Characterisation of biochar from various carbon sources

Hendrix Yulis Setyawan[1*], *Nimas* Mayang Sabrina Sunyoto[1], *Yusron* Sugiarto[2], *Beauty* Suestining Dyah Dewanti[1], *Vindhya* Tri Widayanti[1], *Lukma*n Hakim[4], *Syahrul* Kurniawan[3], *Gabryna* Auliya Nugroho[3], *Devy* Ulandari[1], Annisa'u Choirun[5], Fasa Aditya Hanindipto[6], *Shafira* Arini Sundari[1], *Ilham* Akbar Pamungkas[1], *Andhika* Putra Agus Pratama[1], and *Zhijian* Wan[7]

[1]Department of Agroindustrial Technology, Faculty of Agricultural Technology, Universitas Brawijaya, Jl. Veteran, 65145 Malang, Indonesia
[2]Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Brawijaya, Jl. Veteran, 65145 Malang, Indonesia
[3]Department of Soil Science, Faculty of Agriculture, Universitas Brawijaya, Jl. Veteran, 65145 Malang, Indonesia
[4]Department of Chemistry, Faculty of Mathematics and Natural Science, Universitas Brawijaya, Jl. Veteran, 65145 Malang, Indonesia
[5]Department of Agricultural Technology, Politeknik Negeri Jember, Jl. Mastrip, Krajan Timur, Sumbersari, 68121 Kabupaten Jember, Indonesia
[6]Indonesia Research Institute PT Pupuk Indonesia (Persero), Jl. Taman Anggrek Kemanggisan Jaya, 11480 Jakarta, Indonesia
[7]Energy Business Unit, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Kensington, WA 6151 Australia

Abstract. The purpose of this study was to characterise biochar produced from various carbon sources. This study was conducted using a Nested Design with three replications. Three carbon sources, rice husk (RH), corn cobs (CC), and bagasse sugarcane (BS) were pyrolysed for 2 hours at temperatures of 400, 500 and 600°C. The three types of biochar were then analysed on their moisture content, ash content, fixed carbon content, volatile matter, calorific value, particle size and elemental analysis results. The results of this study were that the temperature of pyrolysis at 600 °C can optimally produce biochar with the lowest moisture content, ash content and volatile matter value, and highest fixed carbon and calorific values. The particle size analysis shows that biochar produced using this optimum condition has the smallest average particle size distribution. The elemental analysis conducted through Scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) shows various elements in each biochar produced from the three different carbon sources.

---

[*] Corresponding author: hendrix@ub.ac.id

1 Introduction

Biochar, a carbon-rich product derived from the pyrolysis of organic materials in the absence of oxygen, has garnered considerable interest for its potential role in carbon sequestration, soil amendment, and as a renewable energy source. The process of biochar production and its resultant properties are influenced by the type of feedstock used and the conditions under which pyrolysis is conducted. Recognizing this, the present study aims to provide a comprehensive characterisation of biochar produced from a variety of carbon sources.

In Indonesia, cheap carbonaceous–lignocellulolytic biomass can be potentially utilised as raw materials for producing biochar. These biomasses include rice husk (RH), corn cobs (CC), and bagasse sugarcane (BS). These materials are abundantly available in East Java, Indonesia. In 2018-2021, the availability of RH, CC and BS in the western part of East Java reached 1,646,777; 1,070,341 and 2,250,985 dry tonnes/year [1]. Rice husk contains cellulose (50%), lignin (25%–30%), silica (15%–20%), and moisture (10%–15%) [2]. Corn cobs contains cellulose (27.71%) and hemicellulose (38.78%) and lignin (9.4%) [3]. Bagasse contains about 40–50% cellulose and 25–35% hemicellulose, and the rest are lignin, wax, and other materials [4]. High content of cellulose, hemicellulose and lignin of the biomass can be converted into biochar through pyrolysis.

