37.90 |  |  |  | 1.55 | 1.13 |
| Wheat straw | 14.40 | 75.30 | 6.30 | 41.40 |  |  |  | 1.62 | 0.96 |
| Dairy | 4.50 | 80.70 | 14.80 | [46.52](https://www.sciencedirect.com/science/article/pii/S0960852411016956?via%3Dihub#tblfn8) | [17.62](https://www.sciencedirect.com/science/article/pii/S0960852411016956?via%3Dihub#tblfn5) | 1.32 | 8.30 | 1.42 | 0.54 |
| Paved-feedlot | 7.90 | 76.70 | 15.40 | 45.05 | 17.66 | 1.02 | 7.30 | 1.46 | 0.54 |
| Poultry litter | 8.80 | 74.30 | 16.90 | 42.15 | 15.11 | 0.57 | 8.20 | 1.49 | 0.62 |
| Swine solids | 5.60 | 73.60 | 20.90 | 47.42 | 19.39 | 0.53 | 7.80 | 1.52 | 0.41 |
| Turkey litter | 5.70 | 74.00 | 20.30 | 40.45 | 15.48 | 1.45 | 7.00 | 1.50 | 0.56 |
| Date palm waste | 22.30 | 70.59 | 7.11 | 43.19 |  |  |  | 1.61 | 0.68 |
| Sewage sludge | 4.60 | 39.70 | 55.70 |  |  | 11.85 | 5.67 |  | 0.56 |
| Sewage sludge | 8.20 | 65.30 | 26.40 | 37.50 |  |  | 6.00 | 1.89 |  |
| Conocarpus wastes |  |  | 3.18 | 44.96 |  |  |  | 1.44 | 0.76 |
| Moso bamboo |  |  | 1.15 | 48.13 |  |  |  | 1.49 | 0.69 |
| Edible date palm | 20.90 | 69.90 | 2.90 | 45.40 |  | 0.98 | 5.90 | 1.47 | 0.67 |
| Rhodes grass | 11.00 | 66.50 | 14.70 | 42.50 |  | 1.97 | 6.10 | 1.54 | 0.51 |

# Results

Table 3 Biochar Yield of general plant waste

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Bagasse | 10 |  | 33.31 |  |  | 27.87 |  |  | 26.43 |  |  |  |  |  |  |
| Chlorella | 8 |  |  |  |  |  | 40.20 |  |  |  |  |  |  |  |  |
| Conocarpus wastes |  | 51.33 |  |  | 31.86 |  |  |  | 27.22 |  |  |  | 27.22 |  |  |
| Cottonseed hull chars |  | 83.40 |  | 36.80 |  |  | 28.90 |  |  | 25.40 |  |  | 24.00 |  |  |
| Date palm waste | 5 |  | 49.97 |  | 36.54 |  | 32.38 |  | 30.88 |  | 28.84 |  | 27.40 |  |  |
| Dry algae | 17.1 |  | 72.80 |  |  | 28.40 |  |  | 24.10 |  |  | 21.00 |  |  |  |
| Dry algae | 17.6 |  | 50.10 |  |  | 25.00 |  |  | 22.90 |  |  | 19.30 |  |  |  |
| Geodae-uksae 1 | 10 |  | 49.54 |  | 30.95 | 29.42 | 27.15 | 26.21 | 25.90 |  | 25.10 |  |  |  |  |
| Grass | 8 |  |  |  |  |  | 27.80 |  |  |  |  |  |  |  |  |
| Green waste | 17.1 |  | 98.40 |  |  | 31.30 |  |  | 24.90 |  |  | 26.40 |  |  |  |
| Green waste | 17.6 |  | 48.60 |  |  | 27.80 |  |  | 24.40 |  |  | 23.70 |  |  |  |
| Lignosulfonate | 1h | 81.99 |  |  | 58.51 |  |  |  | 52.99 |  |  |  |  |  |  |
| Lignosulfonate | 2h | 78.93 |  |  | 57.80 |  |  |  | 48.12 |  |  |  |  |  |  |
| Lignosulfonate | 4h | 74.97 |  |  | 57.24 |  |  |  | 43.85 |  |  |  |  |  |  |
| Peanut shell | 8 |  |  |  |  |  | 32.00 |  |  |  |  |  |  |  |  |
| Rice straw | 10 |  |  |  |  |  |  |  |  |  |  |  |  | 29.33 |  |
| Rice straw | 10 |  | 46.50 |  | 30.40 |  | 25.50 |  | 23.50 |  | 23.00 |  |  |  |  |
| Rice straw | 18000 |  |  |  |  |  |  |  | 31.23 |  | 29.96 |  | 28.69 | 27.36 | 26.22 |
| Safflower seed press cake | 10 |  |  |  | 34.16 | 31.08 | 28.87 | 27.93 | 26.31 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 30.00 | 29.25 | 27.68 | 26.68 | 25.70 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 28.31 | 27.81 | 26.25 | 25.68 | 24.56 |  |  |  |  |  |  |
| Straw | 1h | 84.95 |  |  | 37.30 |  |  |  | 32.48 |  |  |  |  |  |  |
| Straw | 2h | 81.23 |  |  | 35.91 |  |  |  | 32.48 |  |  |  |  |  |  |
| Straw | 4h | 78.24 |  |  | 36.65 |  |  |  | 30.89 |  |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  | 39.36 |  | 35.61 |  | 32.24 |  | 29.62 |  | 28.23 | 27.87 |  |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  | 28.07 |  |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  | 27.11 |  |  |
| Sugar cane straw | 20 |  |  |  | 45.00 |  | 38.00 |  | 35.00 |  | 31.00 |  |  |  |  |
| Timothy grass | 2 |  |  |  |  | 42.50 |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  | 22.00 |  |  |  |  |  |  |  |  |  |
| Waterweeds | 8 |  |  |  |  |  | 58.40 |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  | 41.30 |  |  |  |  |  |  |  |  |  |
| Wheat straw | 8 | 99.30 |  | 52.50 |  |  | 29.80 |  |  | 26.80 |  |  |  |  |  |
| Wheat straw | 17.1 |  | 94.80 |  |  | 28.50 |  |  | 25.40 |  |  | 23.70 |  |  |  |
| Wheat straw | 17.6 |  | 36.80 |  |  | 27.50 |  |  | 25.20 |  |  | 24.40 |  |  |  |
| Wheat straw | 450 |  |  |  |  | 21.00 |  |  |  |  |  |  |  |  |  |
| Wheat straw |  |  |  |  |  |  | 46.40 | 31.60 |  |  |  |  |  |  |  |
| Average1 |  | 79.37 | 58.08 | 44.65 | 39.33 | 29.38 | 33.66 | 27.62 | 30.29 | 26.10 | 27.92 | 23.08 | 27.25 | 28.19 | 26.22 |

Table 4. Biochar yield of the wood waste

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate | 277 | 300 | 327 | 350 | 377 | 400 | 427 | 450 | 475 | 500 | 525 | 550 | 600 | 750 |
| Bamboo | 10 |  | 40.28 |  |  |  |  |  | 26.15 |  |  |  |  | 23.78 |  |
| Beech trunk bark | 120 | 58.60 |  | 53.20 |  | 48.80 |  | 47.10 |  | 43.20 |  | 41.90 |  |  |  |
| Beech trunk bark | 300 | 53.70 |  | 49.00 |  | 43.20 |  | 41.40 |  | 37.80 |  | 36.40 |  |  |  |
| Beech trunk bark | 600 | 51.00 |  | 45.80 |  | 42.00 |  | 40.20 |  | 34.60 |  | 33.50 |  |  |  |
| Beech trunk bark | 1200 | 48.70 |  | 44.60 |  | 41.10 |  | 39.20 |  | 33.70 |  | 32.60 |  |  |  |
| Beech trunk bark | 2400 | 46.50 |  | 43.10 |  | 38.90 |  | 37.00 |  | 32.00 |  | 31.30 |  |  |  |
| Beech trunk bark | 6000 | 43.20 |  | 39.60 |  | 35.80 |  | 34.20 |  | 30.20 |  | 28.90 |  |  |  |
| Douglas Fir bark | 190 |  |  |  | 47.90 |  | 41.10 |  | 35.50 |  | 30.50 |  | 29.80 | 29.60 |  |
| Douglas Fir wood | 190 |  |  |  | 31.90 |  | 28.30 |  | 26.60 |  | 25.50 |  | 21.80 | 20.40 |  |
| Hickory wood | 10 |  | 43.73 |  |  |  |  |  | 28.42 |  |  |  |  | 22.75 |  |
| Hybrid poplar wood | 190 |  |  |  | 31.90 |  | 28.30 |  | 26.60 |  | 25.50 |  | 21.80 | 20.40 |  |
| Moso bamboo |  |  | 53.62 |  |  |  | 31.87 |  |  |  | 25.31 |  |  | 22.79 |  |
| Pine wood | 17.1 |  | 89.80 |  |  |  |  |  | 29.20 |  |  |  |  | 24.40 | 23.00 |
| Pine wood | 17.6 |  | 43.70 |  |  |  |  |  | 27.00 |  |  |  |  | 23.30 | 22.70 |
| Pinewood | 2 |  |  |  |  |  |  |  | 44.00 |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  |  |  |  | 24.00 |  |  |  |  |  |  |
| Pitch pine (Pinus rigida) | 10 |  | 60.70 |  |  |  | 33.50 |  |  |  | 14.40 |  |  |  |  |
| Average2 |  | 50.28 | 55.31 | 45.88 | 37.23 | 41.63 | 32.61 | 39.85 | 29.72 | 35.25 | 24.24 | 34.10 | 24.47 | 23.43 | 22.85 |

Table 5. Biochar yield of animal waste'

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate | 200 | 350 | 500 | 650 |
| Cow manure | 8 |  |  | 57.20 |  |
| Pig manure | 8 | 98.00 | 57.50 | 38.50 | 35.80 |
| Shrimp hull | 8 |  |  | 33.40 |  |
| Bone dregs | 8 |  |  | 48.70 |  |
| Average3 |  | 98.00 | 57.50 | 44.45 | 35.80 |

Table 6. Biochar yield of other waste

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate | 300 | 400 | 500 | 600 | 700 |
| Wastewater sludge | 8 |  |  | 45.90 |  |  |
| Waste paper | 8 |  |  | 36.60 |  |  |
| Sawdust | 8 |  |  | 28.30 |  |  |
| Sewage sludge | 10 |  |  | 63.10 | 60.25 | 58.66 |
| Sewage sludge |  | 83.30 | 74.00 | 69.50 | 67.10 | 65.00 |
| Average4 |  | 83.30 | 74.00 | 48.68 | 63.68 | 61.83 |

After deleting the temperature range with null data, even with the stripped version, the table would occupy large length of the report. Other tables were moved to appendix.

## Yield of the biochar

Figure 2. The yield of the biochar with tending line of 4 feed stock type

Table 7. The tending line of the 4 feed stock types

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.7654 | y = 3249.9x-0.726 |
| Wood (Low-ash) | 0.8435 | y = 10465x-0.943 |
| Animal Waste | 0.9963 | y = 8666.6x-0.85 |
| Other | 0.417 | y = 731.73x-0.392 |

As can be seen from the table and the scatter figure, there is negative correlation between the yield of the biochar and the heating treatment temperature. When the temperature increased, the yield of the biochar decreased. And the feed stock type of the biomass also had a significant effect on the yield. The fitting degree of the yield based on the other waste was not ideal. The R2 here was smaller. According to the data on table 6, there were less original data and significant difference.

The main reason for the decrease of the biochar is that the more organic matters decompose at a higher temperature. (Yuan *et al.*, 2015) it can be further dissociated into low molecular weight organic compounds. The yield of the bio-oil and syngas increase. When the temperature increased, the cellulose and hemi-cellulose pyrolysis occurs.(Zhang, Liu and Liu, 2015) The high yield of the biochar indicates that the raw biomass was only partially pyrolysis.

Commonly, the degradation of the biomass happened at low temperature. The pyrolysis the production of the biochar had sharply dropped at a lower temperature. When the temperature increase to about 500℃, the decrease of the biochar became small as the cellulose and hemi-cellulose were completed pyrolysis. (Lee *et al.*, 2013) There is not a significantt decrease over 700℃ as most volatile distillates had already been removed? The temperatures are also determined by the feedstock type.

The influence of the heating rate and heating time in the pyrolysis process was much significant at lower temperature. When the heating rate and heating time increase, the yield of the biochar decreases. However, there has been convergence at higher temperature. Because of the high heating rate, the time to reach the final pyrolysis temperature may be not enough for the biomass in reaction. (Haykiri-Acma, Yaman and Kucukbayrak, 2006)

## Proximate analysis

Figure 3 Fixed carbon of the biochar with the tending line of 4 types

Table 8. The tending line for the fixed carbon

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.8278 | y = 0.8967x0.6763 |
| Wood (Low-ash) | 0.9132 | y = 0.3329x0.8609 |
| Animal Waste | 0.5477 | y = 0.8877x0.522 |
| Other | 0.0002 | y = 11.937x0.0352 |

The fixed carbon of biochar increases with increasing the temperature. There are huge differences between different feed stocks. The wood based plant waste was very sensitive to the temperature compared with other material, which may be because of the low ash content. Both of the heating rate and the heating time did not have significant influence. It had the same problem like the yield of the biochar, due to the data for other waste. The R2 here is only 0.0002, which indicated that the fitting result was not so satisfying.

