Evaluating Feedstock Properties for Efficient Biochar Production: A Comparative Study

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Abstract

Biochar production via pyrolysis of various organic waste has potential to reduce dependence on conventional energy sources and mitigate global warming potential. However, the performance of biochar is highly dependent on the biomass composition and pyrolysis condition. Here, ANOVA analysis are used to develop a statistical comparison between different features of a wide range of feedstock including proximate and ultimate composition, pyrolysis condition and biochar yield. In total, 226 datasets were collected from different studies to compare statically the difference between main mentioned characteristics of feedstock. The obtained result shows that although there is a significant difference between many feedstocks based on fixed carbon and volatile matter, the difference for ash content was generally insignificant. Moreover, coconut shell has the highest level of C and H and the lowest level of O, but the there is a significant difference between this feedstock with a wide range of other cases just for C and O. Furthermore, the highest temperature (600 ^{0}C) and heating rate (25 ^{0}C/min) are for oat hall and orange bagasse, respectively, however the difference of temperature is generally insignificant for the considered dataset. Finally, the pine wood and coconut fiber show higher biochar yield, 76.3% and 67%, respectively, with a significant difference with all of other feedstocks. In general, using this method can provide a special comparison between different features of biomass feedstock, and this can be helpful in choosing data-driven machine learning models and selecting the best condition in experimental condition such as finding an optimized mixture of feedstock.

Keywords: ANOVA analysis, Biochar yield, Pyrolysis condition, Ultimate composition

1. Introduction

Finding alternative energy sources has become more crucial as awareness of the global energy problem and climate change has grown. One promising sustainable energy source is biomass, which is emerging (Li et al., 2020). On the one hand, biomass is produced at a rate of about 140 billion metric tons annually worldwide. However, when it is improperly disposed of, it pollutes the environment for a variety of reasons, most notably the conversion of biomass to CO2 neutrality (Tripathi et al., 2019). However, biomass has a great deal of potential to replace fossil fuels in energy conversion by generating various energy resources like biogas, biofuel, and biochar.

In a nutshell, biomass is an organic-inorganic complex solid produced contemporaneously (non-fossil) through natural and man-made (technogenic) processes. Biodiversity, source, and origin can all be considered when classifying different types of biomass as solid fuel resources. These categories include: 1) woody biomass; 2) herbaceous and agricultural biomass; 3) aquatic biomass; 4) animal and human waste biomass; and 5) industrial waste biomass (semi-biomass). 6) blends derived from the aforementioned sorts of biomass. According to Vassilev et al. (2009), the current yearly production of biomass resources with potential for use as energy, comprising woody, herbaceous, agricultural, and organic wastes, is approximately 7 billion tons worldwide. According to estimates by Slade et al. (2014), the following biomass sources will contribute to the world's energy supply in the future: energy crops (22–1272 Exajoule (EJ)), agricultural residues (10–66 EJ), forestry residues (3–35 EJ), wastes (12–120 EJ), and forestry (60–230 EJ). Its predicted growth from the current level of 56–145 EJ by 2060 is a result of contemporary bioenergy's greater significance than traditional biomass techniques (Scarlat et al., 2019).

There are two ways to turn biomass into energy: (1) burning it directly to produce heat; and (2) thermochemical conversion, which yields solid, gaseous, and liquid fuels. c) converting chemicals to create liquid fuels 4) biological reaction that yields gaseous and liquid fuels. Pyrolysis is a potential method of converting biomass to energy and value-added compounds from biomass among the processes indicated (Thines et al., 2017). Organic materials are heated to temperatures between 300°C and 1000°C during pyrolysis, almost entirely in the absence of free oxygen. Fuels include biochar, bio-oil, sustainable diesel, methane, and hydrogen are produced through biomass pyrolysis. Of the three products (biochar, bio-oil, and gas), biochar is a solid that can be used in a wide range of applications. These include the production of energy (Suman and Gautam, 2018), iron production (Farrokh et al., 2020), the production of valuable products and chemicals (Liu et al., 2019; Thangalazhy-Gopakumar et al., 2015), soil amelioration (Muigai et al., 2021; Dong et al., 2020), and wastewater treatment (Thines et al., 2017; Deng et al., 2019; Ruthiraan et al., 2017). Therefore, between these byproducts, biochar is gaining interest as one of the most valuable renewable bioresources, having a wide range of applications such as pollutant adsorption, greenhouse gas (GHG) reduction, waste water treatment, soil remediation, energy production, and usage as catalysts (Bolan 2022).Generally, biochar yield (Williams, 1996), physical (Wildman and Derbyshire, 1991), and chemical properties (Shafidazeh, 1982) depend on the conditions during pyrolysis as well as the composition of the feedstock biomass. Therefore, the differences between biochar properties have to be well understood as a function of production conditions and feedstock type.

The yields of pyrolysis procedures for the synthesis of biochar have been extensively studied and predicted over the past few decades through both theoretical and experimental study (Kaczor et al., 2020). Predicting the synthesis of biochar by data-driven modeling has gained popularity due to the availability of a wealth of pyrolysis experimental data and the development of artificial intelligence. These techniques can reproduce complicated data trends with greater accuracy, in less time, and with improved forecast accuracy (Wang et al., 2022). Through training, it determines the relationship between input and output variables and generates findings devoid of any presumptions. As previously stated, the features of biomass exhibited significant variation contingent upon the nature of their feedstock. It would therefore be amazing and useful to know what the differences are between the characteristics of biomass and whether or not these differences are significant. When creating a biomass mixture, this trend would assist the researcher in picking the most appropriate and correct statistical model or the best combination of biomass. Therefore, comparing the differences in biochar yield and composition for a variety of feedstocks derived from various types of biomass is of great scientific interest.

Thus, the present study compares and analysis the characteristics of biochar's feedstock including proximate composition, ultimate composition and pyrolysis condition via statistical analysis. The mentioned feedstocks are included a wide range of biomass based on woody biomass, herbaceous and agricultural biomass (mainly straw- and wood-based) and biomass mixture, more than 200 different cases. During the data assimilation stage, feedstock compositions of various types of organic waste, related pyrolysis process parameters and biochar yields have been considered. The difference between these parameters for different type of feedstock are investigated through ANOVA analysis. Finally, the findings are discussed and concluded, while indicating areas for future improvements.