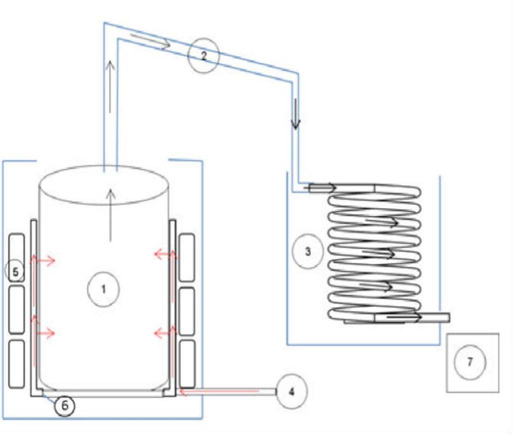
Pyrolysis, a thermochemical decomposition process, is conducted in an oxygen-depleted environment at high temperatures, leading to irreversible changes in the physical state and chemical composition of organic materials. This process diverges from perfect combustion by producing distinct compounds due to the lack of oxygen. Typically, pyrolysis yields syngas (including hydrogen and carbon monoxide), methane, short-chain hydrocarbons, carbon dioxide in the gas phase, aromatic bio-oil in the liquid phase, and biochar as a solid [5]. The process aims to rapidly apply heat to disrupt the chemical bonds in polymers from cellulose, hemicellulose, and lignin within the organic material [6].

Pyrolysis has emerged as an effective technology for managing waste, particularly agricultural and agro-industrial residues. By converting these wastes into biochar and liquid smoke, pyrolysis addresses environmental issues while producing valuable by-products for use in energy, food, agriculture, and plantation sectors [7]. Embodying biorefinery and zero waste principles, this method ensures complete raw material conversion without generating waste [8]. Though generally conducted at temperatures above 300°C for several hours, specific conditions may vary based on the method and materials used [7]. Lignocellulosic components in biomass, such as cellulose and hemicellulose, decompose at 180-350°C, while lignin requires 300-500°C. Water content decreases at temperatures over 200°C, affecting the overall pyrolysis process [9].

Pyrolysis temperature plays an essential role in influencing the characteristics of the activated biochar produced. The surface area and porosity characteristics of biochar are vital things that are influenced by the temperature used in pyrolysis [10]. Other research by [11] also revealed that pyrolysis temperature is the main factor that very dominantly influences the stability of biochar compared to the chemical and mineral composition of biomass. Apart from influencing the characteristics of biochar, the pyrolysis temperature also determines energy requirements, which will impact production costs. In the pyrolysis process, the use of the right temperature must be carefully taken into consideration [12]. Therefore, using three different carbon sources in this study, the characteristics of biochar produced in various temperatures must be investigated.

2 Materials and methods

The rice husk (RH), corn cobs (CC), and bagasse sugarcane (BS) were obtained from Malang, East Java, Indonesia. A pyrolysis unit and a charcoal milling unit are among the tools ut ilised. The materials were dried using a tunnel dryer at 50°C for 4 hours before pyrolysis. Fig. 1 shows the schematic pyrolysis unit. 500 g of each material was added to the pyrolysis apparatus. The slow pyrolysis procedure considered the best way to produce biochar, was carried out at three different temperatures (400 °C, 500 °C, and 600 °C) for two hours. Biochar and pyrolysis oil were the products of each pyrolysis phase. Each sample of the biochar made at various temperatures was then characterised by the moisture content, ash content, fixed carbon content, volatile matter, calorific value, particle size and elemental analysis results.



1) Reactor tube; 2) Gas line; 3) Condensor; 4) Heating mantle;
5) Isolator; 6) Ceramic module; 7) Pyrolysis oil line

Fig. 1. Schematic diagram of pyrolysis unit.

3 Results and discussion

3.1 Moisture content

The moisture content of each type of biochar produced at different temperatures is shown in Fig. 2. Generally, the moisture content of all biochar was under 10%. The moisture content decreased as the temperatures increased. According to the Indonesian National Standard, the maximum moisture content of biochar is 10%. Therefore, the moisture content of all biochar produced was within the national standard for moisture content.