Compared with the raw biomass, the fixed carbon in the biochar increase about 2 times. From the carbon storage point of view, the wood based plant waste is much more suitable for the long term storage.

Figure 4. Ash content of the biochar with tending line of 4 types

Table 9. The tending line for the ash content

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.1541 | y = 6.4633ln(x) - 16.073 |
| Wood (Low-ash) | 0.3883 | y = 1.9122ln(x) - 7.433 |
| Animal Waste | 0.4632 | y = 21.78ln(x) - 83.421 |
| Other | 0.3975 | y = 19.45ln(x) - 49.624 |

The ash content had a positive relationship with the heating treatment temperature. And it was much affected by raw biomass, For example the wood based plant has very low ash content compared with other materials. There was not much increasing on the ash content when the temperature increased. The ash content of high ash biomass such as animal waste increased obviously with the temperature. The reason for the increasing ash content was that mineral compounds were formed in the process. The ash content increase more at lower temperature as the increase volatilization of cellulose and hemi-cellulose at this temperature range(Tsai *et al.*, 2012) It is also related to the sharp decrease of the volatile matters and the concentration of the mineral elements.(Enders *et al.*, 2012) The higher ash content and lower volatile matter may improve the yield of the biochar.(Zhang, Liu and Liu, 2015)

Figure 5. Volatile matter of biochar with tending lines of 4 types

Table 10. The tending line for the volatile matter

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.9117 | y = -37ln(x) + 248.85 |
| Wood (Low-ash) | 0.9435 | y = -57.2ln(x) + 380.18 |
| Animal Waste | 0.838 | y = -31.62ln(x) + 220.57 |
| Other | 0.9548 | y = -25.2ln(x) + 171.24 |

On the contrary, with the increase of the temperature, more volatile matters were removed, and it product stable fixed carbon. (Cantrell *et al.*, 2012) The volatile matters were reduced remarkably with rising temperature. The impact of the feed stock was not as obvious as the temperature. The R2 in the model were all ideal.

### Element analysis

Figure 6. The carbon content of the biochar with tending line of 4 types

Table 11. The tending line for carbon content

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.7059 | y =28.581ln(x) - 105.7 |
| Wood (Low-ash) | 0.9565 | y =29.319ln(x) - 102.11 |
| Animal Waste | 0.0048 | y = -2.807ln(x) + 57.806 |
| Other | 0.6215 | y = -6.867ln(x) + 61.59 |

With the increasing temperature in the pyrolysis process, for the plant waste no matter the ash content, the carbon content increase while the oxygen and hydrogen content decrease. However, the carbon content decreased slightly in some animal waste.(Cantrell *et al.*, 2012) The fitting curve of the animal waste was not ideal, it was mainly influenced by the strange value of cow manure. Other model seemed satisfying

The increase of the carbon content may due to the remove of the volatile matter (Park *et al.*, 2014) or the increases of the carbonation degree(Usman *et al.*, 2015)

The decrease of the hydrogen and oxygen showed that the volatile matters removed in the pyrolysis process mainly consist of oxygen and hydrogen containing compounds. (Suliman *et al.*, 2016)

The high carbon content of biochar made it the suitable material to enhance the soil condition especially for depleted soil.

The ash content of the feed stock had nothing to do with the carbon content of the biochar, as there is not remarkable difference between the general plant waste and the wood waste, which indicated that the ash content in the feed stocks is mainly consist of carbonates.(Enders *et al.*, 2012)

There was still a certain gap between the plant waste and animal waste. The feed stock was still the huge impact. However, if only consider the feed stock in each group, the temperature had a stronger correlation than the feed stock.

The influence by the heating rate and the heat time were still not distinct

### Heating Value, MJ/kg

Figure 7. The higher heating value of biochar with tending line of 4 types

Table 12. The tending line for the higher heating value

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.5086 | y = 0.0142x + 16.685 |
| Wood (Low-ash) | 0.9908 | y = 0.0305x + 15.953 |
| Animal Waste | 1 | y = -0.0104x + 23.394 |
| Other | NaN | NaN |

The temperature impact to the heating value of the biochar was similar to the carbon content. The plant waste had positive correlation while the animal waste had negative correlation. But the heating value of biochar from the wood based biomass was much higher than the general waste which makes sense.

Relative the heating rate of biochar was linearly increased as the heating temperature increase for the plant waste. The heating value of the biochar was much larger than the raw biomass. Some of them could be more than 30 MJ/kg which is closed to anthracite and other solid fuel (EW Lemmon, MO McLinden, DG Friend, P Linstrom, 2005) which suggested that the biochar could be utilized as solid fuel in the future application.

Dry algae was special in the plant waste as the heating value decrease with the increasing temperature. This abnormal situation was that the densification of the heating value only acted on organic material in the pyrolysis process(Ronsse *et al.*, 2013)

### Specific Surface, m2/g

The temperature and the heating rate of the pyrolysis process had some effects to the specific surface. The overall trend of the specific surface was upward along with the rise of temperature. The increase of the heating rate could slightly decrease the BET surface area, but the heating rate had no significant influence. The fault and fracture on the surface of the biochar were more pronounced at higher temperature.

The fault and fracture on the surface of biochar is more pronounced as the temperature because of the breaks down and severe release of volatile matter that the biomass tissue exposed

The biochar pyrolysis from wood based had a higher surface area than the grass based. It was also closed related to the feed stock type. The specific surface of some biochar even decrease at higher temperature owing to the block of the pores in the biochar. As the temperature increase, some of the carbon may melt carbonization or even graphitization, which would affect the characteristics of the biochar.

At low heating rate, it required longer time to reach the final reaction temperature for volatile matters diffusion. The reaction at higher heating time noticeably decreased and the volatiles may interfere with the pores and led to the decrease of the BET surface area.

The surface area partly determined the adsorption dynamics of soil nutrients and the water holding ability. The biochar with larger surface area can reduce the water runoff and fix the nutrients in the soil, which could be applied as the soil amendment in the agricultural area and partly replace the chemical fertilizer. (Lee *et al.*, 2013)

## PH

Figure 8. The pH value of the biochar and the tending line of 4 types

Table 13. The tending line of the 4 types

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.7859 | y = 0.0085x + 4.9404 |
| Wood (Low-ash) | 0.6197 | y = 0.0067x + 5.6195 |
| Animal Waste | 0.8618 | y = 0.0045x + 7.3407 |
| Other | 0.9088 | y = 0.0093x + 4.0065 |

Most of the biochar were alkaline and can be used as the modifier to optimize the plant growth in the acid soil. The heating rate and the heat time had no notable impact on the ph. The pH value of the biochar increase as the temperature increase and vary for different feed stock but the correlation with the temperature was stronger than the feed stock. (Zhao *et al.*, 2013)

Some biochar such as lignosulfonate biochar, wheat straw biochar and Cottonseed Hull Chars were all weakly acidic at low temperature. The regular pH value of biochar was from 7 to 10 even 12 for high ash content biochar.

The biochar came from the wood based low ash feed stock is commonly 2 units small than the general plant wastes in similar pyrolysis condition. The pH value of the biochar was similar to the ash content. There could be a connection to the oxygen-containing functional groups in the biochar. (Ronsse *et al.*, 2013)

For the low ash content biochar, the pH value is mainly depended on the heating treatment temperate, and it would not affect the ash content of biochar. But the high ash content biochar, it had a positive repletion with the ash content. (Enders *et al.*, 2012)

The pH value positively responded to rising of temperature, largely due to the decrease of decreases in acid functional groups which led to calcification, along with the increase form of the basic functional groups and alkali salts such as CaCO3and MgCO3 (Mukherjee, Zimmerman and Harris, 2011)

## Stability of biochar

Biochar could be stable carbon sources which enhance the carbon storage and reduce the emission of carbon dioxide. (Joseph, 2015) The retention time of the biochar in the soil depended on the feature of the biochar and the soil. (Schmidt *et al.*, 2011) To understand the stability of the biochar

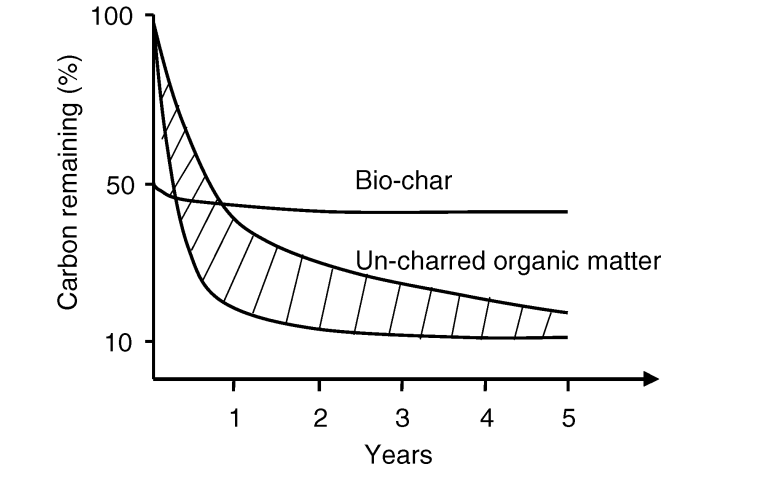


Figure 9. Range of biomass C remaining after decomposition of crop(Lehmann, Gaunt and Rondon, 2006)

Biochar stability has been extensively researched through the ultimate element analysis. The molar ratio of O: C and H: C had been proposed as an index of the stability of biochar. In general, a molar ratio of O: C lower than 0.2 appears to provide, at minimum, a 1000-year biochar half-life. (Spokas, 2010) The molar ratio of O: C and H: C is the tool to measure the aromaticity of biochar. The value decreased with the increasing temperature.(Chen and Chen, 2009) In the pyrolysis process, the H and O were removed. Because of the hydrogen containing compounds in the feed stock, the H: C ratio could be highly affected by the biomass type, while it had little to do with the O content.

Figure 10. The O:C ratio of biochar with tending line of 4 types

Table 14. The tending line of O:C ratio of biochar

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.8159 | y = 2.0024e-0.004x |
| Wood (Low-ash) | 0.6128 | y = 1.0672e-0.004x |
| Animal Waste | 1 | y = 0.5287e-0.002x |
| Other | 0.9303 | y = 0.5931e-0.002x |

Figure 11. The H:C ratio of biochar with tending line of 4 types

Table 15. The tending line of H:C ratio of biochar

|  |  |  |
| --- | --- | --- |
| Feedstock type | R2 | Formula |
| General Plant Waste | 0.6827 | y = -0.0013x + 1.1459 |
| Wood (Low-ash) | 0.7625 | y = -0.0015x + 1.2187 |
| Animal Waste | 1 | y = -0.0019x + 1.6433 |
| Other | 0.7877 | y = -0.003x + 2.4619 |

When the temperature increased, the stability of the biochar increased at the same time. The main component of the biochar under low temperature was labile carbon, which will decompose over time liberating carbon dioxide. In higher temperature, it formed more aromatic biochar.

The temperature of the soil also had the impact on the stability of biochar. The higher temperature (30 to 60℃) would accelerate the rate of the carbon mineralization. (Fang, Singh and Singh, 2015)

Another way to determine the stability of biochar was the index R50(Harvey *et al.*, 2012) At the same temperature, the biochar from different feed stock had similar R50 which indicated that the stability of biochar was not sensitive tothe feed stock type.

# Case study

In the case study, it is an assumption to apply the biochar systems in rural areas, to understand its agricultural application related carbon abatement potential. All the data for the case study were set in India.

Hypothetical condition of the village:

* A rural village with 100 households with average 5 people in each household.(Esri, 2017)
* The average farmland area is 0.12 hectares for each person.(The world bank, 2018) The total farmland area of the village is 60 hectares and they grow rice as the crop.
* The average yield of rice is 3.99 tons per hectare per year. (FAOSTAT, 2013)
* The yield to straw ratio is 1:1.5.(Singh *et al.*, 1995)
* The average electricity demand is 60 units of electricity per month.(Chunekar and Mulay, 2017)
* Using small-scale diesel generators for the electricity in daily life, no industrial power consuming.
* The yield of the biochar: 30% (26% - 46%) of rice straw.