2. Material and methods

2.1. Data collection and preprocessing

In total, 226 datasets were collected from the literature (19 studies) to compare statically the difference between main characteristics of feedstock including proximate and ultimate composition and pyrolysis condition (Bhattacharjee & Biswas, 2019; Biswas et al., 2017; Chen et al., 2015; Crombie & Maˇsek, 2015; Crombie et al., 2013; He et al., 2018; Hong et al., 2020; Lee et al., 2013; Liu et al., 2014; Liu & Han, 2015; Liu et al., 2018a; Liu et al., 2018b; Liu et al., 2018c; Patra et al., 2021; Rout et al., 2016; Shariff et al., 2016; Tag et al., 2016; Ucar & Ozkan, 2008; Zhang et al., 2017). To ensure generalizability, the dataset includes a wide range of feedstocks including woody biomass, herbaceous and agricultural biomass, animal waste and mixture biomass as reported in Table 1,

Table 1. Different types of biomass in the dataset

Mani categories	feedstocks	Number of cases
Woody biomass	Bamboo	12
	Cassava stem	5
	Cassava rhizome	5
	hinoki cypress	4
	pine	4
	pine wood	6
	pinewood sawdust	5
	Straw pallet	2
	Wood bark	1
	Wood stem	1
	vine pruning	5
Herbaceous and agricultural biomass	Bagasse	1
	Canola hull	1
	Corncob	22
	Corn Stover	12
	Cotton stalk	31
	Rape stalk	12
	rapeseed oil cake	3
	Rice husk	4
	Rice straw	23
	Oat hull	1
	Palm kernel shell	1

	Wheat straw	20
	Cocopeat	1
	Coconut fiber	6
	Coconut shell	7
	Orange bagasse	1
	Orange pomace	5
Animal and human waste biomass	Poultry litter	5
Biomass mixture	Agro-food waste	10

Various attributes considered during the data collection stage are categorized in the three main group:

(1) proximate composition of biomass feedstock (fixed carbon, volatile matter and ash)

(2) ultimate composition of biomass feedstock (C, H, O, N, S)

(3) major pyrolysis conditions (residence time, temperature, heating rate)

Furthermore, biochar yield as the main parameter for evaluating efficiency process of biochar production are compared for the mentioned feedstock. Although other features such as lignocellulosic composition and particle size of feedstock has been considered as important characteristics of feedstock (Khan et al., 2022; Zhu et al., 2019), they were not included in the present work due to uncertainties associated with the data collection phase.

2.2. ANOVA analysis:

ANOVA, which stands for Analysis of Variance, is a statistical test used to analyze the difference between the means of more than two groups. In other words, ANOVA is a statistical method that simultaneously compares means across several groups to determine if observed differences are due to chance or reflect genuine distinctions. A one-way ANOVA uses one independent variable, while a two-way ANOVA uses two independent variables. By partitioning total variance into components, ANOVA unravels relationships between variables and identifies true sources of variation. ANOVA can handle multiple factors and their interactions, providing a robust way to better understand intricate relationships (Henson et al., 2015). Therefore, the purpose of this study was to compare how feedstock composition and pyrolysis temperature differ between a large dataset of biomass to evaluate there is a meaning significant between them or not, that can affect biochar agronomic value and stability properties.

3. Results and discussion

3.1. Feedstock Proximate analysis (vol. % db.)

The phrase "proximate analysis" refers to the fact that they were not accurate, which is where the name comes from. In addition to determining a fuel's calorific value, the proximate analysis serves as a foundation for the fuel trade. Ash, fixed carbon, volatile matter, and moisture are all determined on a mass percent basis. According to Zimmerman (2010) and Deenik et al. (2010), the volatile content may provide some insight into the material's stability as well as its impact on N availability and plant growth. However, the ASTM method's high temperatures may cause metal volatilization, which could be a serious issue for biochar with high ash concentrations (Dean, 1999). The amount of volatile materials in biochar indicates its thermal.

3.1.1. the mean of Fixed carbon (vol. % db.)

The mean of fixed carbon (vol. % db.) for different types of feedstocks is illustrates in Fig. 1. As observed, the orange pomace exhibits the highest level of fixed carbon, about 27%, and there is a statistically significant difference between this type of feedstock and the others, except cocopeat and vine pruning.