Increasing pyrolysis temperatures leads to a reduction in moisture content due to several thermal and chemical processes [13]. At higher temperatures, water within the biomass rapidly evaporates as the heat energy supplied exceeds the binding energy of the water molecules, turning them into steam. This process is enhanced as temperatures rise, facilitating a quicker and more complete evaporation. Additionally, the chemical structure of the biomass undergoes decomposition at elevated temperatures. This breakdown involves cleaving chemical bonds, such as hydroxyl groups, which can release water as a by-product [14]. Alongside evaporation and chemical decomposition, the volatilization of various other compounds also occurs. These volatile substances, which can include water, are released as gases into the atmosphere. Furthermore, the changes in the physical structure of the biomass at higher temperatures can decrease its ability to hold onto water, as it may become more hydrophobic [15]. This inherent change in the material's properties thus contributes to the overall decrease in moisture content.

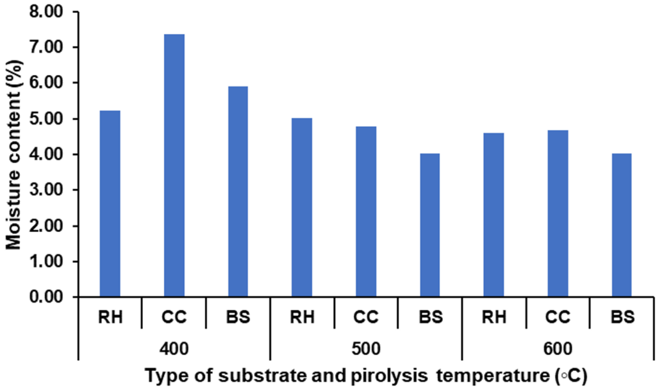


Fig 2. Moisture content of biochar from RH, CC and BS produced at 400, 500 and 600°C.

3.2. Ash content

The ash content of each type of biochar produced at different temperatures is shown in Fig. 3. Generally, the ash content of all biochar was in the range of 16.00 – 21.17%. The highest ash content was observed in biochar made from RH. The effect of temperature on ash content is a complex interaction of thermal decomposition, volatilization, mineral transformation, and selective retention of constituents [16]. The exact outcome will depend on the specific types of biomass and their inherent mineral makeup. BS, RH and CC chemical composition determine how much the ash content produced. For example, rice husk contains a high level of silica, which may not volatilize at the same rate as other minerals. This could explain why the reduction in ash content with increasing temperature may not be as significant for rice husk as it might be for other substrates with different mineral compositions.

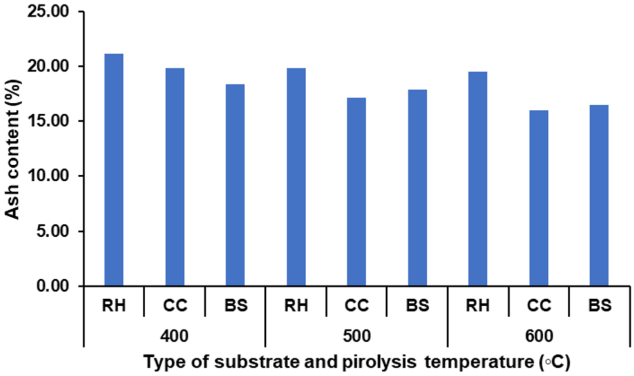


Fig 3. Ash content of biochar from RH, CC and BS produced at 400, 500 and 600°C.

3.3 Fixed carbon content

The fixed carbon content of each type of biochar produced at different temperatures is shown in Fig. 4. Generally, the fixed carbon content of all biochar was in the range of 49.14 – 61.08%. The highest fixed carbon content was observed in biochar made from BS. As the pyrolysis temperature increases, the fixed carbon content in the biomass samples are also increases. This is due to the enhanced thermal decomposition that occurs at elevated temperatures, where the heat breaks down the biomass more thoroughly. As volatile substances, inclu ding water vapor, carbon dioxide, and various organic gases, are driven off, the proportion of carbon in the residue becomes more concentrated. This process, known as devolatilization, leads to an increase in the fixed carbon content [17]. Concurrently, the higher temperatures promote carbonization, which is the conversion of the remaining organic material into a char that is rich in fixed carbon.

The structure of the carbon also changes during this process, becoming more ordered. This transition, moving from amorphous carbon towards more aromatic and graphitic structures, results in a stable and high fixed carbon residue [18]. The variations in the increase across different biomasses—RH, CC, and BS—can be attributed to their unique compositions and structures. For instance, rice husks have high silica content, which can affect the carbon yield, whereas the fibrous nature of Bagasse might facilitate a more complete carbonization. Fig 4 clearly shows that, irrespective of the initial differences in their composition, all three types of biomass tend to yield higher percentages of fixed carbon as the pyrolysis temperature is ramped up from 400°C to 600°C.