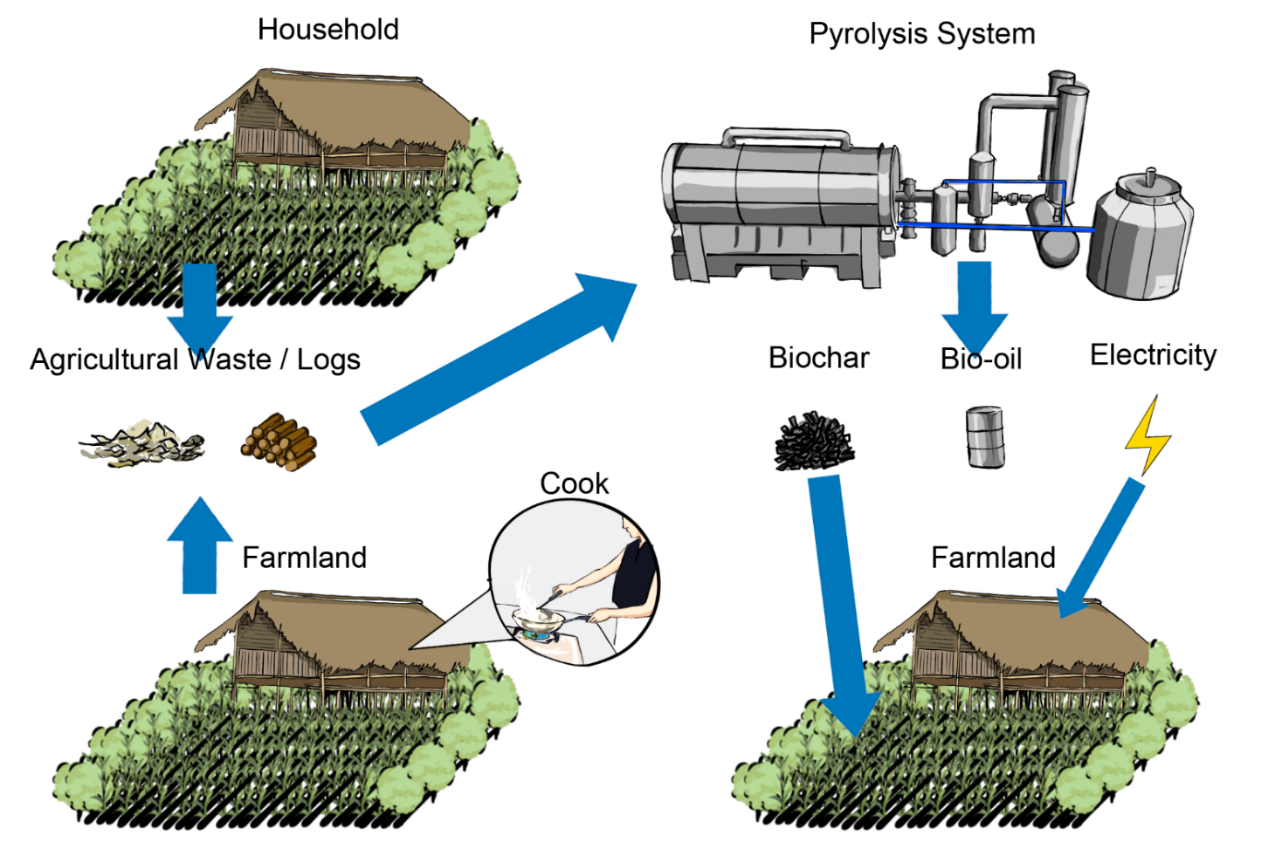


Figure 12. The technological process of the biochar system in the rural village

The agricultural waste from the farmland (rice straw in the case study) is transfer to the pyrolysis system. As the transfer of the waste to the pyrolysis system could be human handing, the carbon emission in the process could be ignored.

The pyrolysis system could produce biochar, bio-oil and electricity for the village. Assume that the syngas was used for power generation. The biochar could be re buried into the soil as the soil amendment to enhance the soil nutrient, improve the activity of soil microbe, which could increase crop yield and turn into a positive cycle.

The biochar in the soil can also be the carbon storage which increased the carbon abatement potential. Compared with direct burn the rice straw or bury the straw into the soil. The biochar could be stored in the soil for decades owing to its stability.

The side product of the pyrolysis process could be used in daily life such as replacing cooking on rural wood fired oven. The burning of the raw materials in the traditional wood fired oven would have the problem of incomplete combustion and make large amount of PM emission and other toxic gas which would do great harm to the people who was cooking,

# Carbon abatement potential

According to the Kyoto Protocol(Ki-moon, 2008), every country had to fulfil their obligation to reduce carbon emission and to lower the impact to the climate change. Carbon emission trading is one of the form for the counties to obey the rule. Due to the different cost for the carbon reduction, the country could purchase carbon emission index for higher carbon emission, and the country with lower carbon emission could sell their emission right. This kind of trading market would push the countries to develop low cost carbon reduction methods. However, there were still some views against the Kyoto Protoco such as(Lohmann, 2010).

Although the biochar will increase the carbon emission during the incubation, the carbon mineralization and the labile carbon in the soil had the negative effect, the overall carbon storage in the soil was much remarkable influenced by the biochar. (Yousaf *et al.*, 2017)

It has been realized that the biochar could contribute to the reduction of carbon in the atmosphere. The Terra Preta in the Amazon basin is the most effective proof of the long term carbon storage.(Singh, Cowie and Smernik, 2012)Assume the application of the biochar, it could not only reduce the carbon but also generate 14 to 35 EJ per year (Exa 1018).(Smith, 2016)

For different type of the biochar, with it applied to soil, the potential carbon abatement from the pyrolysis process could range from 2.6 to 16 ton CO2e ton-1biochar per year, on the basis of the feedstock.(Gaunt and Cowie, 2012) For the case study, the typical biochar comes from rice straw. From the existing research, this biochar had the maximum 1.06 ton CO2e ton-1ricestraw carbon abatement per year (Clare *et al.*, 2015), which is about 3.5 ton CO2e ton-1 biochar per year for 30% yield of biochar. It was a reasonable abatement potential that the value of biochar pyrolysis from similar feedstock, the stover, is 2.9 to 3 ton CO2e ton-1 biochar per year.(Roberts *et al.*, 2010)The other greenhouse gases effect to the climate such as methane (CH4) and nitrous oxide (N2O) is calculated to expressed in terms of carbon dioxide equivalent ( 25,298 CO2e)(Forster and Ramaswamy, 2007)

With the assumptions of the average annual yield of rice on average was 240 tons in total and the yield ratio of rice to straw is 1:1.5. We can conduct that the total yield of straw in this case study is 360 tons per year. Hence, the potentiality of CO2e abatement is 381.6 tons per year.

Besides applying biochar to soil for carbon storage, to optimize the abatement potential, the side products in the pyrolysis system could also contribute to it. For example, the bio-oil and syngas could replace the diesel oil to generate electricity. Assuming the whole village is powered by the diesel generator, the total electricity demand in this rural village is 72000 kWh per year. The emission factor of diesel electricity was 1.27 kgCO2/kWh. (Jakhrani *et al.*, 2012) and the emission factor of syngas electricity was0.525kg CO2/kWh.(Hsu, 2012) The carbon abatement potential could be 53.64 tons.

# Plant growth effected by biochar

Figure 13. The improvement of the yield by only using biochar as the soil amendment

Directly rebury the straw back to the soil had some positive effect to improve the soil fertility. However, due to the decrease of the pH value, the improvement could not compensate the adverse effect (Dong *et al.*, 2013)

Some researches mentioned that when the agricultural waste is applied in the soil. It cannot improve the soil carbon. Compared with direct use of rice straw, using biochar as the soil amendment can the yield and the effect can last for years.

The growth and the yield of the crops were much more easily influenced by the type of crop, biochar, soil and the use of the biochar.(Ippolito, Laird and Busscher, 2012)

The difference of the biochar characteristics and the soil condition was the main reason for the huge difference of the crop growth and yield. The micro-nutrient elements in the soil played the leading role in the process. However, benefits from the micro nutrient element could not last for long term. (Dong *et al.*, 2013)

Other factors such as increase the pH value of the soil, improve the water holding and soil porosity can also contribute the growth and yield of the crops.(Zhao *et al.*, 2014)

If fractionize the function of the biochar, only using biochar as the fertilizer. The contribution to the yield was much lower than using it as the conditioner, which indicated that the biochar had indirect effects to the soil fertility. The improvement of biochar was to optimize the efficiency of the nutrient in the soil.(Peng *et al.*, 2011)

However, it did not perfectly control variables in the experiment as the annual yield is determined by too many factors. In some situation, the biochar had not significantly contribute to the yield and growth of the crops, even decrease the yield of the biochar. (Shen *et al.*, 2014)

# Discussion

Although there were 50 kinds of feed stock collected in the project, the heating treatment temperature had a large range from 200 to 1000℃ with different heating rate, the final present from the data still had small boundaries. For each feed stocks, the pyrolysis condition was relatively short with only few values. Almost the existing researches focused on the limited situation. Some of the them even lack of condition such as heating rate. The classification in the project was initial. Dry algae, which was special in the higher heating value, should be separate. It is better for future study to expand the feed stock type and the pyrolysis conditions.

The assumptions in the case study were based on the average situation in India. However, this simple model could be expanded to other conditions. The further application could add more crop types and find the optimized carbon reduction by changing the percentages of the corps. It could be more realistic if based on a real village.

The carbon abatement potential analysis in the project was mainly based on the case study. The only biochar came from rice straw. The main subject was a rural area. It could apply to the urban area but it would be more complex. For more elements in the life cycle.The improvement in the yield of crops was affected by too many factors that it could not apply to other areas.

# Conclusion

This project was to analyze what can biochar contribute to the carbon reduction and factors that influence the characteristics of carbon. From the data analysis, the biochar could be produced by different kind of feed stock under different pyrolysis condition. The heating rate, heating time, heating treatment temperature and feed stock type would contribute the different characteristics of biochar. The prominent factors that had the impact on the physicochemical properties in the pyrolysis process were heating temperature and feed stock type of the raw materials. The heating rate and the heating time had only silghtly influence on the outputs, especially under lower temperature. As the temperature increases, the stability, fixed carbon, ash content, specific surface, pH value and heating value increase but the yield, volatile matters, H: C ratio and O: C ratio decrease. Most of the characteristics of the biochar were more sensitive to the heating treatment temperature, such as the yield of the biochar, pH value, the stability and the volatile matters. The feed stock types had more contribution to the properties such as fix carbon, ash content, higher heating value and specific surface of the biochar.

The stability of the biochar could be recognized by different tools. When the H: C and O: C decreased, the biochar became more stable. As H: C ratio would be affected by the feed stock type, it was not the suitable index. Other tools such as O: C ratio and the new index R50 were more reasonable. To analyze the stability of biochar, the soil condition should also be considered as the temperature of the environment, the soil type and moisture would have impacts on the biochar. With the soil temperature increase, there would be more carbon mineralization in the soil. The temperature was the most sensitive factors in the process. The higher heating treatment temperature was, the more stable the biochar would be. Overall the higher temperature could enhance the biochar stability and reduce the influence from the soil condition.

Compared with other carbon reduction technologies, the biochar was not the most efficient one, but it could widely apply in agricultural countries especially for developing countries. As the biochar could not only apply to carbon abatement but also enhance the soil and raise the yield of the crops. Even in the small scale village based on the case study, it could reduce 380 tons carbon dioxides a year. It could be an impressive number when the technology was popularized. Another advantage of the biochar is that it could provide huge amount power at the same time. Under the guidance of the Kyoto Protocol, it could expand the scope of benefits.

The application of biochar in the soil can improve soil structure and organic matter and neutralizes the pH, which has a positive effect on plant growth. . Due to the complex factors, the final improvement of the yield and growth may be negative. It was also affected by the biochar type, crop type and the soil condition. The heating treatment temperature of the biochar did not play the leading role in the improvement. The main benefits of using biochar were to improve the soil condition instead of the direct provide of the micro nutrient in the biochar. The improvement from biochar could last for years.