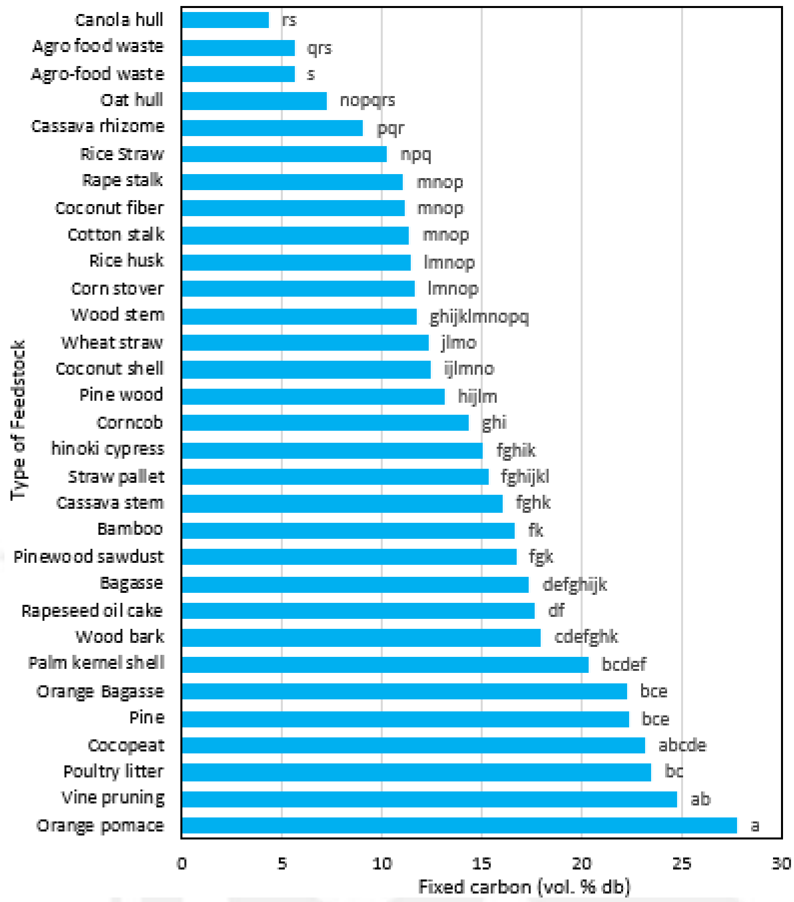

Fig. 1. The mean of fixed carbon (vol. % db.) for different type of feedstocks

However, the lowest one is obtained in canola hall, roughly 4.5%. Also, generally it can be reported that crop residues and agro-food waste had the lower level of fixed carbon in feedstock proximate analysis, while woody grass (such as vine pruning, wood bark and pine) has the higher amount of fixed carbon as feedstock. Moreover, the comparison the different feedstock shows that the difference between a wide range of the mentioned feedstock is not significant, for example, among many crop residues such as wheat straw, cotton stalk, rice straw, corn stover, rape stalk.

3.1.2. The mean of volatile matter (vol. % db.)

Fig 2. Shows the mean of volatile mater (vol. % db.) for different types of feedstocks. Although the level of fixed carbon between these feedstocks has a wide range (see Fig.2), the reports data illustrate that the percentage of volatile mater varied in a small range, from 68.20% for orange pomace to 87.83% for wood stem.

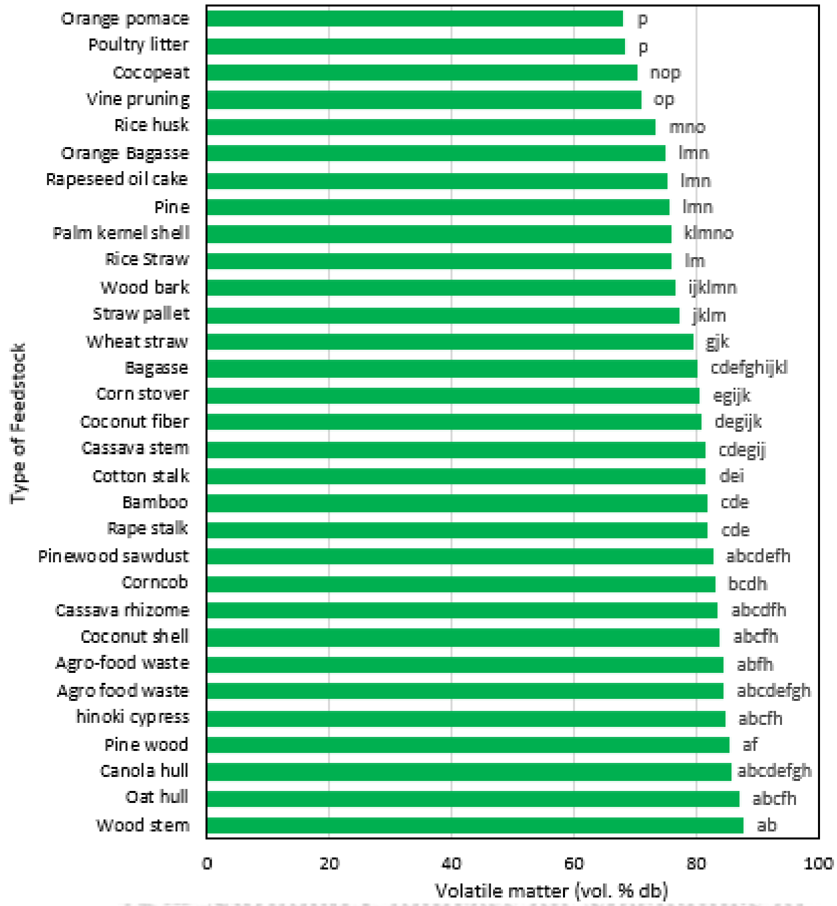

Fig. 2. The mean of volatile matter (vol. % db.) for different type of feedstocks

Generally, it can be seen that the feedstock with high level of fixed carbon would have the low level of volatile mater, for example orange pomace feedstock with the lowest level of fixed carbon was a case with the highest percentage of volatile mater. Notably, the figure highlights a significant difference ($P > 0.05$) in volatile mater of orange pomace with other species, expect poultry litter, cocopeat and vine pruning. However, for other type of feedstocks difference between the means of this parameter with a wide range of other types of feedstock is not significant. For example, the difference between canola and eighteen other species is not significant.

3.1.3. The mean of ash (vol. % db.)

Comparing the mean of ash content (vol. % db.) for different type of feedstock in Fig. 3 shows that the range of change for this parameter is more remarkable than volatile mater and fixed carbon.

