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Potential of Rice Husk Biochar and Bio-Oil with Varying Soaking Times as Environmentally Friendly Fertilisers to Increase Cayenne Pepper Productivity

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ABSTRACT

This research examines the potential of rice husk biochar activated by soaking in bio-oil for varying durations as an environmentally friendly organic fertiliser to support the growth of cayenne pepper plants. Proximate and ultimate analysis showed that rice husk contains carbon (33.89 wt.%), cellulose (33.80 wt.%), and lignin (19.84 wt.%), which support the formation of high-quality biochar. The biochar was characterised using XRF, identifying essential elements such as SiO_2, K_2O, P_2O_5, SO_3, and MgO, which play a role in soil fertility. Plant growth observations on day 21 showed that soaking durations of 2 and 6 hours yielded the best results, with plant heights of 7.5 and 9.2 cm and leaf widths of 1.6 and 1.7 cm, respectively. Although the number of leaves did not differ significantly, it remained four across all treatments. XRF analysis of biochar-treated soil soaked for 6 hours showed a substantial increase in essential minerals compared to untreated soil, with increases ranging from over 38% to over 100% for elements such as SiO_2, K_2O, P_2O_5, Cl, SO_3, and MgO. This increase in mineral elements contributes to improved soil structure, enhanced nutrient absorption, and better vegetative growth in chilli peppers. Overall, the research indicates that rice husk biochar soaked in bio-oil for 2 to 6 hours is highly promising as an organic fertiliser based on agricultural waste, supporting sustainable agriculture by improving soil fertility, reducing dependence on chemical fertilisers, and increasing the productivity of horticultural crops such as chilli peppers.

1. Introduction

The availability of fertilizer in Indonesia remains a fundamental issue in supporting agricultural productivity. Increased food demand due to population growth is driving higher fertilizer demand. However, domestic synthetic fertilizer production remains limited, leading to high prices. This situation results in fertilizer scarcity, which directly impacts reduced agricultural yields [1], [2], [3]. One commodity that is highly affected is chili peppers, a high-value horticultural crop that requires a balanced, sufficient nutrient supply to support its growth and productivity. Therefore, there is a need for alternative fertilizers that are more environmentally friendly, efficient, and accessible [4], [5], [6].

Indonesia, as an agrarian country, produces substantial agricultural waste, including rice [7]. This waste is a byproduct of the rice milling process and is made in enormous quantities. In 2024, the rice harvest area reached approximately 10.5 million hectares with a total production of 52.66 million tons of milled dry grain. Of this amount, the rice husk produced is estimated at 10.8-16 million tons, or about 20–30% of the grain weight [8]. So far, rice husks have been widely used as simple fuel, animal feed mix, or building material, resulting in a low contribution to increasing the added value of the agricultural sector [9].

One potential use for rice husks that could increase their value is pyrolysis. Pyrolysis is a thermochemical process that occurs at high temperatures in the absence of oxygen. This process yields three main products: biochar, bio-oil, and pyrolysis gas [10], [11]. Of the three products, biochar and bio-oil have enormous potential for use in agriculture. Biochar is high in carbon and contains minerals such as potassium (K), calcium (Ca), magnesium (Mg), and silica (Si), which increase cation exchange capacity (CEC), neutralize soil acidity, improve physical structure, and support soil microorganisms. This condition directly impacts plant growth, for example, by increasing nutrient absorption, strengthening the root system, and boosting crop yield productivity. Thus, biochar can improve soil fertility while reducing dependence on chemical fertilizers [12], [13]. Meanwhile, bio-oil is a liquid rich in organic compounds that can be processed into liquid fertilizer. Its application in agriculture not only increases nutrient availability for plants but also enhances their resistance to environmental stress, leading to more optimal growth and crop yields [14]. Thus, the utilization of biochar and bio-oil can be an alternative solution to reduce dependence on chemical fertilizers while supporting more sustainable agriculture.

One horticultural plant that requires fertilizer for growth is the chili pepper. This plant is widely cultivated in Indonesia due to its high economic value, rising consumer demand, and its role as a commodity in the agricultural sector. Additionally, cayenne pepper was chosen for this study because its growth is quite sensitive to nutrient availability, making it effective as an indicator for evaluating the potential of biochar and bio-oil fertilizers in improving soil fertility [15], [16].

Although extensive research has been conducted on biomass pyrolysis, studies specifically highlighting the unique combination of biochar from rice husks impregnated with bio-oil from pyrolysis are still very limited, especially regarding its use as an organic fertilizer for cayenne pepper plants. This research uses two pyrolysis products and investigates the effect of biochar soaking time in bio-oil, a key variable that can influence its effectiveness on plant growth. This approach makes a new contribution to the development of organic fertilizers from agricultural waste and offers innovative strategies to support sustainable agriculture in Indonesia.