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# Appendice

## Appendix 1 Fixed carbon of the four feed stock type

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Chlorella | 8 |  |  |  |  |  | 17.40 |  |  |  |  |  |  |  |  |
| Conocarpus wastes |  | 44.50 |  |  | 72.30 |  |  |  | 79.50 |  |  |  | 81.50 |  |  |
| Cottonseed hull chars |  | 22.30 |  | 52.60 |  |  | 67.00 |  |  | 70.30 |  |  | 69.49 |  |  |
| Date palm waste | 5 |  | 45.49 |  | 63.41 |  | 71.00 |  | 72.44 |  | 73.49 |  | 74.70 |  |  |
| Dry algae | 17.1 |  | 30.00 |  |  | 72.50 |  |  | 81.10 |  |  | 89.90 |  |  |  |
| Dry algae | 17.6 |  | 44.80 |  |  | 80.90 |  |  | 84.30 |  |  | 96.10 |  |  |  |
| Fronds of edible date palm | 5 |  |  |  | 45.00 |  |  |  |  |  |  |  |  |  |  |
| Geodae-uksae 1 | 10 |  | 53.34 |  | 73.89 | 78.48 | 82.59 |  | 88.07 |  | 91.66 |  |  |  |  |
| Grass | 8 |  |  |  |  |  | 59.20 |  |  |  |  |  |  |  |  |
| Green waste | 17.1 |  | 25.70 |  |  | 74.70 |  |  | 88.50 |  |  | 96.50 |  |  |  |
| Green waste | 17.6 |  | 51.40 |  |  | 81.50 |  |  | 91.20 |  |  | 98.10 |  |  |  |
| Lignosulfonate | 1h | 29.06 |  |  | 33.56 |  |  |  | 36.83 |  |  |  |  |  |  |
| Lignosulfonate | 2h | 28.79 |  |  | 34.13 |  |  |  | 35.56 |  |  |  |  |  |  |
| Lignosulfonate | 4h | 28.64 |  |  | 32.28 |  |  |  | 35.05 |  |  |  |  |  |  |
| Peanut shell | 8 |  |  |  |  |  | 72.90 |  |  |  |  |  |  |  |  |
| Rhodes grass | 5 |  |  |  | 56.60 |  |  |  |  |  |  |  |  |  |  |
| Rice husk | 5 |  |  | 32.40 |  | 36.40 |  | 38.50 |  | 40.50 |  |  |  |  |  |
| Rice husk | 100 |  |  | 39.30 |  | 35.00 |  | 37.00 |  | 38.60 |  |  |  |  |  |
| Rice straw | 10 |  | 28.06 |  | 35.39 |  | 38.72 |  | 39.87 |  | 39.52 |  |  |  |  |
| Safflower seed press cake | 10 |  |  |  | 67.30 | 71.80 | 75.00 | 77.20 | 79.20 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 70.20 | 72.80 | 76.20 | 78.60 | 79.90 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 71.70 | 74.00 | 77.00 | 79.50 | 80.70 |  |  |  |  |  |  |
| Straw | 1h | 33.63 |  |  | 40.41 |  |  |  | 49.87 |  |  |  |  |  |  |
| Straw | 2h | 34.47 |  |  | 42.66 |  |  |  | 54.34 |  |  |  |  |  |  |
| Straw | 4h | 34.72 |  |  | 42.76 |  |  |  | 55.37 |  |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  | 60.72 |  | 69.60 |  | 74.66 |  | 76.67 |  | 78.63 |  |  |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  | 78.17 |  |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  | 79.32 |  |  |
| Timothy grass | 2 |  |  |  |  | 88.40 |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  | 87.70 |  |  |  |  |  |  |  |  |  |
| Waterweeds | 8 |  |  |  |  |  | 3.84 |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  | 88.10 |  |  |  |  |  |  |  |  |  |
| Wheat straw | 5 |  |  | 49.50 |  | 59.20 |  | 62.80 |  | 64.40 |  |  |  |  |  |
| Wheat straw | 8 | 22.50 |  | 53.20 |  |  | 63.70 |  |  | 72.10 |  |  |  |  |  |
| Wheat straw | 17.1 |  | 23.70 |  |  | 80.60 |  |  | 91.20 |  |  | 95.80 |  |  |  |
| Wheat straw | 17.6 |  | 66.50 |  |  | 84.10 |  |  | 92.60 |  |  | 95.90 |  |  |  |
| Wheat straw | 450 |  |  |  |  | 87.90 |  |  |  |  |  |  |  |  |  |
| Average1 |  | 30.96 | 41.00 | 45.40 | 52.64 | 73.77 | 59.55 | 62.27 | 69.51 | 57.18 | 70.34 | 95.38 | 76.97 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Douglas Fir bark | 190 |  |  | 51.50 | 59.18 | 61.60 | 66.42 | 71.39 | 73.89 |  |  |  |  |  |  |
| Douglas Fir wood | 190 |  |  | 49.58 | 63.20 | 70.75 | 76.10 | 79.83 | 83.15 |  |  |  |  |  |  |
| Hybrid poplar wood | 190 |  |  | 54.34 | 64.75 | 68.06 | 71.27 | 72.38 | 75.01 |  |  |  |  |  |  |
| Pine | 5 |  |  | 47.80 |  | 62.20 |  | 73.90 |  | 78.90 |  |  |  |  |  |
| Pine | 100 |  |  | 58.00 |  | 63.60 |  | 77.70 |  | 81.60 |  |  |  |  |  |
| Pine wood | 17.1 |  | 22.00 |  |  | 78.60 |  |  | 91.80 |  |  | 97.40 |  |  |  |
| Pine wood | 17.6 |  | 57.40 |  |  | 83.20 |  |  | 93.60 |  |  | 97.40 |  |  |  |
| Pinewood | 2 |  |  |  |  | 86.40 |  |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  | 86.30 |  |  |  |  |  |  |  |  |  |
| Average2 |  |  | 39.70 | 52.24 | 62.38 | 73.41 | 71.26 | 75.04 | 83.49 | 80.25 |  | 97.40 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Cow manure | 8 |  |  |  |  |  | 14.70 |  |  |  |  |  |  |  |  |
| Pig manure | 8 | 12.60 |  | 34.70 |  |  | 40.20 |  |  | 19.20 |  |  |  |  |  |
| Shrimp hull | 8 |  |  |  |  |  | 18.90 |  |  |  |  |  |  |  |  |
| Bone dregs | 8 |  |  |  |  |  | 10.50 |  |  |  |  |  |  |  |  |
| Dairy (MD) | 6000 |  |  | 23.20 |  |  |  |  |  |  | 34.70 |  |  |  |  |
| Paved-feedlot (FL) | 6000 |  |  | 23.50 |  |  |  |  |  |  | 36.30 |  |  |  |  |
| Poultry litter (PL) | 6000 |  |  | 27.00 |  |  |  |  |  |  | 35.50 |  |  |  |  |
| Swine solids (SW) | 6000 |  |  | 17.70 |  |  |  |  |  |  | 33.80 |  |  |  |  |
| Turkey litter (TL) | 6000 |  |  | 23.10 |  |  |  |  |  |  | 29.20 |  |  |  |  |
| Average3 |  | 12.60 |  | 24.87 |  |  | 21.08 |  |  | 19.20 | 33.90 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Wastewater sludge | 8 |  |  |  |  |  | 20.60 |  |  |  |  |  |  |  |  |
| Waste paper | 8 |  |  |  |  |  | 16.40 |  |  |  |  |  |  |  |  |
| Sawdust | 8 |  |  |  |  |  | 72.00 |  |  |  |  |  |  |  |  |
| Sewage sludge |  |  |  |  | 26.70 | 27.10 | 28.20 | 28.50 |  |  |  |  |  |  |  |
| Sewage sludge |  |  | 6.80 |  | 8.50 |  | 9.20 |  | 7.60 |  | 7.70 |  |  |  |  |
| Average4 |  |  | 6.80 |  | 17.60 | 27.10 | 29.28 | 28.50 | 7.60 |  | 7.70 |  |  |  |  |

## Appendix 2. Volatile matters of the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Chlorella | 8 |  |  |  |  |  | 29.30 |  |  |  |  |  |  |  |  |
| Cottonseed hull chars |  | 69.30 |  | 34.90 |  |  | 18.60 |  |  | 13.27 |  |  | 11.42 |  |  |
| Date palm waste | 5 |  | 40.08 |  | 20.25 |  | 9.31 |  | 6.85 |  | 5.47 |  | 3.91 |  |  |
| Dry algae | 17.1 |  | 70.00 |  |  | 27.50 |  |  | 18.90 |  |  | 10.10 |  |  |  |
| Dry algae | 17.6 |  | 55.20 |  |  | 19.10 |  |  | 15.70 |  |  | 3.90 |  |  |  |
| Fronds of edible date palm | 5 |  |  |  | 43.20 |  |  |  |  |  |  |  |  |  |  |
| Grass | 8 |  |  |  |  |  | 18.90 |  |  |  |  |  |  |  |  |
| Green waste | 17.1 |  | 74.30 |  |  | 25.30 |  |  | 11.50 |  |  | 3.50 |  |  |  |
| Green waste | 17.6 |  | 48.60 |  |  | 18.50 |  |  | 8.80 |  |  | 1.90 |  |  |  |
| Lignosulfonate | 1h | 35.08 |  |  | 20.83 |  |  |  | 7.05 |  |  |  |  |  |  |
| Lignosulfonate | 2h | 35.06 |  |  | 18.26 |  |  |  | 6.32 |  |  |  |  |  |  |
| Lignosulfonate | 4h | 34.43 |  |  | 17.89 |  |  |  | 5.26 |  |  |  |  |  |  |
| Peanut shell | 8 |  |  |  |  |  | 16.00 |  |  |  |  |  |  |  |  |
| Rhodes grass | 5 |  |  |  | 11.80 |  |  |  |  |  |  |  |  |  |  |
| Rice husk | 5 |  |  | 30.30 |  | 19.10 |  | 14.60 |  | 9.30 |  |  |  |  |  |
| Rice husk | 100 |  |  | 20.70 |  | 19.40 |  | 11.30 |  | 11.30 |  |  |  |  |  |
| Rice straw | 10 |  | 1.23 |  | 0.53 |  | 0.27 |  | 0.17 |  | 0.15 |  |  |  |  |
| Safflower seed press cake | 10 |  |  |  | 25.20 | 20.00 | 16.50 | 13.90 | 11.60 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 21.40 | 18.70 | 15.20 | 12.30 | 10.80 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 19.80 | 17.40 | 14.30 | 11.40 | 9.80 |  |  |  |  |  |  |
| Straw | 1h | 54.46 |  |  | 33.85 |  |  |  | 17.80 |  |  |  |  |  |  |
| Straw | 2h | 53.24 |  |  | 29.80 |  |  |  | 12.10 |  |  |  |  |  |  |
| Straw | 4h | 52.49 |  |  | 28.84 |  |  |  | 10.31 |  |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  | 27.06 |  | 17.49 |  | 11.49 |  | 8.96 |  | 6.05 | 16.12 |  |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  | 6.52 |  |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  | 4.95 |  |  |
| Timothy grass | 2 |  |  |  |  | 7.50 |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  | 8.30 |  |  |  |  |  |  |  |  |  |
| Waterweeds | 8 |  |  |  |  |  | 32.40 |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  | 7.20 |  |  |  |  |  |  |  |  |  |
| Wheat straw | 5 |  |  | 39.60 |  | 23.20 |  | 17.20 |  | 14.20 |  |  |  |  |  |
| Wheat straw | 8 | 70.20 |  | 31.30 |  |  | 17.60 |  |  | 11.10 |  |  |  |  |  |
| Wheat straw | 17.1 |  | 76.30 |  |  | 19.40 |  |  | 8.80 |  |  | 4.20 |  |  |  |
| Wheat straw | 17.6 |  | 33.50 |  |  | 15.90 |  |  | 7.40 |  |  | 4.10 |  |  |  |
| Wheat straw | 450 |  |  |  |  | 7.70 |  |  |  |  |  |  |  |  |  |
| Average1 |  | 50.53 | 49.90 | 31.36 | 22.77 | 17.14 | 17.16 | 13.45 | 10.04 | 11.83 | 4.86 | 4.62 | 6.57 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Douglas Fir bark | 190 |  |  | 43.78 | 34.61 | 31.09 | 26.01 | 20.61 | 17.25 |  |  |  |  |  |  |
| Douglas Fir wood | 190 |  |  | 49.82 | 36.14 | 28.43 | 22.12 | 19.16 | 15.72 |  |  |  |  |  |  |
| Hybrid poplar wood | 190 |  |  | 42.15 | 29.96 | 25.62 | 22.69 | 20.37 | 17.81 |  |  |  |  |  |  |
| Pine | 5 |  |  | 50.80 |  | 34.90 |  | 22.00 |  | 15.20 |  |  |  |  |  |
| Pine | 100 |  |  | 38.70 |  | 33.00 |  | 21.60 |  | 13.40 |  |  |  |  |  |
| Pine wood | 17.1 |  | 78.00 |  |  | 21.40 |  |  | 8.20 |  |  | 2.60 |  |  |  |
| Pine wood | 17.6 |  | 42.60 |  |  | 16.80 |  |  | 6.40 |  |  | 2.60 |  |  |  |
| Pinewood | 2 |  |  |  |  | 8.20 |  |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  | 8.90 |  |  |  |  |  |  |  |  |  |
| Average2 |  |  | 60.30 | 45.05 | 33.57 | 23.15 | 23.61 | 20.75 | 13.08 | 14.30 |  | 2.60 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Cow manure | 8 |  |  |  |  |  | 17.20 |  |  |  |  |  |  |  |  |
| Pig manure | 8 | 50.70 |  | 27.40 |  |  | 11.00 |  |  | 10.70 |  |  |  |  |  |
| Shrimp hull | 8 |  |  |  |  |  | 26.60 |  |  |  |  |  |  |  |  |
| Bone dregs | 8 |  |  |  |  |  | 11.00 |  |  |  |  |  |  |  |  |
| Dairy (MD) | 6000 |  |  | 53.50 |  |  |  |  |  |  | 27.70 |  |  |  |  |
| Paved-feedlot (FL) | 6000 |  |  | 47.90 |  |  |  |  |  |  | 19.80 |  |  |  |  |
| Poultry litter (PL) | 6000 |  |  | 42.30 |  |  |  |  |  |  | 18.30 |  |  |  |  |
| Swine solids (SW) | 6000 |  |  | 49.80 |  |  |  |  |  |  | 13.40 |  |  |  |  |
| Turkey litter (TL) | 6000 |  |  | 42.10 |  |  |  |  |  |  | 20.80 |  |  |  |  |
| Average3 |  | 50.70 |  | 43.83 |  |  | 16.45 |  |  | 10.70 | 20.00 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Wastewater sludge | 8 |  |  |  |  |  | 15.80 |  |  |  |  |  |  |  |  |
| Waste paper | 8 |  |  |  |  |  | 30.00 |  |  |  |  |  |  |  |  |
| Sawdust | 8 |  |  |  |  |  | 17.50 |  |  |  |  |  |  |  |  |
| Sewage sludge |  |  |  |  | 21.30 | 17.30 | 14.20 | 13.00 |  |  |  |  |  |  |  |
| Sewage sludge |  |  | 27.40 |  | 16.00 |  | 10.20 |  | 8.60 |  | 5.50 |  |  |  |  |
| Average4 |  |  | 27.40 |  | 18.65 | 17.30 | 17.54 | 13.00 | 8.60 |  | 5.50 |  |  |  |  |