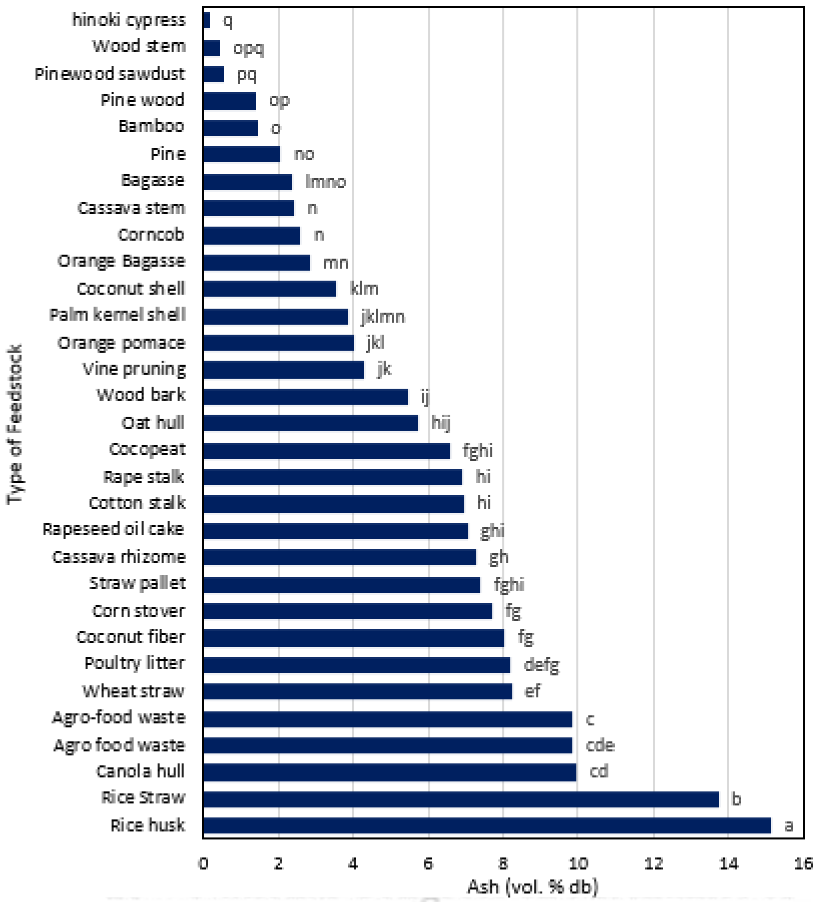

Fig. 3. The mean of ash (vol. % db.) for different type of feedstocks

While the rice husk has the highest level of ash content, roughly 15.14%, and that of hinoki cypress, as the feedstock with lowest level, was about 0.16%. Also, it can be seen there is a significant difference between rice husk with all of other feedstocks, and the difference between with hinoki cypress with other feedstocks was also significant, expect with wood stem and pinewood sawdust. The result indicate that woody biomass has lower content of ash, while poultry litter (as animal waste) and agro-food waste were between among feedstocks with high level of ash. Generally, it can be reported that based on ash it would be easier to find a significant difference between one especial feedstock with many of other feedstocks.

3.2. Feedstock Ultimate analysis (vol. % db.)

The final composition, which consists of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S), is another significant compositional factor. Therefore, the primary contributions to biomass's energy content are carbon, hydrogen, and oxygen; nitrogen and sulfur are present in biomass in smaller amounts. According to a report, increasing C and O levels in feedstocks may increase biochar's yields and net calorific value (Leng and Huang, 2018). In generated biochar, the H/C and O/C ratios dictate its polarity, aromaticity, and stability. One important consideration when applying fertilizer to charcoal is its nitrogen content. Biochar will have a high N content if the feedstock contains a lot of proteins and macromolecular amino acids.

3.2.1. The mean of C (vol. % db.)

Fig. 4 depicts the mean of C compositions for different biomass from different sources. The high carbon content is the characteristic of woody and agricultural biomass. Presence of this elements in biomass leads to more char formation as well as to the high calorific value of the product, while biomass possess has highest amount of hydrogen is suitable for the hydrogen production. As can be seen, coconut shell shows the highest level of carbon, about 64%, while poultry litter as an animal waste has the lowest one, roughly 35%. Also, it is clear that there is a significant different for both of these feedstocks with other ones, expect for coconut shell with cocopeat. Moreover, it can be concluded although there is a significant difference between the mean of C composition of agro-food waste with poultry litter, this difference was not significant between this and many types of agricultural and woody biomass.

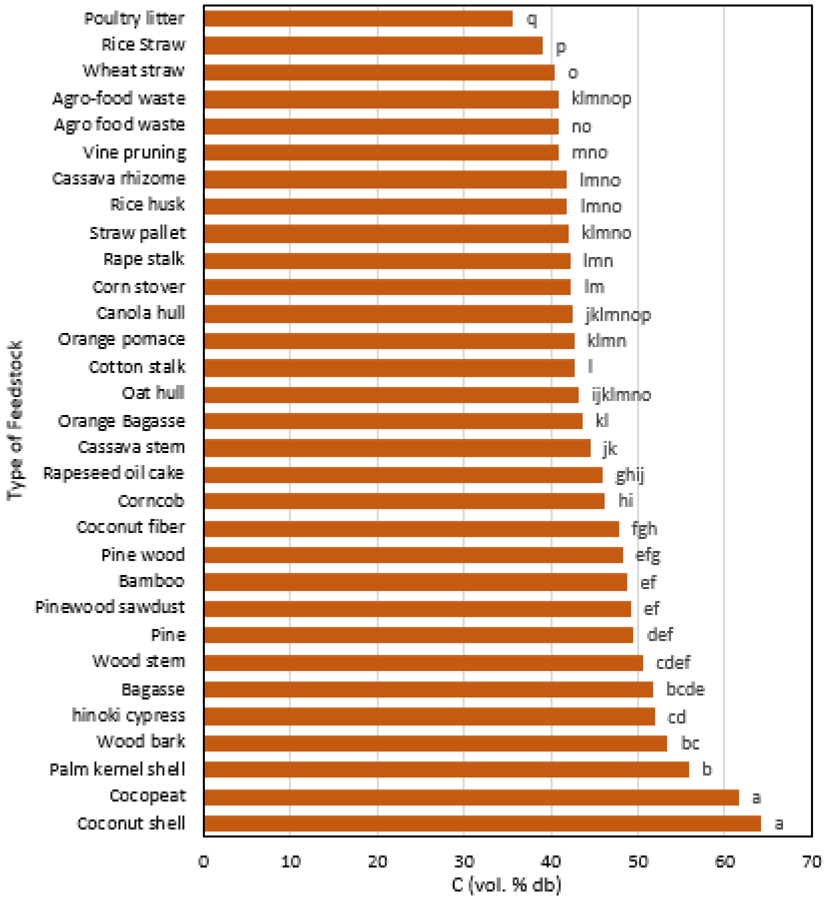

Fig. 4. The mean of C (vol. % db.) for different type of feedstocks

3.2.2. The mean of H (vol. % db.)

Comparing the mean of H composition between mentioned biomass feedstock in Fig. 5, shows that although the coconut shell has the highest level of H, almost 7%, there is not a significant different between this type of feedstock with a wide range of other feedstocks, including wheat straw, pine wood, rape stalk, wood bark, bagasse and many other cases. The agro-food waste as the feedstock with lowest level of H shows the similar trend. Generally, it can be the difference for these components is not significant. Moreover, It should be noted the coconat shell has the highest level of H and C among the considered feedstock in this study, while agro-food waste were between the cases with low level of H and C composition.