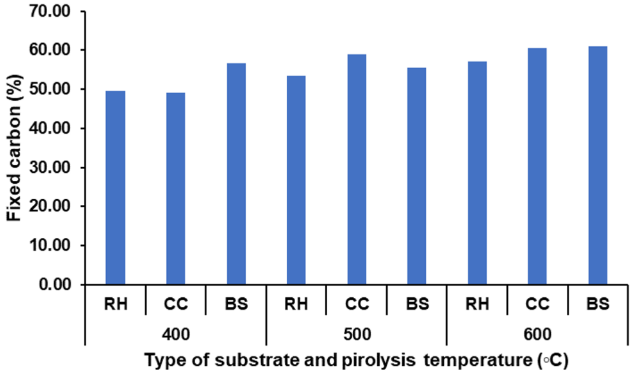


Fig 4. Fixed carbon content of biochar from RH, CC and BS produced at 400, 500 and 600°C.

3.4 Volatile matter

The volatile matter of each type of biochar produced at different temperatures is shown in Fig. 5. Generally, the volatile matter of all biochar was in the range of 18.40 – 23.94%. The highest volatile matter was observed in biochar made from RH at all temperatures tested. For all three biomass sources, there is a general trend of decreasing volatile matter with increasing temperature. This is because higher temperatures cause more extensive thermal decomposition of the organic components within the biomass, leading to greater devolatilization [17]. As a result, a larger fraction of the biomass is converted into gas and vapor, which is then released, leaving behind a char with a higher proportion of fixed carbon and ash.

The rice husk (RH) starts with the highest volatile matter content at 400°C, which significantly decreases as the temperature rises. This suggests that rice husk has a high proportion of components that are susceptible to thermal degradation. In contrast, the corncob (CC) shows a more moderate reduction in volatile matter across the temperature range, indicating that it may contain more thermally stable components or a different composition of volatile substances. Bagasse sugarcane (BS) exhibits a behavior similar to RH, with a notable decrease in volatile matter as temperature increases, again reflecting its composition and the reactivity of its volatile components.

It is also noteworthy that the impact of temperature on the reduction of volatile matter appears to be more pronounced between 400°C and 500°C than between 500°C and 600°C f or all substrates. This could imply that a significant portion of the volatile matter is released at the lower end of the temperature spectrum, and that the remaining material is more thermally stable [19].

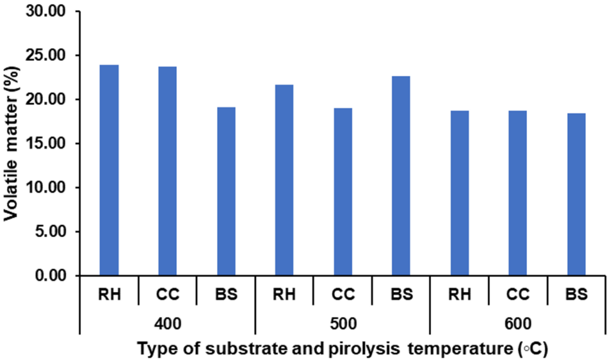


Fig 5. Volatile matter of biochar from RH, CC and BS produced at 400, 500 and 600°C.

3.5 Calorific value

The calorific value of each type of biochar produced at different temperatures is shown in Fig. 6. Generally, the volatile matter of all biochar was in the range of 4415.2 – 7727.8 cal. The caloric values for biochar from rice husk (RH), corncob (CC), and Bagasse sugarcane (BS) vary significantly across different pyrolysis temperatures (400°C, 500°C, and 600°C). Initially, at 400°C, the caloric values for all three biomass sources are relatively lower, with RH showing the lowest energy content. This might be due to incomplete pyrolysis at this temperature, leaving behind a higher proportion of volatile matter which generally has a lower energy content compared to fixed carbon.