## Appendix 3. Ash content of the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 |
| Bagasse | 10 |  | 15.80 |  |  | 13.68 |  |  |  |  |  | 15.36 |  |  |  |  |
| Chlorella | 8 |  |  |  |  |  |  | 52.60 |  |  |  |  |  |  |  |  |
| Conocarpus wastes |  | 4.53 |  |  |  |  |  |  |  |  |  | 8.56 |  |  |  | 8.64 |
| Cottonseed hull chars |  | 3.10 |  | 5.70 |  |  |  | 7.90 |  |  |  |  | 8.30 |  |  | 9.20 |
| Date palm waste | 5 |  | 14.42 |  | 16.34 |  |  | 19.68 |  |  |  | 20.71 |  | 21.05 |  | 21.39 |
| Dry algae | 17.1 |  | 46.30 |  |  | 68.60 |  |  |  |  |  | 72.20 |  |  | 74.80 |  |
| Dry algae | 17.6 |  | 55.80 |  |  | 71.80 |  |  |  |  |  | 73.00 |  |  | 76.40 |  |
| Fronds of edible date palm | 5 |  |  |  | 7.10 |  |  |  |  |  |  |  |  |  |  |  |
| Grass | 8 |  |  |  |  |  |  | 20.80 |  |  |  |  |  |  |  |  |
| Green waste | 17.1 |  | 3.60 |  |  | 11.10 |  |  |  |  |  | 13.20 |  |  | 13.90 |  |
| Green waste | 17.6 |  | 6.80 |  |  | 12.00 |  |  |  |  |  | 13.40 |  |  | 13.40 |  |
| Lignosulfonate | 1h | 35.86 |  |  | 45.61 |  |  |  |  |  |  | 56.13 |  |  |  |  |
| Lignosulfonate | 2h | 36.15 |  |  | 47.61 |  |  |  |  |  |  | 58.12 |  |  |  |  |
| Lignosulfonate | 4h | 36.93 |  |  | 49.83 |  |  |  |  |  |  | 59.69 |  |  |  |  |
| Peanut shell | 8 |  |  |  |  |  |  | 10.60 |  |  |  |  |  |  |  |  |
| Rhodes grass | 5 |  |  |  | 28.80 |  |  |  |  |  |  |  |  |  |  |  |
| Rice husk | 5 |  |  | 37.30 |  | 44.50 |  |  |  | 46.90 |  |  | 50.30 |  |  |  |
| Rice husk | 100 |  |  | 40.10 |  | 45.60 |  |  |  | 51.70 |  |  | 50.00 |  |  |  |
| Rice straw | 10 |  | 37.40 |  | 45.86 |  |  | 50.67 |  |  |  | 53.24 |  | 54.60 |  |  |
| Safflower seed press cake | 10 |  |  |  | 7.50 | 8.20 |  | 8.50 |  | 8.90 |  | 9.20 |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 8.40 | 8.50 |  | 8.60 |  | 9.10 |  | 9.30 |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 8.50 | 8.60 |  | 8.70 |  | 9.10 |  | 9.50 |  |  |  |  |
| Straw | 1h | 11.90 |  |  | 25.74 |  |  |  |  |  |  | 32.33 |  |  |  |  |
| Straw | 2h | 12.29 |  |  | 27.54 |  |  |  |  |  |  | 33.57 |  |  |  |  |
| Straw | 4h | 12.78 |  |  | 28.40 |  |  |  |  |  |  | 34.31 |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  | 12.22 |  |  | 12.91 |  |  |  | 13.85 |  | 14.37 |  | 15.32 |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 15.31 |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 15.73 |
| Sugar cane straw | 20 |  |  |  | 11.30 |  |  | 11.70 |  |  |  | 13.10 |  | 13.20 |  |  |
| Timothy grass | 2 |  |  |  |  | 3.50 |  |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  | 3.10 |  |  |  |  |  |  |  |  |  |  |
| Waterweeds | 8 |  |  |  |  |  |  | 63.50 |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  | 3.90 |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 5 |  |  | 10.90 |  | 17.60 |  |  |  | 20.00 |  |  | 21.30 |  |  |  |
| Wheat straw | 8 | 7.21 |  | 14.70 |  |  |  | 18.00 |  |  |  |  | 16.20 |  |  |  |
| Wheat straw | 17.1 |  | 8.00 |  |  | 22.40 |  |  |  |  |  | 24.50 |  |  | 26.20 |  |
| Wheat straw | 17.6 |  | 19.10 |  |  | 22.90 |  |  |  |  |  | 24.50 |  |  | 25.80 |  |
| Wheat straw | 450 |  |  |  |  | 3.60 |  |  |  |  |  |  |  |  |  |  |
| Wheat straw |  |  |  |  |  |  | 15.80 | 20.10 | 21.60 | 26.40 | 27.90 |  |  |  |  |  |
| Average1 |  | 17.86 | 23.02 | 21.74 | 24.72 | 21.74 | 15.80 | 22.45 | 21.60 | 24.59 | 27.90 | 30.85 | 29.22 | 25.81 | 38.42 | 14.27 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 |
| Bamboo | 10 |  | 6.51 |  |  | 8.83 |  |  |  |  |  | 11.86 |  |  |  |  |
| Douglas Fir bark |  |  |  | 4.72 | 6.21 | 7.31 |  | 7.57 |  | 8.00 |  | 8.85 |  |  |  |  |
| Douglas Fir wood | 190 |  |  | 0.60 | 0.66 | 0.85 |  | 0.78 |  | 1.01 |  | 1.13 |  |  |  |  |
| Hickory wood | 10 |  | 6.00 |  |  | 6.47 |  |  |  |  |  | 4.18 |  |  |  |  |
| Hybrid poplar wood |  |  |  | 3.50 | 5.28 | 6.31 |  | 7.03 |  | 7.25 |  | 7.17 |  |  |  |  |
| Moso bamboo |  |  | 3.31 |  | 3.52 |  |  | 3.95 |  |  |  | 4.13 |  | 4.15 |  |  |
| Pine | 5 |  |  | 1.40 |  | 2.90 |  |  |  | 4.20 |  |  | 5.90 |  |  |  |
| Pine | 100 |  |  | 3.40 |  | 3.40 |  |  |  | 0.70 |  |  | 5.00 |  |  |  |
| Pine wood | 17.1 |  | 0.30 |  |  | 1.00 |  |  |  |  |  | 1.20 |  |  | 1.10 |  |
| Pine wood | 17.6 |  | 0.50 |  |  | 1.20 |  |  |  |  |  | 1.30 |  |  | 1.10 |  |
| Pinewood | 2 |  |  |  |  | 4.60 |  |  |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  | 4.10 |  |  |  |  |  |  |  |  |  |  |
| Pitch pine (*Pinus rigida*) | 10 |  | 4.50 |  | 7.90 |  |  | 7.70 |  |  |  |  |  |  |  |  |
| Average2 |  |  | 3.52 | 2.72 | 4.71 | 4.27 |  | 5.41 |  | 4.23 |  | 4.98 | 5.45 | 4.15 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 |
| Cow manure | 8 |  |  |  |  |  |  | 67.50 |  |  |  |  |  |  |  |  |
| Pig manure | 8 | 35.70 |  | 37.20 |  |  |  | 48.40 |  |  |  |  | 69.60 |  |  |  |
| Shrimp hull | 8 |  |  |  |  |  |  | 53.80 |  |  |  |  |  |  |  |  |
| Bone dregs | 8 |  |  |  |  |  |  | 77.60 |  |  |  |  |  |  |  |  |
| Dairy (MD) | 6000 |  |  | 24.20 |  |  |  |  |  |  |  |  |  | 39.50 |  |  |
| Paved-feedlot (FL) | 6000 |  |  | 28.70 |  |  |  |  |  |  |  |  |  | 44.00 |  |  |
| Poultry litter (PL) | 6000 |  |  | 30.70 |  |  |  |  |  |  |  |  |  | 46.20 |  |  |
| Swine solids (SW) | 6000 |  |  | 32.50 |  |  |  |  |  |  |  |  |  | 52.90 |  |  |
| Turkey litter (TL) | 6000 |  |  | 34.80 |  |  |  |  |  |  |  |  |  | 49.90 |  |  |
| Average3 |  | 35.70 |  | 31.35 |  |  |  | 61.83 |  |  |  |  | 69.60 | 46.50 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 |
| Wastewater sludge | 8 |  |  |  |  |  | 61.90 |  |  |  |  |  |  |  |  |  |
| Waste paper | 8 |  |  |  |  |  | 53.50 |  |  |  |  |  |  |  |  |  |
| Sawdust | 8 |  |  |  |  |  | 9.94 |  |  |  |  |  |  |  |  |  |
| Sewage sludge | 10 |  |  |  |  |  | 74.21 |  |  |  | 77.90 |  | 81.53 |  | 83.93 | 88.07 |
| Sewage sludge |  |  |  | 52.00 | 55.60 |  | 57.60 |  | 58.50 |  |  |  |  |  |  |  |
| Sewage sludge |  | 65.80 |  | 75.50 |  |  | 80.60 |  |  |  | 83.80 |  | 86.80 |  |  |  |
| Average4 |  | 65.80 |  | 63.75 | 55.60 |  | 56.29 |  | 58.50 |  | 80.85 |  | 84.17 |  | 83.93 | 88.07 |