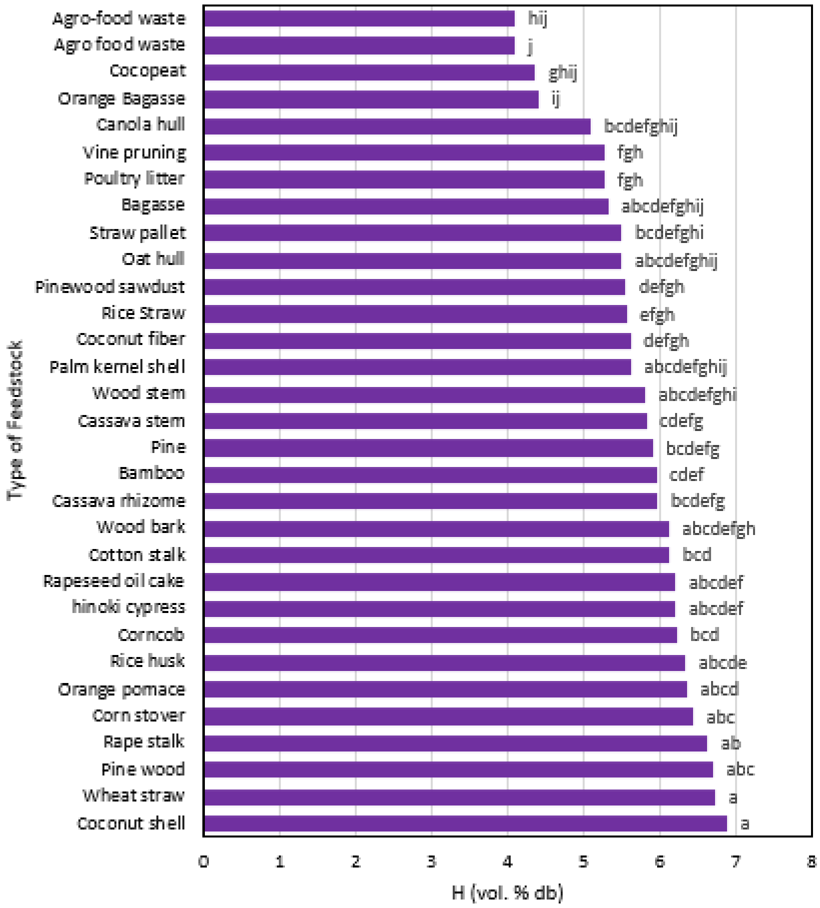

Fig. 5. The mean of H (vol. % db.) for different type of feedstocks

3.2.3. The mean of O (vol. % db.)

The obtained result in Fig. 6 shows that the mean of O for the different type of feedstock is between 51.78% and 27.61% for orange bagasse (as maximum) and coconut shell (as minimum), respectively. Also, the figure highlights a significant difference ($P > 0.05$) in the mean of O between the different type of feedstock. As observed, there is a statistically significant difference between orange bagasse and the others, except cassava rhizome. Also, coconut shell, as the cases with lowest level of O, has a significant difference with all of other feedstocks. Moreover, taking the different group of biomasses indicate that feedstock from different group have variable behavior, meaning that also vine pruning are between the cases with high level of O, wood bark as another woody biomass include low percentage of this element, and its difference is significant. This result can be obtained for different feedstock from agricultural biomass.