2. Research Methodology

2.1. Materials

The materials used in this study include biochar, bio-oil, and soil produced from rice husk pyrolysis from Ngunan Unan Village and cayenne pepper seedlings (*Capsicum frutescens L.*).

2.2. Procedures

1) Rice Husk pyrolysis

Biochar and bio-oil were obtained through the pyrolysis process of rice husks using a fixed-bed reactor with a height of 1 meter, an inner diameter of 57 cm, and an outer diameter of 60 cm. The pyrolysis temperature ranged from 300°C to 400°C. The rice husk samples were placed in the reactor and heated to the predetermined temperature. The products of pyrolysis, biochar and bio-oil, have characteristics of soil organic matter (SOM), which is an element of fertilizer [17].

2) The process involves mixing biochar and bio-oil from rice husks

The process of making fertilizer from biochar and bio-oil begins with preparing the two main ingredients. The biochar is then ground to a 20-mesh size. After crushing, the biochar is mixed with bio-oil at a ratio of 1 kg biochar to 2 liters of bio-oil, then soaked for 1, 2, 3, 4, 5, or 6 hours, depending on the treatment. After washing, the mixture is dried in the sun until its moisture content is reduced. Once dry, the biochar and bio-oil combination fertilizer is ready for application to various plant types.

3) The process of applying biochar and bio-oil mixed fertilizer to chili plants

The application of biochar and bio-oil mixed fertilizer to chili plants was carried out across several treatment variations. These variations included soil without fertilizer (control) and soil mixed with biochar fertilizer soaked in bio-oil for 1 to 6 hours. Each treatment is given a special code to facilitate identification and analysis. Details of the application variations are shown in Table 1 below.

Table 1. Application Code for Biochar and Bio-Oil Fertilizer on Plants

Variation	Code	Soil (grams)	Biochar and bio-oil mixed fertilizer (grams)
1	TA	50	0
2	TAS1	25	25
3	TAS2	25	25
4	TAS3	25	25
5	TAS4	25	25
6	TAS5	25	25
7	TAS6	25	25

Explanation:
TA: Just the soil (control),
TAS1: 25 g soil + 25 g biochar fertilizer, soaked in bio-oil for 1 hour,
TAS2: 25 g soil + 25 g biochar fertilizer soaked in bio-oil for 2 hours,
TAS3: 25 g soil + 25 g biochar fertilizer soaked in bio-oil for 3 hours,
TAS4: 25 g soil + 25 g biochar fertilizer soaked in bio-oil for 4 hours,
TAS5: 25 g soil + 25 g biochar fertilizer soaked in bio-oil for 5 hours,
TAS6: 25 g soil + 25 g biochar fertilizer soaked in bio-oil for 6 hours.

Once the growing medium is ready, japlak chili seeds (*Capsicum frutescens L.*) are planted using a Completely Randomized Design (CRD) with five treatments for biochar soaking time and five replications per treatment. Each experimental unit used a seedling tray measuring 48 mm × 23 mm × 50 mm (length × width × depth) filled with 50 g of soil and biochar fertilizer. As shown in Fig. 1, the amount of media was adjusted to the initial growth stage (seedling phase) observed over 21 days, ensuring that the relatively small soil volume remained sufficient to support plant growth. The plants were placed in an experimental garden with natural environmental conditions. The top of the experimental area is covered with white plastic to protect the plants from rainwater and with shade cloth to reduce sunlight intensity. Watering is done every morning with the same volume, using ambient temperature as the natural growing condition. Observations were made every 3 days on plant height, leaf number, and leaf width. Height measurements were taken with a meter stick, and leaf width measurements were taken with calipers to ensure accuracy.

Fig. 1. Seedling tray

4) Analysis is to be conducted

The raw materials were characterized through proximate and ultimate analysis. X-ray fluorescence (XRF) analysis was performed on the biochar. Initial characterization was performed using XRF analysis before planting. After the plants grew, observations were made to assess their growth.

3. Results and Discussion

3.1. Proximate and Ultimate Analysis Results of Rice Husk

One of the methods used is proximate and ultimate analysis. This testing is essential because the elemental and compound content in rice husks plays a significant role in determining its potential for utilization, both as an energy raw material and as a source of organic matter for soil improvement. The results of the proximate and ultimate analyses are presented in Table 2.