## Appendix 4. Carbon content of the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Bagasse | 10 |  | 69.50 |  |  | 78.60 |  |  |  |  |  | 76.45 |  |  |  |  |  |  |
| Conocarpus wastes |  | 64.19 |  |  | 76.83 |  |  |  |  |  |  | 82.93 |  |  |  | 84.97 |  |  |
| Cottonseed hull chars |  | 51.90 |  | 77.00 |  |  |  | 87.50 |  |  |  |  | 91.00 |  |  | 90.00 |  |  |
| Date palm waste | 5 |  | 57.99 |  | 66.87 |  |  | 72.30 |  |  |  | 72.89 |  | 73.42 |  | 74.63 |  |  |
| Dry algae | 17.1 |  | 62.70 |  |  | 74.50 |  |  |  |  |  | 80.10 |  |  | 86.40 |  |  |  |
| Dry algae | 17.6 |  | 69.50 |  |  | 78.70 |  |  |  |  |  | 83.40 |  |  | 90.60 |  |  |  |
| E. Saligna leaves |  |  |  |  | 66.28 |  |  |  |  | 71.98 |  |  |  |  |  |  |  |  |
| Fronds of edible date palm | 5 |  |  |  | 60.90 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Geodae-uksae 1 | 10 |  | 66.19 |  | 74.69 | 78.29 |  | 79.42 |  |  |  | 83.67 |  | 85.93 |  |  |  |  |
| Green waste | 17.1 |  | 53.20 |  |  | 78.80 |  |  |  |  |  | 87.70 |  |  | 87.50 |  |  |  |
| Green waste | 17.6 |  | 69.30 |  |  | 82.90 |  |  |  |  |  | 88.40 |  |  | 93.20 |  |  |  |
| Lignosulfonate | 1h | 30.33 |  |  | 33.58 |  |  |  |  |  |  | 34.52 |  |  |  |  |  |  |
| Lignosulfonate | 2h | 31.07 |  |  | 33.67 |  |  |  |  |  |  | 34.60 |  |  |  |  |  |  |
| Lignosulfonate | 4h | 31.94 |  |  | 33.60 |  |  |  |  |  |  | 36.81 |  |  |  |  |  |  |
| Pecan shells |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 68.00 |  |  |
| Rhodes grass | 5 |  |  |  | 56.70 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Rice husk | 5 |  |  | 66.14 |  | 74.93 |  |  |  | 84.03 |  |  | 95.13 |  |  |  |  |  |
| Rice husk | 100 |  |  | 70.87 |  | 76.86 |  |  |  | 89.98 |  |  | 89.61 |  |  |  |  |  |
| Rice straw | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 88.94 |  |
| Rice straw | 10 |  | 68.72 |  | 75.47 |  |  | 81.43 |  |  |  | 87.52 |  | 91.15 |  |  |  |  |
| Rice straw | 18000 |  |  |  |  |  |  |  |  |  |  | 82.66 |  | 83.88 |  | 87.72 | 92.03 | 95.83 |
| Safflower seed press cake | 10 |  |  |  | 68.76 | 70.43 |  | 71.37 |  | 72.96 |  | 73.72 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 68.22 | 68.65 |  | 70.01 |  | 71.76 |  | 73.75 |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 68.54 | 70.25 |  | 71.79 |  | 72.13 |  | 73.16 |  |  |  |  |  |  |
| Straw | 1h | 45.57 |  |  | 57.07 |  |  |  |  |  |  | 59.17 |  |  |  |  |  |  |
| Straw | 2h | 46.33 |  |  | 57.59 |  |  |  |  |  |  | 59.09 |  |  |  |  |  |  |
| Straw | 4h | 46.52 |  |  | 57.92 |  |  |  |  |  |  | 60.80 |  |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  | 71.34 |  |  | 75.03 |  |  |  | 78.48 |  | 79.48 |  | 79.51 | 79.86 |  |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 79.18 |  |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 78.81 |  |  |
| Sugar cane straw | 20 |  |  |  | 67.00 |  |  | 71.00 |  |  |  | 74.00 |  | 73.00 |  |  |  |  |
| Timothy grass | 2 |  |  |  |  | 67.50 |  |  |  |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  | 63.70 |  |  |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  | 65.20 |  |  |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 5 |  |  | 70.88 |  | 83.11 |  |  |  | 86.21 |  |  | 94.90 |  |  |  |  |  |
| Wheat straw | 17.1 |  | 50.30 |  |  | 84.10 |  |  |  |  |  | 90.10 |  |  | 92.20 |  |  |  |
| Wheat straw | 17.6 |  | 76.20 |  |  | 86.40 |  |  |  |  |  | 90.30 |  |  | 93.70 |  |  |  |
| Wheat straw | 450 |  |  |  |  | 64.80 |  |  |  |  |  |  |  |  |  |  |  |  |
| Wheat straw |  |  |  |  |  |  | 53.70 | 60.20 | 64.30 | 67.00 | 69.20 |  |  |  |  |  |  |  |
| Average1 |  | 43.48 | 64.36 | 71.22 | 60.84 | 74.87 | 53.70 | 74.01 | 64.30 | 77.01 | 69.20 | 72.36 | 92.66 | 81.14 | 90.60 | 80.35 | 86.94 | 95.83 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Bamboo | 10 |  | 66.20 |  |  | 76.89 |  |  |  |  |  | 80.89 |  |  |  |  |  |  |
| Douglas Fir bark |  |  |  | 69.97 | 75.85 | 76.84 |  | 78.61 |  | 78.92 |  | 83.03 |  |  |  |  |  |  |
| Douglas Fir wood | 190 |  |  | 70.58 | 75.63 | 77.51 |  | 79.84 |  | 85.17 |  | 87.81 |  |  |  |  |  |  |
| Eucalyptus saligna wood |  |  |  |  | 69.74 |  |  |  |  | 83.61 |  |  |  |  |  |  |  |  |
| Hickory wood | 10 |  | 69.13 |  |  | 83.62 |  |  |  |  |  | 81.81 |  |  |  |  |  |  |
| Hybrid poplar wood |  |  |  | 65.81 | 69.54 | 72.18 |  | 75.00 |  | 75.79 |  | 77.82 |  |  |  |  |  |  |
| Moso bamboo |  |  | 64.38 |  | 72.26 |  |  | 79.59 |  |  |  | 82.45 |  | 86.34 |  |  |  |  |
| Pine | 5 |  |  | 69.64 |  | 79.86 |  |  |  | 89.93 |  |  | 94.61 |  |  |  |  |  |
| Pine | 100 |  |  | 70.97 |  | 77.34 |  |  |  | 82.32 |  |  | 87.89 |  |  |  |  |  |
| Pine wood | 17.1 |  | 54.10 |  |  | 82.50 |  |  |  |  |  | 90.00 |  |  | 92.50 |  |  |  |
| Pine wood | 17.6 |  | 71.30 |  |  | 86.30 |  |  |  |  |  | 92.30 |  |  | 92.50 |  |  |  |
| Pinewood | 2 |  |  |  |  | 81.40 |  |  |  |  |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  | 75.50 |  |  |  |  |  |  |  |  |  |  |  |  |
| Pitch pine (*Pinus rigida*) | 10 |  | 63.90 |  | 70.70 |  |  | 90.50 |  |  |  |  |  |  |  |  |  |  |
| Average2 |  |  | 64.84 | 69.39 | 72.29 | 79.09 |  | 80.71 |  | 82.62 |  | 84.51 | 91.25 | 86.34 | 92.50 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Dairy (MD) | 6000 |  |  | 55.80 |  |  |  |  |  |  |  |  |  | 56.67 |  |  |  |  |
| Paved-feedlot (FL) | 6000 |  |  | 53.32 |  |  |  |  |  |  |  |  |  | 52.41 |  |  |  |  |
| Poultry litter (PL) | 6000 |  |  | 51.07 |  |  |  |  |  |  |  |  |  | 45.91 |  |  |  |  |
| Swine solids (SW) | 6000 |  |  | 51.51 |  |  |  |  |  |  |  |  |  | 44.06 |  |  |  |  |
| Turkey litter (TL) | 6000 |  |  | 49.28 |  |  |  |  |  |  |  |  |  | 44.77 |  |  |  |  |
| Poultry litter |  |  |  |  | 43.11 |  |  |  |  | 41.32 |  |  |  |  |  |  |  |  |
| Cow manure |  |  |  |  | 17.50 |  |  |  |  | 16.53 |  |  |  |  |  |  |  |  |
| Broiler litter |  |  |  | 62.30 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Average3 |  |  |  | 53.88 | 30.31 |  |  |  |  | 28.93 |  |  |  | 48.76 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 475 | 500 | 525 | 550 | 575 | 600 | 650 | 700 | 750 | 800 | 900 | 1000 |
| Sewage sludge | 10 |  |  |  |  |  | 17.46 |  |  |  | 18.40 |  | 16.92 |  | 16.20 | 15.92 |  |  |
| Sewage sludge |  |  |  |  | 22.60 | 18.60 |  | 17.70 |  | 19.60 |  |  |  |  |  |  |  |  |
| Sewage sludge |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Average4 |  |  |  |  | 22.60 | 18.60 | 17.46 | 17.70 |  | 19.60 | 18.40 |  | 16.92 |  | 16.20 | 15.92 |  |  |

## Appendix 5. Heating value

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 277 | 300 | 327 | 350 | 377 | 400 | 427 | 450 | 477 | 500 | 527 | 550 | 600 | 700 | 750 | 800 | 900 | 1000 |
| Dry algae | 17.1 |  |  |  |  |  |  |  | 9.22 |  |  |  |  | 8.29 |  |  |  |  |  |
| Dry algae | 17.6 |  |  |  |  |  |  |  | 8.68 |  |  |  |  | 8.17 |  |  |  |  |  |
| Green waste | 17.1 |  |  |  |  |  |  |  | 27.50 |  |  |  |  | 27.90 |  |  |  |  |  |
| Green waste | 17.6 |  |  |  |  |  |  |  | 27.90 |  |  |  |  | 28.00 |  |  |  |  |  |
| Rice straw | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 28.88 |  |
| Rice straw | 10 |  | 16.60 |  |  |  | 15.30 |  |  |  | 13.50 |  |  | 13.90 | 13.60 |  |  |  |  |
| Rice straw | 18000 |  |  |  |  |  |  |  |  |  |  |  |  | 25.99 | 26.45 |  | 28.29 | 30.38 | 32.30 |
| Safflower seed press cake | 10 |  |  |  |  |  | 28.15 |  | 28.86 |  | 29.39 |  | 29.71 | 30.06 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  |  |  | 28.51 |  | 28.98 |  | 29.59 |  | 29.97 | 30.17 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  |  |  | 28.77 |  | 29.20 |  | 29.73 |  | 30.12 | 30.27 |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  |  |  | 27.32 |  |  |  | 27.68 |  |  | 27.61 | 26.66 |  | 26.96 | 27.05 |  |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 26.63 |  |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 27.01 |  |  |
| Timothy grass | 2 |  |  |  |  |  |  |  | 20.80 |  |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  |  |  |  | 21.10 |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  |  |  |  | 20.50 |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 17.1 |  |  |  |  |  |  |  | 25.10 |  |  |  |  | 25.60 |  |  |  |  |  |
| Wheat straw | 17.6 |  |  |  |  |  |  |  | 25.50 |  |  |  |  | 25.50 |  |  |  |  |  |
| Wheat straw | 450 |  |  |  |  |  |  |  | 20.80 |  |  |  |  |  |  |  |  |  |  |
| Average1 |  |  | 16.60 |  |  |  | 25.61 |  | 22.63 |  | 25.98 |  | 29.93 | 23.46 | 22.24 |  | 27.22 | 28.77 | 32.30 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 277 | 300 | 327 | 350 | 377 | 400 | 427 | 450 | 477 | 500 | 527 | 550 | 600 | 700 | 750 | 800 | 900 | 1000 |
| Beech trunkbark | 120 | 22.60 |  | 24.00 |  | 25.20 |  | 26.30 |  | 27.80 |  | 29.00 |  |  |  |  |  |  |  |
| Beech trunkbark | 300 | 23.50 |  | 23.10 |  | 26.30 |  | 27.80 |  | 28.90 |  | 30.10 |  |  |  |  |  |  |  |
| Beech trunkbark | 600 | 23.50 |  | 25.70 |  | 27.30 |  | 28.60 |  | 29.70 |  | 30.80 |  |  |  |  |  |  |  |
| Beech trunkbark | 1200 | 24.90 |  | 26.40 |  | 27.80 |  | 29.40 |  | 30.50 |  | 31.70 |  |  |  |  |  |  |  |
| Beech trunkbark | 2400 | 25.60 |  | 27.00 |  | 28.70 |  | 30.30 |  | 31.80 |  | 33.00 |  |  |  |  |  |  |  |
| Beech trunkbark | 6000 | 26.40 |  | 28.10 |  | 29.80 |  | 31.50 |  | 33.20 |  | 34.80 |  |  |  |  |  |  |  |
| Pine wood | 17.1 |  |  |  |  |  |  |  | 32.50 |  |  |  |  | 34.40 |  |  |  |  |  |
| Pine wood | 17.6 |  |  |  |  |  |  |  | 32.90 |  |  |  |  | 34.40 |  |  |  |  |  |
| Pinewood | 2 |  |  |  |  |  |  |  | 28.60 |  |  |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  |  |  |  | 27.10 |  |  |  |  |  |  |  |  |  |  |
| Average2 |  | 24.42 |  | 25.72 |  | 27.52 |  | 28.98 | 30.28 | 30.32 |  | 31.57 |  | 34.40 |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 277 | 300 | 327 | 350 | 377 | 400 | 427 | 450 | 477 | 500 | 527 | 550 | 600 | 700 | 750 | 800 | 900 | 1000 |
| Dairy (MD) | 6000 |  |  |  | 20.90 |  |  |  |  |  |  |  |  |  | 18.97 |  |  |  |  |
| Paved-feedlot (FL) | 6000 |  |  |  | 20.39 |  |  |  |  |  |  |  |  |  | 17.23 |  |  |  |  |
| Poultry litter (PL) | 6000 |  |  |  | 19.03 |  |  |  |  |  |  |  |  |  | 14.75 |  |  |  |  |
| Swine solids (SW) | 6000 |  |  |  | 21.12 |  |  |  |  |  |  |  |  |  | 15.07 |  |  |  |  |
| Turkey litter (TL) | 6000 |  |  |  | 17.28 |  |  |  |  |  |  |  |  |  | 14.45 |  |  |  |  |
| Average3 |  |  |  |  | 19.74 |  |  |  |  |  |  |  |  |  | 16.09 |  |  |  |  |