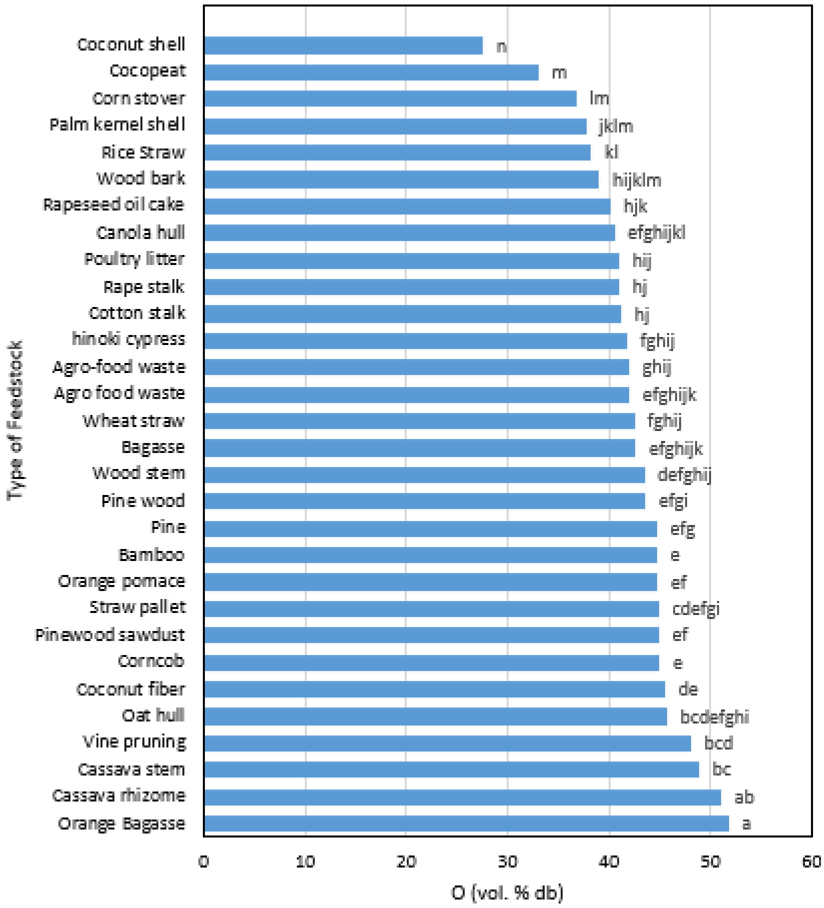

Fig. 6. The mean of O (vol. % db.) for different type of feedstocks

3.2.4. The mean of N (vol. % db.)

It is seen from Fig.7 that poultry litter and agro-food waste have the highest percentage of N in ultimate analysis, and their difference is statically significant. On the other hands many of woody biomass shows the low level of C while the difference between them were not significant (comparing pine, straw pallet, wood stem and bamboo). Moreover, the mean of this for agricultural biomass or crop residues is almost between 0.5% to 1.55, and their difference is generally insignificant. Finally, although the amount of N is lower than other composition, the largest range of changes is for this species, from 9.6% to roughly 0.01%.

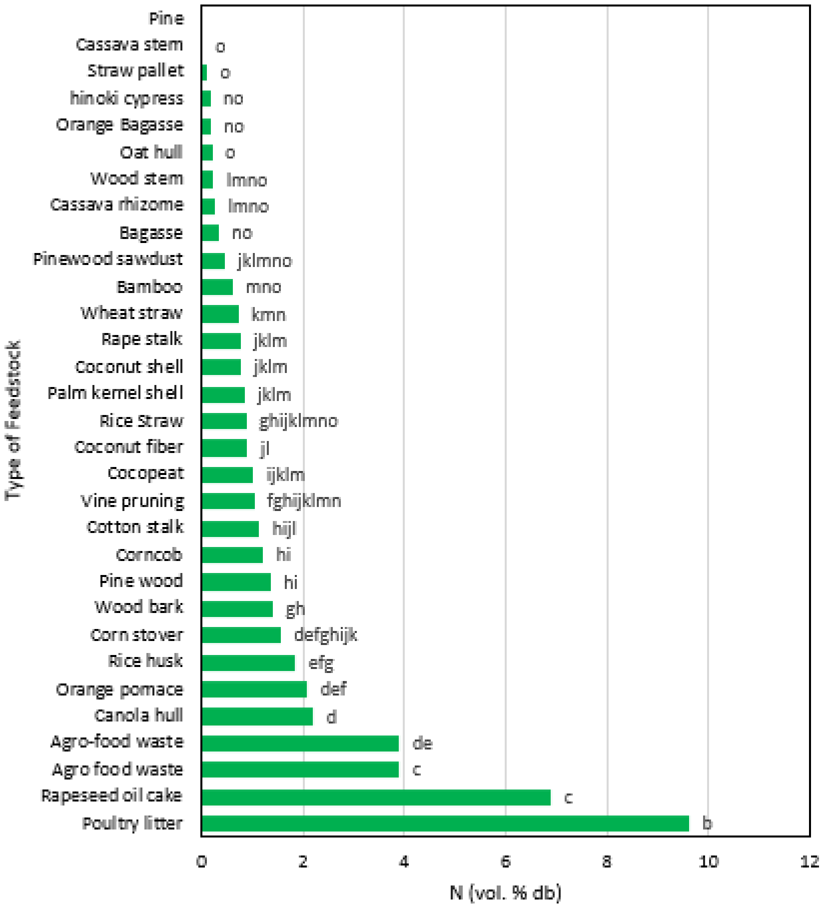

Fig. 7. The mean of N (vol. % db.) for different type of feedstocks

3.3. Pyrolysis condition

The pyrolysis process parameters and the kinds and composition of biomass feedstocks determine how applying biochar will affect soil quality and carbon abatement. For instance, pyrolysis yields less biochar when temperatures, heating rates, pressures, or particle sizes are higher, as these conditions encourage the breakdown of biomass polymer (Lee et al., 2013). On the other hand, greater formation of biochar requires low temperature and a lengthy vapor residence time. Furthermore, extending the vapor residence time facilitates the repolymerization of the biomass elements by allowing them enough time to react, and it can also impact the final composition of biochar. This trade-off suggests that there are ideal pyrolysis process conditions for the formation of biochar (Brassard et al.,2018).

3.3.1. Residence time

Fig. 8 shows that the mean of residence time, as one of the most important pyrolysis conditions, varies from 60 min to 1 min, for the considered dataset. the highest time residence

(60min) were for a large group of woody and agricultural biomass, from cocopeat to bagasse (see Fig.8), and the difference between them was insignificant. Another common residence time was 30 min, for orange pomace to corn stover (see Fig.8), and this difference was also insignificant. Furthermore, taking the agro-food biomass shows that only one group of them (46.67 min residence time) has a statistically significant difference with the cases with small residence time, while this difference was insignificant in comparison with the cases with large residence time. In generally, this difference for residence time was insignificant between the different groups of biomasses.