Table 2. Results of The Proximate and Ultimate Analyses of Rice Husks

Ultimate Analysis					Proximate Analysis		
C (wt.%)	*H (wt.%)*	*O (wt.%)*	*N (wt.%)*	*S (wt.%)*	*Cellulose (wt.%)*	*Hemicellulose (wt.%)*	*Lignin (wt.%)*
33.89	5.87	59.06	0.38	0.79	33.80	28.34	19.40

The ultimate analysis results indicate that rice husk is dominated by oxygen (O) at 59.06%, making it the most abundant element. The second-largest element is carbon (C) at 33.89%, followed by hydrogen (H) at 5.87%. Meanwhile, the sulfur (S) and nitrogen (N) content is relatively small, at 0.79% and 0.38%, respectively. These results are consistent with the previous report, which also reported oxygen levels of 59.06%, carbon 33.89%, hydrogen 5.87%, sulfur 0.79%, and nitrogen 0.38% [17]. However, there were variations in the results of other studies. [18] Reported lower oxygen content, at 56.3%, but higher carbon levels of 40.8%. The study also showed lower sulfur values (0.65%) and higher nitrogen (0.52%). Meanwhile, the previous study reported a lower hydrogen content, namely 4.79% [19]. Some of these differences indicate that the chemical composition of rice husk is not absolute but can be influenced by the rice variety used and growing environmental conditions [20].

The proximate analysis results reveal that cellulose, at 33.80%, is the most significant component in rice husk. This result is consistent with the report by a previous researcher, which also reported a cellulose content of 33.80% [17]. However, the previous study recorded a slightly higher value of 35% [21]. The next major component is hemicellulose, with a content of 28.34%, which is in line with the previous research results [17]. However, the previous study reported a lower value of 25% [21]. Furthermore, the lignin content in rice husk was recorded at 19.40%, which is consistent with the research results of [17]. However, the previous study reported a higher value of 20%. The variation in results across these studies may be due to differences in rice varieties, environmental conditions, and analytical methods [21].

3.2. Results of XRF analysis of biochar produced from rice husk pyrolysis

The XRF analysis was chosen because it can provide detailed information about the composition of metal oxides and micronutrients in the soil. The results of the XRF analysis can serve as a basis for understanding the potential of biochar for plant growth, the roles of each element in supporting plant growth, and its possible use in sustainable agricultural systems, as shown in Table 3.

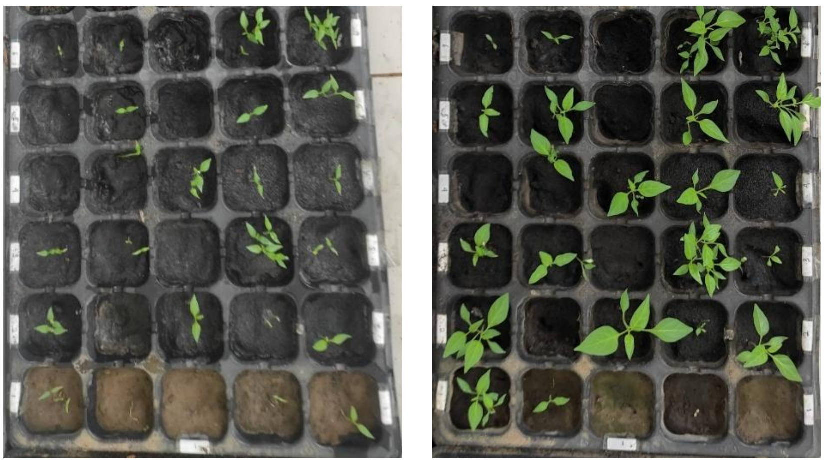
Table 3. XRF Analysis Results of Biochar Produced from Rice Husk Pyrolysis at 250-550°C

Coumpond	Temperature				
	300°C	*250°C*	*350°C*	*450°C*	*550°C*
SiO_2 (%)	38.70	85.35	87.07	89.57	89.07
K_2O (%)	2.69	4.73	4.82	5.48	4.73
Fe_2O_3 (%)	2.68	1.13	0.78	1.12	1.38
CaO (%)	1.99	2.03	1.65	1.57	2.07
P_2O_5 (%)	1.30	2.43	2.16	0.39	0.51
MnO (%)	4.61	0.45	0.44	0.11	0.14
Reference	This study	[22]	[22]	[23]	[23]