## Appendix 6. BET specific surface of the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Bagasse | 10 | 5.20 |  |  | 13.60 |  |  | 388.30 |  |  |  |  |  |
| Chlorella | 8 |  |  |  |  | 2.78 |  |  |  |  |  |  |  |
| Cottonseed hull chars |  |  | 4.70 |  |  |  |  |  | 34.00 |  |  | 322.00 |  |
| Dairy (MD) | 17.1 |  | 1.64 |  |  |  |  |  |  | 186.50 |  |  |  |
| Dry algae | 17.1 |  |  |  | 14.00 |  |  | 19.00 |  |  |  |  |  |
| Fronds of edible date palm | 5 |  |  | 1.99 |  |  |  |  |  |  |  |  |  |
| Geodae-uksae 1 | 10 | 0.49 |  | 3.11 | 21.93 | 180.96 |  | 293.04 |  | 368.98 |  |  |  |
| Grass | 8 |  |  |  |  | 3.33 |  |  |  |  |  |  |  |
| Green waste | 17.6 |  |  |  | 17.00 |  |  | 46.00 |  |  |  |  |  |
| Paved-feedlot (FL) | 17.6 |  | 1.34 |  |  |  |  |  |  | 145.20 |  |  |  |
| Peanut shell | 8 |  |  |  |  | 43.50 |  |  |  |  |  |  |  |
| Rhodes grass | 5 |  |  | 16.78 |  |  |  |  |  |  |  |  |  |
| Rice straw | 17.6 | 4.50 |  | 21.20 |  | 45.80 |  | 84.80 |  | 22.50 |  |  |  |
| Safflower seed press cake | 10 |  |  | 2.67 | 3.33 | 4.23 | 3.78 | 3.41 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  | 2.26 | 2.92 | 3.98 | 3.26 | 2.85 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  | 1.89 | 2.71 | 3.64 | 2.83 | 2.47 |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  | 16.04 |  | 15.70 |  | 17.58 |  | 19.26 |  | 19.01 | 140.41 |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  | 32.26 |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  | 119.78 |  |
| Waterweeds | 8 |  |  |  |  | 3.78 |  |  |  |  |  |  |  |
| Wheat straw | 8 |  | 3.48 |  |  | 33.20 |  |  | 182.00 |  |  |  |  |
| Wheat straw | 17.1 |  |  |  | 16.00 |  |  | 22.00 |  |  |  |  |  |
| Average1 |  | 3.40 | 2.79 | 8.24 | 11.44 | 30.99 | 3.29 | 87.94 | 108.00 | 148.49 |  | 123.26 | 140.41 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Bamboo | 10 | 1.30 |  |  | 10.20 |  |  | 375.50 |  |  |  |  |  |
| Hickory wood | 10 | Below 0.1 |  |  | 12.90 |  |  | 401.00 |  |  |  |  |  |
| Pine wood | 17.1 |  |  |  | 4.00 |  |  | 196.00 |  |  | 128.00 |  |  |
| Pine wood | 17.6 | 6.00 |  |  | 23.00 |  |  | 127.00 |  |  |  |  |  |
| Pitch pine (*Pinus rigida*) | 10 | 2.90 |  | 4.80 |  |  | 175.40 |  |  |  |  |  |  |
| Average2 |  | 3.40 |  | 4.80 | 12.53 |  | 175.40 | 274.88 |  |  | 128.00 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Cow manure | 8 |  |  |  |  | 21.90 |  |  |  |  |  |  |  |
| Pig manure | 8 |  | 4.26 |  |  | 47.40 |  |  | 42.40 |  |  |  |  |
| Shrimp hull | 8 |  |  |  |  | 13.30 |  |  |  |  |  |  |  |
| Bone dregs | 8 |  |  |  |  | 113.00 |  |  |  |  |  |  |  |
| Poultry litter (PL) | 6000 |  | 3.93 |  |  |  |  |  |  | 50.90 |  |  |  |
| Swine solids (SW) | 6000 |  | 0.92 |  |  |  |  |  |  | 4.11 |  |  |  |
| Turkey litter (TL) | 6000 |  | 2.60 |  |  |  |  |  |  | 66.70 |  |  |  |
| Broiler litter |  |  | 60.00 |  |  |  |  |  |  | 94.00 |  |  |  |
| Average3 |  |  | 14.34 |  |  | 48.90 |  |  | 42.40 | 53.93 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Wastewater sludge | 8 |  |  |  |  | 71.60 |  |  |  |  |  |  |  |
| Waste paper | 8 |  |  |  |  | 133.00 |  |  |  |  |  |  |  |
| Sawdust | 8 |  |  |  |  | 203.00 |  |  |  |  |  |  |  |
| Sewage sludge | 10 |  |  |  |  | 25.42 |  | 20.27 |  | 32.17 |  | 48.50 | 67.60 |
| Sewage sludge |  |  |  | 0.10 | 2.90 | 3.20 | 13.30 |  |  |  |  |  |  |
| Sewage sludge |  | 14.37 |  | 22.68 |  | 24.53 |  | 26.66 |  | 26.70 |  |  |  |
| Average4 |  | 14.37 |  | 11.39 | 2.90 | 76.79 | 13.30 | 23.46 |  | 29.43 |  | 48.50 | 67.60 |

## Appendix 7. pH value of the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Bagasse | 10 |  | 7.30 |  |  | 7.50 |  |  | 7.50 |  |  |  |  |  |
| Chlorella | 8 |  |  |  |  |  | 10.80 |  |  |  |  |  |  |  |
| Conocarpus wastes |  | 7.37 |  |  | 9.67 |  |  |  | 12.21 |  |  |  | 12.38 |  |
| Cottonseed hull chars |  | 3.70 |  | 6.90 |  |  | 8.50 |  |  | 8.60 |  |  | 7.70 |  |
| Date palm waste | 5 |  | 8.32 |  | 9.25 |  | 9.59 |  | 9.57 |  | 11.50 |  | 11.49 |  |
| Dry algae | 17.1 |  | 4.90 |  |  | 9.10 |  |  | 11.10 |  |  | 12.40 |  |  |
| Dry algae | 17.6 |  | 7.70 |  |  | 9.30 |  |  | 11.90 |  |  | 12.50 |  |  |
| Fronds of edible date palm | 5 |  |  |  | 9.50 |  |  |  |  |  |  |  |  |  |
| Grass | 8 |  |  |  |  |  | 10.20 |  |  |  |  |  |  |  |
| Green waste | 17.1 |  | 7.40 |  |  | 9.60 |  |  | 10.40 |  |  | 11.40 |  |  |
| Green waste | 17.6 |  | 8.10 |  |  | 10.00 |  |  | 11.30 |  |  | 11.60 |  |  |
| Lignosulfonate | 1h | 4.18 |  |  | 9.75 |  |  |  | 10.68 |  |  |  |  |  |
| Lignosulfonate | 2h | 4.56 |  |  | 9.65 |  |  |  | 12.50 |  |  |  |  |  |
| Lignosulfonate | 4h | 4.37 |  |  | 9.35 |  |  |  | 12.95 |  |  |  |  |  |
| Peanut shell | 8 |  |  |  |  |  | 10.50 |  |  |  |  |  |  |  |
| Rhodes grass | 5 |  |  |  | 9.70 |  |  |  |  |  |  |  |  |  |
| Rice straw | 10 |  | 9.00 |  | 10.10 |  | 10.50 |  | 10.60 |  | 10.60 |  |  |  |
| Safflower seed press cake | 10 |  |  |  | 8.18 | 9.13 | 9.44 | 9.67 | 9.89 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 7.59 | 8.71 | 9.52 | 9.70 | 10.15 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 8.07 | 8.46 | 9.30 | 9.56 | 9.77 |  |  |  |  |  |
| Straw | 1h | 5.34 |  |  | 10.82 |  |  |  | 10.93 |  |  |  |  |  |
| Straw | 2h | 5.91 |  |  | 10.86 |  |  |  | 10.96 |  |  |  |  |  |
| Straw | 4h | 6.11 |  |  | 10.78 |  |  |  | 10.99 |  |  |  |  |  |
| Sugar cane straw | 20 |  |  |  | 8.60 |  | 9.80 |  | 9.70 |  | 10.10 |  |  |  |
| Waterweeds | 8 |  |  |  |  |  | 10.30 |  |  |  |  |  |  |  |
| Wheat straw | 8 | 5.43 |  | 8.69 |  |  | 10.20 |  |  | 10.20 |  |  |  |  |
| Wheat straw | 17.1 |  | 6.10 |  |  | 9.80 |  |  | 10.90 |  |  | 12.10 |  |  |
| Wheat straw | 17.6 |  | 9.40 |  |  | 10.10 |  |  | 11.30 |  |  | 11.90 |  |  |
| Average1 |  | 5.22 | 7.58 | 7.80 | 9.46 | 9.17 | 9.89 | 9.64 | 10.77 | 9.40 | 10.73 | 11.98 | 10.52 |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Bamboo | 10 |  | 7.90 |  |  | 8.50 |  |  | 9.20 |  |  |  |  |  |
| Douglas Fir bark |  |  |  | 7.90 | 8.40 | 9.30 | 9.80 | 9.90 | 10.20 |  |  |  |  |  |
| Douglas Fir wood | 190 |  |  | 8.50 | 8.30 | 8.60 | 8.90 | 9.00 | 9.00 |  |  |  |  |  |
| Hickory wood | 10 |  | 7.10 |  |  | 7.90 |  |  | 8.40 |  |  |  |  |  |
| Hybrid poplar wood |  |  |  | 9.40 | 10.10 | 10.50 | 10.60 | 10.40 | 10.40 |  |  |  |  |  |
| Pine wood | 17.1 |  | 4.50 |  |  | 6.60 |  |  | 6.70 |  |  | 10.20 |  |  |
| Pine wood | 17.6 |  | 5.70 |  |  | 6.70 |  |  | 9.10 |  |  | 10.40 |  |  |
| Average2 |  |  | 6.30 | 8.60 | 8.93 | 8.30 | 9.77 | 9.77 | 9.00 |  |  | 10.30 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Cow manure | 8 |  |  |  |  |  | 10.20 |  |  |  |  |  |  |  |
| Pig manure | 8 | 8.22 |  | 9.65 |  |  | 10.50 |  |  | 10.80 |  |  |  |  |
| Shrimp hull | 8 |  |  |  |  |  | 10.30 |  |  |  |  |  |  |  |
| Bone dregs | 8 |  |  |  |  |  | 9.57 |  |  |  |  |  |  |  |
| Dairy (MD) | 6000 |  |  | 9.20 |  |  |  |  |  |  | 9.90 |  |  |  |
| Paved-feedlot (FL) | 6000 |  |  | 9.10 |  |  |  |  |  |  | 10.30 |  |  |  |
| Poultry litter (PL) | 6000 |  |  | 8.70 |  |  |  |  |  |  | 10.30 |  |  |  |
| Swine solids (SW) | 6000 |  |  | 8.40 |  |  |  |  |  |  | 9.50 |  |  |  |
| Turkey litter (TL) | 6000 |  |  | 8.00 |  |  |  |  |  |  | 9.90 |  |  |  |
| Average3 |  | 8.22 |  | 8.84 |  |  |  |  |  | 10.80 | 9.98 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 900 |
| Wastewater sludge | 8 |  |  |  |  |  | 8.82 |  |  |  |  |  |  |  |
| Waste paper | 8 |  |  |  |  |  | 9.88 |  |  |  |  |  |  |  |
| Sawdust | 8 |  |  |  |  |  | 10.50 |  |  |  |  |  |  |  |
| Sewage sludge | 10 |  |  |  |  |  | 8.81 |  | 9.54 |  | 11.11 |  | 12.18 | 12.15 |
| Sewage sludge |  |  |  |  | 7.70 | 8.20 | 9.00 | 9.90 |  |  |  |  |  |  |
| Sewage sludge |  |  | 6.66 |  | 7.40 |  | 7.50 |  | 8.10 |  | 8.40 |  |  |  |
| Average4 |  |  | 6.66 |  | 7.55 | 8.20 | 9.09 | 9.90 | 8.82 |  | 9.76 |  | 12.18 | 12.15 |