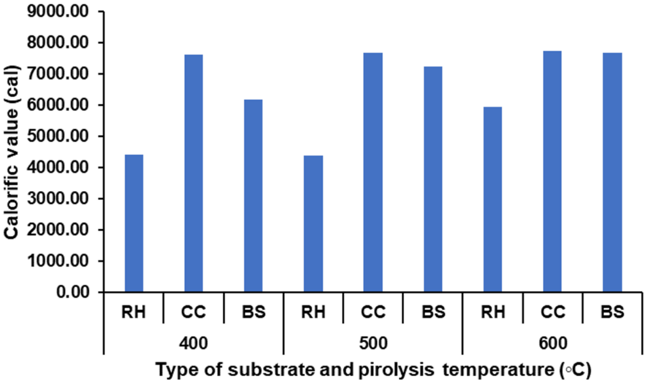


Fig 6. Calorific value of biochar from RH, CC and BS produced at 400, 500 and 600°C.

As the temperature increases to 500°C and further to 600°C, the caloric values for the biochars generally increase. This trend suggests that higher pyrolysis temperatures lead to a higher degree of thermal decomposition, which reduces the volatile matter and increases the fixed carbon content [20]. Since fixed carbon has a higher caloric value than volatile components, this results in a higher energy content in the biochar.

The biochar from CC shows the highest increase in caloric value as the temperature rises, indicating that the constituents of corncob may be particularly amenable to forming high-energy compounds at elevated temperatures. Meanwhile, the caloric value of BS biochar also increases with temperature but seems to plateau between 500°C and 600°C, suggesting that the optimal temperature for maximizing its energy content might be around 500°C.

The caloric value of RH biochar shows an interesting trend: it starts the lowest at 400°C, surpasses CC at 500°C, and remains relatively stable at 600°C. This could be attributed to the specific composition of rice husks, which may undergo significant structural changes leading to a high caloric value at an intermediate temperature but does not benefit as much from further temperature increases.

3.6 Particle size

The particle size of each type of biochar produced at different temperatures is shown in Fig. 7. Generally, the particle size of all biochar was 24.24 – 53.39%. The smallest particle size was observed in biochar produced at 600◦C. Rice husk (RH) biochar has the largest particle size at 400°C, which significantly decreases as the pyrolysis temperature is increased to 600°C. This decrease may be due to the breaking down of the physical structure of the rice husk under the influence of higher temperatures, causing a reduction in the size of the particles. Corncob (CC) also follows a similar trend, starting with larger particles at 400°C that become smaller at elevated temperatures. This indicates that the structural integrity of the corncob is also compromised at higher temperatures, leading to smaller particles.

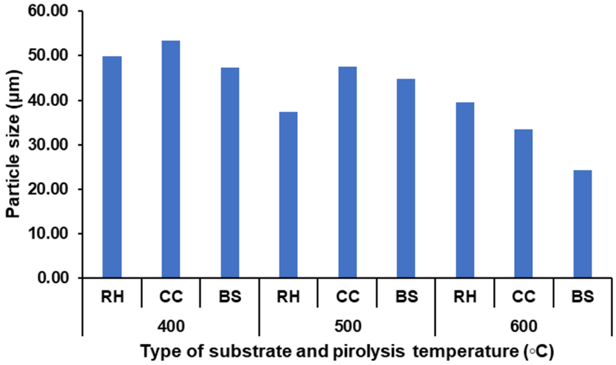


Fig 7. Particle size of biochar from RH, CC and BS produced at 400, 500 and 600°C.

Bagasse sugarcane (BS), on the other hand, shows a less pronounced decrease in particle size with an increase in temperature. It starts with a smaller particle size compared to RH and CC at 400°C and decreases slightly at 500°C, but then shows a more noticeable reduction at 600°C. The initial smaller size could be due to the fibrous nature of bagasse, which may already be in a form that lends itself to smaller particles post-pyrolysis. However, it still exhibits a reduction in size at the highest temperature, likely due to further thermal degradation of the material.

Elevated pyrolysis temperatures generally result in smaller biochar particle sizes across different biomass types [21]. This trend could be attributed to the intensification of thermal degradation processes at higher temperatures, which leads to a breakdown of the larger biomass particles into smaller fragments. The specific rates of size reduction and the initial sizes vary depending on the structure and composition of the original biomass material [22]. These changes in particle size can impact the surface area and porosity of the biochar, where smaller particles might be preferred for their greater surface area and higher reactivity.