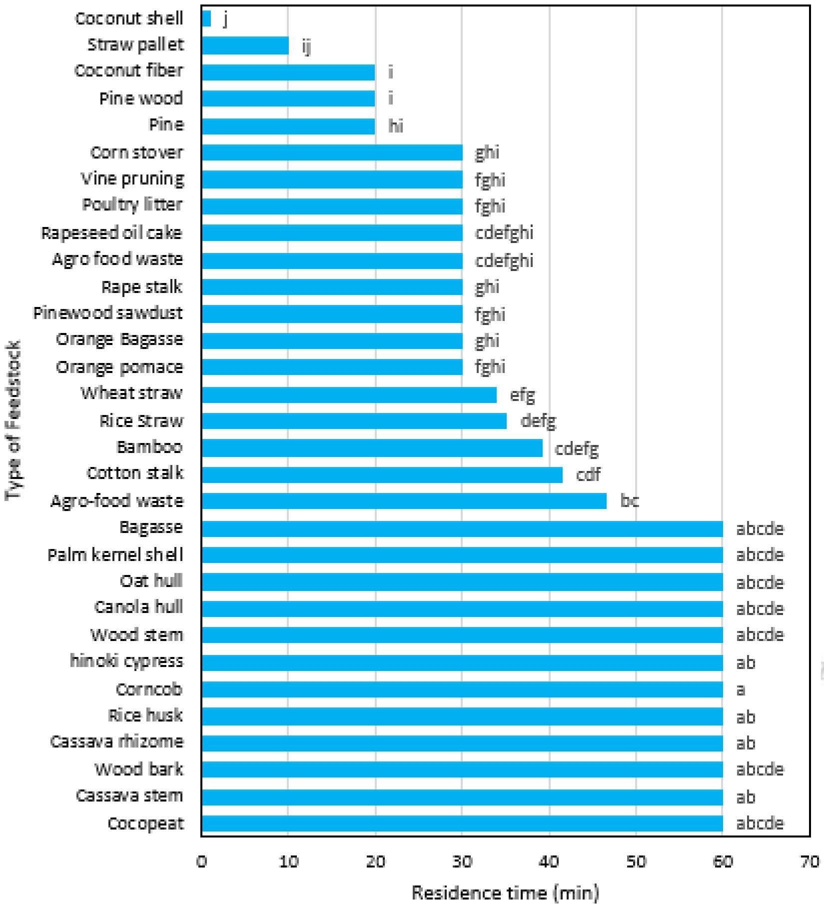

Fig. 8. The mean of residence time (min) for different type of feedstocks

3.3.2. Temperature

Comparison the mean of temperature between different groups of biomasses in this study shows that this parameter varies between 600 ◦C and 263 ◦C, the highest temperature is for oat hull, pinewood sawdust, canola hull and the lowest temperatures for coconut fiber and pinewood, see Fig.9. The difference between the mentioned cases in this study, was generally insignificant. For example, the oat hull, as a case with the highest temperature shows a statistically significant difference with coconut fiber and pine wood, as cases with the lowest temperature, while this difference was insignificant compared to twenty-nine other cases. Furthermore, the highest temperature was 600

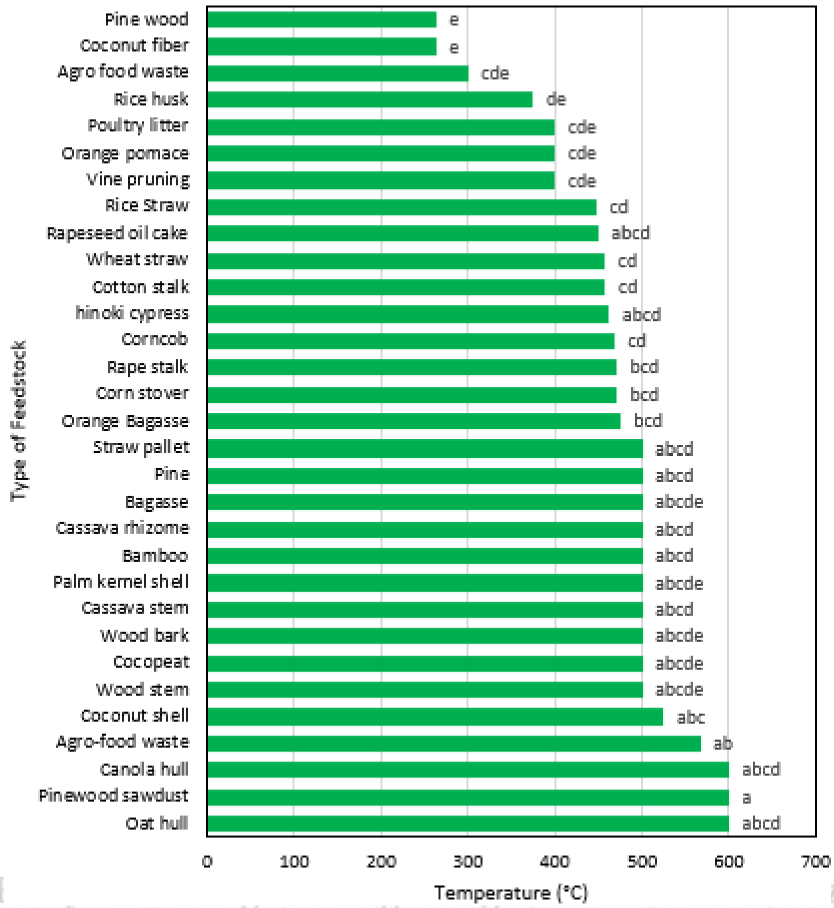

Fig. 9. The mean of temperature (°C) for different type of feedstocks

3.3.3. Heating rate

Finally, Fig. 10 presents the comparison of the mean of heating rate (◦C/min) among different type of feedstocks using the ANOVA analysis. Notably, the figure highlights a significant difference in heating rate between the orange bagasse, as the cases with the highest heating rate, and all of other feedstocks. Also, as observed, many of cases (from pine to cassava stem) shows the heating rate 5 °C/min, as the lowest one, and their difference between them and many other cases was insignificant.