## Appendix 8. H:C ratioof the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 277 | 300 | 350 | 400 | 450 | 477 | 500 | 550 | 600 | 650 | 677 | 700 | 750 | 777 | 800 | 900 |
| Bagasse | 10 |  |  |  | 0.06 |  | 0.04 |  |  |  | 0.04 |  |  |  |  |  |  |  |
| Conocarpus wastes |  | 0.74 |  |  |  | 0.44 |  |  |  |  | 0.19 |  |  |  |  |  | 0.09 |  |
| Cottonseed hull chars |  | 1.38 |  |  | 0.70 |  |  |  | 0.39 |  |  | 0.17 |  |  |  |  | 0.08 |  |
| Date palm waste | 5 |  |  | 0.84 |  | 0.63 |  |  | 0.35 |  | 0.28 |  |  | 0.19 |  |  | 0.14 |  |
| Dry algae | 17.1 |  |  | 1.38 |  |  | 0.72 |  |  |  | 0.41 |  |  |  | 0.21 |  |  |  |
| Dry algae | 17.6 |  |  | 1.19 |  |  | 0.61 |  |  |  | 0.29 |  |  |  | 0.19 |  |  |  |
| Fronds of edible date palm | 5 |  |  |  |  | 0.49 |  |  |  |  |  |  |  |  |  |  |  |  |
| Green waste | 17.1 |  |  | 1.41 |  |  | 0.63 |  |  |  | 0.32 |  |  |  | 0.21 |  |  |  |
| Green waste | 17.6 |  |  | 0.94 |  |  | 0.51 |  |  |  | 0.27 |  |  |  | 0.16 |  |  |  |
| Lignosulfonate | 1h | 1.51 |  |  |  | 0.65 |  |  |  |  | 0.38 |  |  |  |  |  |  |  |
| Lignosulfonate | 2h | 1.39 |  |  |  | 0.62 |  |  |  |  | 0.38 |  |  |  |  |  |  |  |
| Lignosulfonate | 4h | 1.16 |  |  |  | 0.56 |  |  |  |  | 0.41 |  |  |  |  |  |  |  |
| Pecan shells |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0.55 |  |
| Rhodes grass | 5 |  |  |  |  | 0.46 |  |  |  |  |  |  |  |  |  |  |  |  |
| Rice husk | 5 |  |  |  | 0.33 |  | 0.21 |  |  | 0.11 |  | 0.02 |  |  |  |  |  |  |
| Rice husk | 100 |  |  |  | 0.25 |  | 0.18 |  |  | 0.05 |  | 0.06 |  |  |  |  |  |  |
| Rice straw | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0.07 |
| Rice straw | 10 |  |  | 0.08 |  | 0.06 |  |  | 0.03 |  | 0.02 |  |  | 0.01 |  |  |  |  |
| Rice straw | 18000 |  |  |  |  |  |  |  |  |  | 0.09 |  |  | 0.07 |  |  | 0.07 | 0.06 |
| Safflower seed press cake | 10 |  |  |  |  | 0.71 | 0.59 |  | 0.50 | 0.44 | 0.38 |  |  |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  |  | 0.60 | 0.55 |  | 0.49 | 0.45 | 0.38 |  |  |  |  |  |  |  |
| Safflower seed press cake | 50 |  |  |  |  | 0.64 | 0.54 |  | 0.48 | 0.47 | 0.43 |  |  |  |  |  |  |  |
| Straw | 1h | 1.52 |  |  |  | 0.70 |  |  |  |  | 0.31 |  |  |  |  |  |  |  |
| Straw | 2h | 1.46 |  |  |  | 0.67 |  |  |  |  | 0.29 |  |  |  |  |  |  |  |
| Straw | 4h | 1.42 |  |  |  | 0.63 |  |  |  |  | 0.26 |  |  |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  |  | 0.66 |  |  | 0.42 |  | 0.28 |  |  | 0.18 |  |  | 0.11 | 0.06 |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0.12 |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 0.13 |  |
| Timothy grass | 2 |  |  |  |  |  | 0.40 |  |  |  |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  |  | 0.70 |  |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 2 |  |  |  |  |  | 0.40 |  |  |  |  |  |  |  |  |  |  |  |
| Wheat straw | 5 |  |  |  | 0.31 |  | 0.12 |  |  | 0.11 |  | 0.00 |  |  |  |  |  |  |
| Wheat straw | 17.1 |  |  | 1.47 |  |  | 0.51 |  |  |  | 0.32 |  |  |  | 0.20 |  |  |  |
| Wheat straw | 17.6 |  |  | 0.79 |  |  | 0.49 |  |  |  | 0.28 |  |  |  | 0.16 |  |  |  |
| Wheat straw | 450 |  |  |  |  |  | 0.60 |  |  |  |  |  |  |  |  |  |  |  |
| Average1 |  | 1.32 |  | 1.01 | 0.33 | 0.57 | 0.46 |  | 0.38 | 0.27 | 0.29 | 0.06 |  | 0.11 | 0.19 |  | 0.16 | 0.06 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 277 | 300 | 350 | 400 | 450 | 477 | 500 | 550 | 600 | 650 | 677 | 700 | 750 | 777 | 800 | 900 |
| Bamboo | 10 |  |  |  | 0.07 |  | 0.05 |  |  |  | 0.03 |  |  |  |  |  |  |  |
| Beech trunkbark | 6000 |  | 0.07 |  |  |  |  | 0.03 |  |  |  |  | 0.02 |  |  | 0.01 |  |  |
| Douglas Fir bark | 190 |  |  |  | 0.88 | 0.78 | 0.68 |  | 0.61 | 0.55 | 0.50 |  |  |  |  |  |  |  |
| Douglas Fir wood | 190 |  |  |  | 0.93 | 0.80 | 0.69 |  | 0.64 | 0.55 | 0.49 |  |  |  |  |  |  |  |
| Hickory wood | 10 |  |  |  | 0.07 |  | 0.04 |  |  |  | 0.03 |  |  |  |  |  |  |  |
| Hybrid poplar wood | 190 |  |  |  | 0.91 | 0.72 | 0.67 |  | 0.62 | 0.57 | 0.50 |  |  |  |  |  |  |  |
| Moso bamboo |  |  |  | 0.71 |  | 0.58 |  |  | 0.43 |  | 0.28 |  |  | 0.22 |  |  |  |  |
| Pine | 5 |  |  |  | 0.29 |  | 0.16 |  |  | 0.07 |  | 0.03 |  |  |  |  |  |  |
| Pine | 100 |  |  |  | 0.24 |  | 0.17 |  |  | 0.13 |  | 0.07 |  |  |  |  |  |  |
| Pine wood | 17.1 |  |  | 1.30 |  |  | 0.56 |  |  |  | 0.35 |  |  |  | 0.19 |  |  |  |
| Pine wood | 17.6 |  |  | 0.79 |  |  | 0.49 |  |  |  | 0.30 |  |  |  | 0.15 |  |  |  |
| Pinewood | 2 |  |  |  |  |  | 0.40 |  |  |  |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  |  | 0.60 |  |  |  |  |  |  |  |  |  |  |  |
| Pitch pine (*Pinus rigida*) | 10 |  |  | 1.01 |  | 0.58 |  |  | 0.33 |  |  |  |  |  |  |  |  |  |
| Average2 |  |  |  | 0.95 | 0.48 | 0.69 | 0.41 |  | 0.53 | 0.37 | 0.31 | 0.05 |  | 0.22 | 0.17 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 277 | 300 | 350 | 400 | 450 | 477 | 500 | 550 | 600 | 650 | 677 | 700 | 750 | 777 | 800 | 900 |
| Dairy (MD) | x |  |  |  | 0.92 |  |  |  |  |  |  |  |  | 0.20 |  |  |  |  |
| Paved-feedlot (FL) | x |  |  |  | 0.91 |  |  |  |  |  |  |  |  | 0.21 |  |  |  |  |
| Poultry litter (PL) | x |  |  |  | 0.89 |  |  |  |  |  |  |  |  | 0.52 |  |  |  |  |
| Swine solids (SW) | x |  |  |  | 1.14 |  |  |  |  |  |  |  |  | 0.20 |  |  |  |  |
| Turkey litter (TL) | x |  |  |  | 0.88 |  |  |  |  |  |  |  |  | 0.24 |  |  |  |  |
| Broiler litter |  |  |  |  | 1.06 |  |  |  |  |  |  |  |  | 0.37 |  |  |  |  |
| Average3 |  |  |  |  | 0.97 |  |  |  |  |  |  |  |  | 0.29 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 277 | 300 | 350 | 400 | 450 | 477 | 500 | 550 | 600 | 650 | 677 | 700 | 750 | 777 | 800 | 900 |
| Sewage sludge | 10 |  |  |  |  |  |  |  | 0.48 |  | 0.22 |  |  | 0.15 |  |  | 0.03 | 0.09 |
| Sewage sludge |  |  |  |  |  | 1.43 | 1.29 |  | 1.15 | 1.10 |  |  |  |  |  |  |  |  |
| Average4 |  |  |  |  |  | 1.43 | 1.29 |  | 0.82 | 1.10 | 0.22 |  |  | 0.15 |  |  | 0.03 | 0.09 |

## Appendix 9. O:C ratio of the feed stock types

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 800 | 900 | 1000 |
| Bagasse | 10 |  | 0.35 |  |  | 0.20 |  |  | 0.24 |  |  |  |  |  |
| Conocarpus wastes |  | 0.31 |  |  | 0.14 |  |  |  | 0.06 |  |  | 0.04 |  |  |
| Cottonseed hull chars |  | 0.59 |  | 0.15 |  |  | 0.07 |  |  | 0.05 |  | 0.06 |  |  |
| Date palm waste | 5 |  | 0.27 |  | 0.13 |  | 0.05 |  | 0.03 |  | 0.03 | 0.02 |  |  |
| Fronds of edible date palm | 5 |  |  |  | 0.32 |  |  |  |  |  |  |  |  |  |
| Lignosulfonate | 1h | 0.86 |  |  | 0.62 |  |  |  | 0.55 |  |  |  |  |  |
| Lignosulfonate | 2h | 0.79 |  |  | 0.61 |  |  |  | 0.60 |  |  |  |  |  |
| Lignosulfonate | 4h | 0.75 |  |  | 0.60 |  |  |  | 0.61 |  |  |  |  |  |
| Pecan shells |  |  |  |  |  |  |  |  |  |  |  | 0.30 |  |  |
| Rhodes grass | 5 |  |  |  | 0.11 |  |  |  |  |  |  |  |  |  |
| Rice husk | 5 |  |  | 0.84 |  | 0.65 |  | 0.49 |  | 0.36 |  |  |  |  |
| Rice husk | 100 |  |  | 0.90 |  | 0.66 |  | 0.48 |  | 0.36 |  |  |  |  |
| Rice straw | 10 |  |  |  |  |  |  |  |  |  |  |  | 0.08 |  |
| Rice straw | 10 |  | 0.33 |  | 0.22 |  | 0.19 |  | 0.09 |  | 0.08 |  |  |  |
| Rice straw | 18000 |  |  |  |  |  |  |  | 0.14 |  | 0.13 | 0.09 | 0.05 | 0.02 |
| Safflower seed press cake | 10 |  |  |  | 0.26 | 0.24 | 0.23 | 0.21 | 0.20 |  |  |  |  |  |
| Safflower seed press cake | 30 |  |  |  | 0.27 | 0.26 | 0.25 | 0.22 | 0.21 |  |  |  |  |  |
| Safflower seed press cake | 50 |  |  |  | 0.26 | 0.25 | 0.23 | 0.22 | 0.21 |  |  |  |  |  |
| Straw | 1h | 0.63 |  |  | 0.22 |  |  |  | 0.14 |  |  |  |  |  |
| Straw | 2h | 0.59 |  |  | 0.20 |  |  |  | 0.14 |  |  |  |  |  |
| Straw | 4h | 0.58 |  |  | 0.20 |  |  |  | 0.13 |  |  |  |  |  |
| Straw-Stalk of Rapeseed Plant | 5 |  |  |  | 0.11 |  | 0.07 |  | 0.04 |  | 0.03 | 0.02 | 0.01 |  |
| Straw-Stalk of Rapeseed Plant | 10 |  |  |  |  |  |  |  |  |  |  | 0.03 |  |  |
| Straw-Stalk of Rapeseed Plant | 15 |  |  |  |  |  |  |  |  |  |  | 0.03 |  |  |
| Timothy grass | 2 |  |  |  |  | 0.30 |  |  |  |  |  |  |  |  |
| Timothy grass | 450 |  |  |  |  | 0.40 |  |  |  |  |  |  |  |  |
| Wheat stra | 5 |  |  | 0.92 |  | 0.77 |  | 0.50 |  | 0.46 |  |  |  |  |
| Wheat straw | 2 |  |  |  |  | 0.40 |  |  |  |  |  |  |  |  |
| Wheat straw | 450 |  |  |  |  | 0.40 |  |  |  |  |  |  |  |  |
| Average1 |  | 0.64 | 0.32 | 0.70 | 0.29 | 0.41 | 0.15 | 0.35 | 0.23 | 0.31 | 0.07 | 0.07 | 0.05 | 0.02 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 800 | 900 | 1000 |
| Bamboo | 10 |  | 0.42 |  |  | 0.24 |  |  | 0.18 |  |  |  |  |  |
| Beech trunkbark | 6000 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Douglas Fir bark | 190 |  |  | 0.27 | 0.20 | 0.16 | 0.13 | 0.12 | 0.09 |  |  |  |  |  |
| Douglas Fir wood | 190 |  |  | 0.25 | 0.19 | 0.16 | 0.14 | 0.08 | 0.06 |  |  |  |  |  |
| Hickory wood | 10 |  | 0.35 |  |  | 0.14 |  |  | 0.17 |  |  |  |  |  |
| Hybrid poplar wood | 190 |  |  | 0.22 | 0.14 | 0.11 | 0.11 | 0.09 | 0.06 |  |  |  |  |  |
| Moso bamboo |  |  | 0.32 |  | 0.20 |  | 0.12 |  | 0.09 |  | 0.06 |  |  |  |
| Pine | 5 |  |  | 0.65 |  | 0.40 |  | 0.21 |  | 0.25 |  |  |  |  |
| Pine | 100 |  |  | 0.83 |  | 0.57 |  | 0.43 |  | 0.32 |  |  |  |  |
| Pinewood | 2 |  |  |  |  | 0.10 |  |  |  |  |  |  |  |  |
| Pinewood | 450 |  |  |  |  | 0.20 |  |  |  |  |  |  |  |  |
| Pitch pine (*Pinus rigida*) | 10 |  | 0.36 |  | 0.27 |  | 0.06 |  |  |  |  |  |  |  |
| Average2 |  |  | 0.36 | 0.44 | 0.20 | 0.23 | 0.11 | 0.19 | 0.11 | 0.29 | 0.06 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 800 | 900 | 1000 |
| Dairy (MD) | x |  |  | 0.25 |  |  |  |  |  |  | 0.05 |  |  |  |
| Paved-feedlot (FL) | x |  |  | 0.22 |  |  |  |  |  |  | 0.10 |  |  |  |
| Poultry litter (PL) | x |  |  | 0.23 |  |  |  |  |  |  | 0.17 |  |  |  |
| Swine solids (SW) | x |  |  | 0.16 |  |  |  |  |  |  | 0.07 |  |  |  |
| Turkey litter (TL) | x |  |  | 0.23 |  |  |  |  |  |  | 0.10 |  |  |  |
| Broiler litter |  |  |  | 0.30 |  |  |  |  |  |  | 0.12 |  |  |  |
| Average3 |  |  |  | 0.23 |  |  |  |  |  |  | 0.10 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Feedstock | Heating rate ℃/min | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 800 | 900 | 1000 |
| Sewage sludge | 10 |  |  |  |  |  | 0.45 |  | 0.30 |  | 0.30 | 0.17 | 0.12 |  |
| Sewage sludge | x |  | 0.33 |  | 0.32 |  | 0.09 |  | 0.06 |  | 0.05 |  |  |  |
| Average4 |  |  | 0.33 |  | 0.32 |  | 0.27 |  | 0.18 |  | 0.18 | 0.17 | 0.12 |  |