3.7 Elemental analysis results

The elemental analysis results of each type of biochar produced at different temperatures are shown in Table 1-3. The general trend of carbon content increasing with temperature up to a point before decreasing or plateauing, which corresponds with the removal of volatiles and increased carbonization. Oxygen generally decreases as pyrolysis temperature increases, indicating the loss of oxygenated compounds. The presence and variation of mineral elements suggest changes in the inorganic component of the biochar, which can affect its properties and potential applications. The deviations indicate the nature of an EDX analysis based on the selected spots, which can be a general guideline of the actual contents.

Table 1. Results of elemental analysis of biochar from rice husk produced at 400, 500 and 600°C.

Element	**400°C**			**500°C**			**600°C**		
	Weight %	**Weight % σ**	**Atomic %**	**Weight %**	**Weight % σ**	**Atomic %**	**Weight %**	**Weight % σ**	**Atomic %**
Carbon	56.638	0.595	66.322	83.384	0.31	89.524	64.356	0.583	73.866
Oxygen	31.796	0.47	27.952	10.857	0.273	8.751	25.151	0.454	21.672
Magnesium	0.143	0.021	0.083	-	-	-	0.053	0.018	0.03
Silicon	10.885	0.155	5.451	2.512	0.045	1.153	8.105	0.135	3.978
Potassium	0.384	0.026	0.138	0.417	0.025	0.137	0.368	0.026	0.13
Calcium	0.154	0.024	0.054	0.176	0.024	0.057	0.139	0.024	0.048
Zinc	-	-	-	0.053	0.05	0.01	-	-	-
Zirconium	-	-	-	2.602	0.089	0.368	1.828	0.085	0.276

Table 2. Results of elemental analysis of biochar from corn cob produced at 400, 500 and 600°C.

Element	**400°C**			**500°C**			**600°C**		
	Weight %	**Weight % σ**	**Atomic %**	**Weight %**	**Weight % σ**	**Atomic %**	**Weight %**	**Weight % σ**	**Atomic %**
Carbon	82.37	0.337	87.797	75.131	0.992	88.051	86.606	0.334	92.306
Oxygen	14.368	0.314	11.497	8.615	0.674	7.58	8.108	0.305	6.488
Magnesium	0.002	0.019	0.001	0.059	0.056	0.034	-	-	-
Silicon	0.154	0.019	0.07	1.266	0.104	0.634	0.523	0.031	0.238
Sulfur	-	-	-	-	-	-	0.171	0.033	0.068
Chlorine	0.156	0.022	0.056	0.95	0.146	0.377	0.262	0.035	0.095
Potassium	0.856	0.03	0.28	5.626	0.268	2.025	1.055	0.045	0.345
Calcium	0.023	0.022	0.007	-	-	-	-	-	-
Bromine	-	-	-	0.422	0.138	0.074	-	-	-
Zirconium	2.07	0.08	0.291	7.932	0.461	1.224	3.274	0.124	0.459

Table 3. Results of elemental analysis of biochar from bagasse sugarcane produced at 400, 500 and 600°C.

Element	**400°C**			**500°C**			**600°C**		
	Weight %	**Weight % σ**	**Atomic %**	**Weight %**	**Weight % σ**	**Atomic %**	**Weight %**	**Weight % σ**	**Atomic %**
Carbon	87.197	0.342	92.81	82.796	0.278	89.238	85.329	0.325	89.334

Oxygen	7.39	0.301	5.905	11.049	0.258	8.94	12.274	0.322	9.647
Magnesium	0.156	0.026	0.082	0.141	0.02	0.075			
Silicon	0.905	0.035	0.412	2.295	0.039	1.058	1.822	0.042	0.816
Sulfur	0.168	0.031	0.067	-	-	-	-	-	-
Chlorine	-	-	-	-	-	-	-	-	-
Aluminum	-	-	-	-	-	-	0.129	0.026	0.06
Potassium	0.527	0.037	0.172	0.857	0.031	0.284	0.446	0.034	0.143
Calcium	0.218	0.035	0.069	-	-	-	-	-	-
Bromine	-	-	-	-	-	-	-	-	-
Zirconium	3.438	0.124	0.482	2.863	0.092	0.406	-	-	-