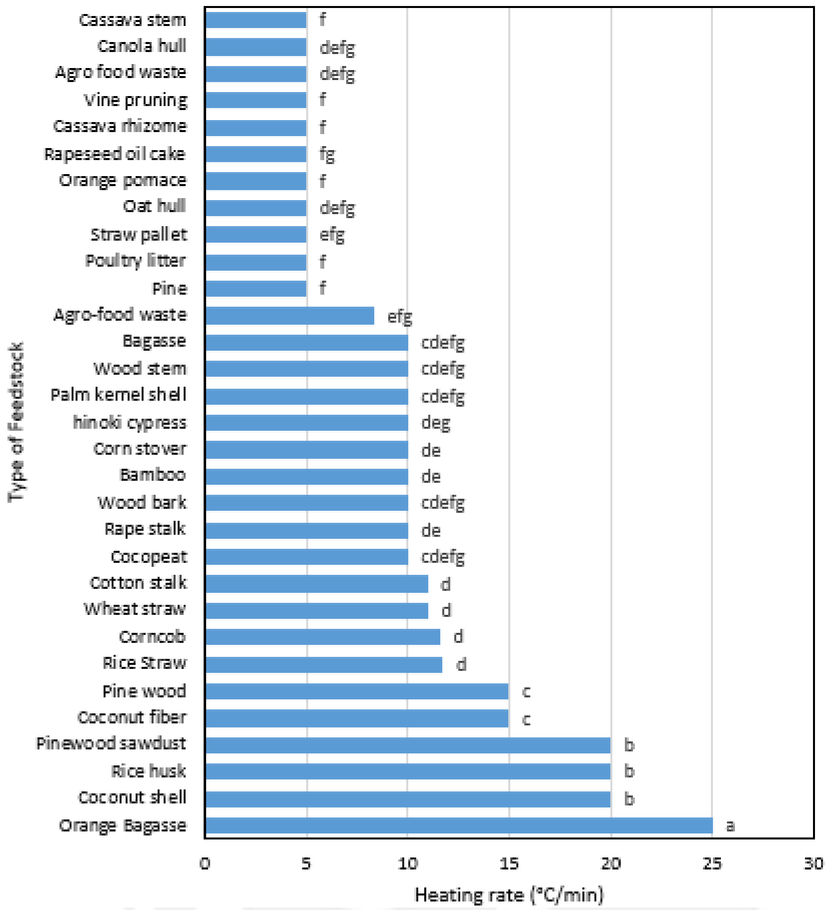

Fig. 10. The mean of heating rate (°C/min) for different type of feedstocks

3.3.3. Biochar yield

Figure 4 present the comparison of biochar yield (%) for different types of feedstock. As it can be seen, the biochar yield of pine wood, coconut fiber and agro-food waste were above 50%, exactly 76.32%, 67.03% and 52.30%, respectively, while there isn't a statistically significant difference between these cases. However, pine wood and coconut fiber show a significant difference with all of other feedstocks. In addition, the lowest biochar yield (lower than 25%) were for bagasse, pinewood sawdust and wood stem, and the difference between these cases was also insignificant. Finally, in general, comparison between the different types of feedstock present that there is not a statistically significant difference between a wide range of the mentioned feedstock of this study.

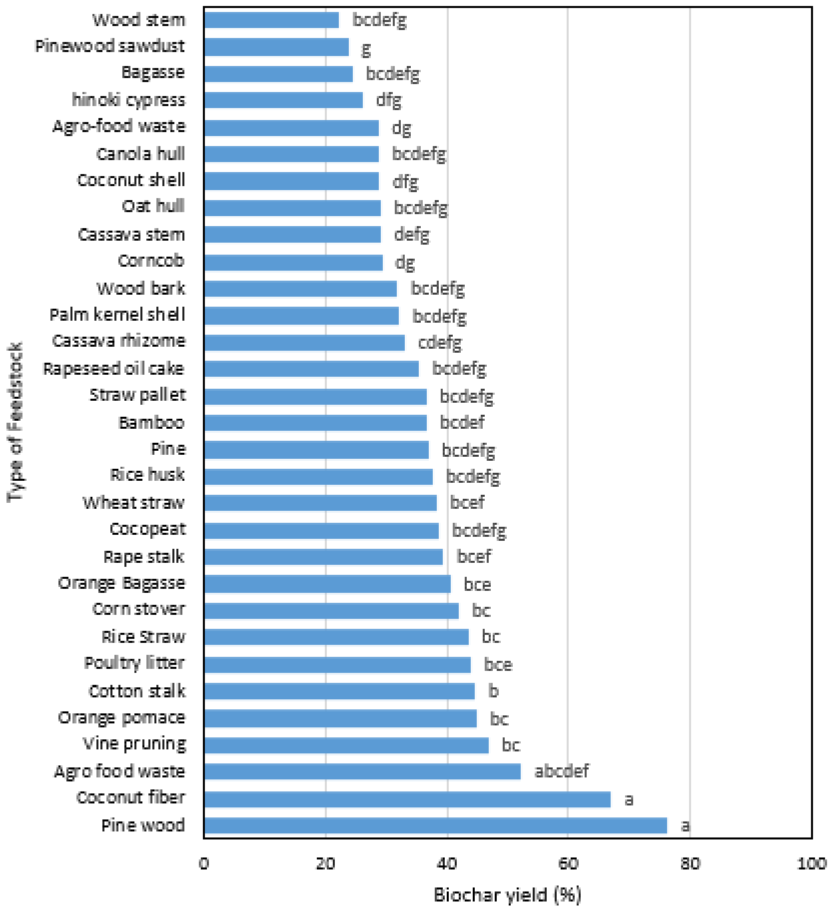

Fig. 3. The mean of biochar yield for different type of feedstocks

Conclusion

In this study, comprehensive statistical analysis was developed to compare the difference of biomass feedstock compositions, pyrolysis condition and biochar yield between a wide range of different biomass. The obtained result can be summarized as follow:

Orange pomace and wood stem has the highest level of fixed carbon and volatile matter, respectively, and although the difference of fixed carbon was generally significant compared to other feedstocks, that of volatile matter was insignificant for wood stem with a wide range of feedstock. Moreover, rice husk and hinoki cypress show the highest and the lowest level of ash, respectively, and both of them has a significant difference with many types of different feedstock. Taking proximate composition shows that there is a significant difference between coconut shell and cocopeat as the highest level of C and poultry litter as the lowest level of C, with all of other feedstocks. However, coconut shell and wheat straw with the highest content of H don't have a significant different with many types of feedstocks. Also, although the difference between the mean of N for different types of feedstock was larger than other ultimate composition, this difference was insignificant between many feedstocks, expect for poultry litter, rapeseed oil cake and agro-food waste.

For coconut shell, the difference of residence time was significant with all of other cases, expect straw shell. Although based on temperature there is not a significant difference between many types of feedstocks, this difference was significant for higher level of heating rate in orange bagasse. Finally, there was a significant difference between pine wood and coconut fiber, as the feedstock with the highest biochar yield, with many types of other biomass.

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