4 Conclusions

The preparation and characterisation of biochar derived from various carbon sources, namely RH, CC and BS were successfully conducted. The results of this study were that the increasing pyrolysis temperature reduced biochar moisture content, ash content and volatile matter value, and increased fixed carbon and calorific values. The ash content, moisture content and volatile matter of the samples from highest to lowest is in the order of RH>CC>BS. This result is corresponding with the fixed carbon and caloric value of the samples from highest to lowest is in the order of BS>CC>RH. The BS have a better characteristics compared to the other samples. The particle size analysis shows that increasing pyrolysis temperature produced smaller biochar size due to the change of biochar structure affected by temperature. The BS produced smaller biochar size. The elemental analysis conducted through Scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) shows carbon as the main content and some minerals in each biochar produced from the three different carbon sources.

The authors would like to acknowledge the financial funding and support from The Ministry of Education, Culture, Research and Technology of Indonesia and PT Pupuk Indonesia through the Matching Fund-Kedaireka Program 2023.

References

1. Disnak Jawa Timur. Potensi Sumber Bahan Pakan Lokal di Jawa Timur (2019) https://disnak.jatimprov.go.id/web/posts/read/1494-potensi-sumber-bahan-pakan-lokal-di-jawa-timur.
2. B. Singh, Waste and Supplementary Cementitious Materials in Concrete (2018)
3. M. Kapoor, D. Panwar, G. S. Kaira, Agro-Industrial Wastes as Feedstock for Enzyme Production (2016)
4. Md.A. Mahmud, F.R. Anannya, Heliyon **7**, 8 (2021)
5. T.Y.A. Fahmy, Y. Fahmy, F. Mobarak, M. El-Sakhawy, R.E. Abou-Zeid, Environment, Development and Sustainability **22**, 1 (2018)
6. X. Tong, H. Chen, J. Hu, Y. Bi, Z. Sun, W. Fan, ChemBioEng Reviews **2**, 3 (2015)
7. K. Ridhuan, D. Irawan, Y. Zanaria, F. Firmansyah, Media Mesin: Majalah Teknik Mesin **20**, 1 (2019)
8. E.R. Kuryani, *Pirolisis sampah dengan variasi jenis ranting dan kantong plastik HDP*

E, Undergraduate Thesis, Departemen Teknik Lingkungan Fakultas Teknik Sipil dan Perencanaan ITS (2017)

9. M. Samer, *Pyrolysis* (InTech, Rijeka, 2017)
10. L. Leng *et al.*, Science of The Total Environment **763** (2021)
11. L. Leng, H. Huang, Bioresource Technology **270** (2018)
12. M. He, Z. Xu, Y. Sun, P.S. Chan, I. Lui, D.C. Tsang, Bioresource Technology **341**, 12 5811 (2021)
13. A. Qurat ul. M. Shafiq, S.C. Capareda, B. Firdaus e, Journal of Saudi Chemical Societ y **25**, 3 (2021)
14. S. Rangabhashiyam, B. Balasubramanian, Industrial Crops and Products **128** (2019)
15. H.Y. Setyawan, L. Safira, A.R. Mulyarto, S. Wijana, D. Pranowo, Sustainable Enviro nment **9**, 1 (2023)
16. W. Xiao, S. Wang, B. Wei, J. Wang, L. Chen, K. Liu, T. Wang, Fuel **340** (2023)
17. D. Aboelela, H. Saleh, A.M. Attia, Y. Elhenawy, T. Majozi, M. Bassyouni, Sustainabi lity **15**, 14 (2023)
18. R. Rajarao, I. Mansuri, R. Dhunna, R. Khanna, V. Sahajwalla, Fuel **134** (2014)
19. A. Baby, S. Tretsiakova-McNally, P. Joseph, *et al.*, J Therm Anal Calorim **148** (2023)
20. A. Tomczyk, Z. Sokołowska, P. Boguta, Rev Environ Sci Biotechnol **19** (2020)
21. A. Demirbas, Journal of analytical and applied pyrolysis **72**, 2 (2004)