The results of the XRF analysis of biochar in this study show that the main component detected is SiO_2 with a content of 38.70% at a pyrolysis temperature of 300°C. This value is significantly lower than the findings of previous research, which reported an SiO_2 content of 85.35% at 250°C and 87.07% at 350°C [22]. Previous research also reported higher SiO_2 content at pyrolysis temperatures of 450°C and 550°C, with 89.57% and 89.07%, respectively [23]. This difference indicates significant influence from the pyrolysis reactor used, suboptimal heat transfer between the heater and rice husks, and the characteristics of the raw material on the stability and release of silica fractions in the resulting biochar [24], [25]. The second-largest component in this study is K_2O, with a content of 2.69% at 300°C. This content is also lower than the previous results at 250°C (4.73%) and 350°C (4.82%) [22]. Previous research reported higher K_2O content at 450°C (5.48%) and 550°C (4.73%) [23]. These differences indicate that the release and transformation of potassium minerals are strongly influenced by pyrolysis temperature, with the concentration of K_2O increasing at higher temperatures due to the volatility of other minerals, which enrich the ash residue [26], [27]. The next element is Fe_2O_3 with a content of 2.68% at 300°C. This value is higher than the previous report, which was 1.13% at 250°C and 0.78% at 350°C [22]. Previous research also recorded lower Fe_2O_3 content at 450°C (1.12%) and 550°C (1.38%) [23]. This difference in Fe_2O_3 concentration may be influenced by differences in biomass sources and by the reactor's efficiency in distributing heat and facilitating the partial oxidation of metal elements [28], [29]. The CaO content in this study reached 1.99% at 300°C, slightly lower than the value reported at 250°C (2.03%) [22], but higher than the value at 350°C (1.65%) [22]. Previous research reported varying CaO content at 450°C (1.57%) and an increase at 550°C (2.07%) [23]. This variation indicates that the transformation of calcium minerals proceeds gradually and is strongly influenced by temperature, with carbonate decomposition and stable oxide formation occurring at different temperature ranges [30]. Furthermore, the P_2O_5 content of 1.30% at 300°C is also lower than the previously reported values of 2.43% at 250°C and 2.16% at 350°C [22]. This value is higher than the previous report at 450°C (0.39%) and 550°C (0.51%) [23]. This difference in pattern indicates that phosphorus undergoes complex phase transformations during pyrolysis, including partial volatilization and the formation of new mineral complexes that affect the detection of P_2O_5 by XRF instruments [31], [32]. The final component is MnO with a content of 0.16% at 300°C. This value is lower than the previous report, which recorded 0.45% at 250°C and 0.44% at 350°C [22]. Meanwhile, previous research reported an MnO content of 0.11% at 450°C and 0.14% at 550°C [23]. This difference indicates that manganese tends to be present in small concentrations and is highly sensitive to changes in pyrolysis temperature and the characteristics of the organic material [33], [34], [35]. Thus, differences in the levels of SiO_2, K_2O, Fe_2O_3, CaO, P_2O_5, and MnO indicate that the biochar composition is strongly influenced by technical factors, including pyrolysis temperature and feedstock type, as well as reactor design and operating conditions. This confirms the importance of reasonable process control to obtain biochar with more consistent characteristics [36], [37], [38].

3.3. Implementation of Biochar and Bio-oil Combination in Chilli Planting

The research process began by planting chilli seedlings under various treatments: soil without treatment (TA) and soil mixed with biochar that had been soaked in bio-oil (TAS1, TAS2, TAS3, TAS4, TAS5, and TAS6). All treatments were placed under uniform environmental conditions, so any differences in growth were solely due to variations in biochar soaking duration. This stage aims to evaluate the effectiveness of bio-oil-activated biochar in improving the quality of the growing medium. After planting, initial observations were made on the third day. The results of chilli plant growth on the 3rd day are presented in Fig. 2.a. In the image, the entire plant is still in the early growth phase, so the differences between treatments are not yet significant. Observations were then continued every three days until day 21. Fig. 2.b. presents the growth results of the chilli plants on day 21.



a. b.

Fig. 2. a. Chilli growth on day 3, b. Observation of chilli growth on day 21

On day 21, differences in growth between treatments became apparent. Treatments TAS2 and TAS6 showed better vegetative development than the other treatments, characterised by greater plant height, more leaves, and narrower, more optimal leaf width. Conversely, treatments TAS, TAS1, TAS3, TAS4, and TAS5 showed slower, less stable growth. Based on observations from day 3 to day 21, it can be concluded that TAS2 and TAS6 provided the most optimal growth response. Therefore, these two treatments were selected as the primary focus for XRF analysis. The data from the chilli plant observations were then presented in Fig. 3, which includes measurements of plant height, leaf number, and leaf width.

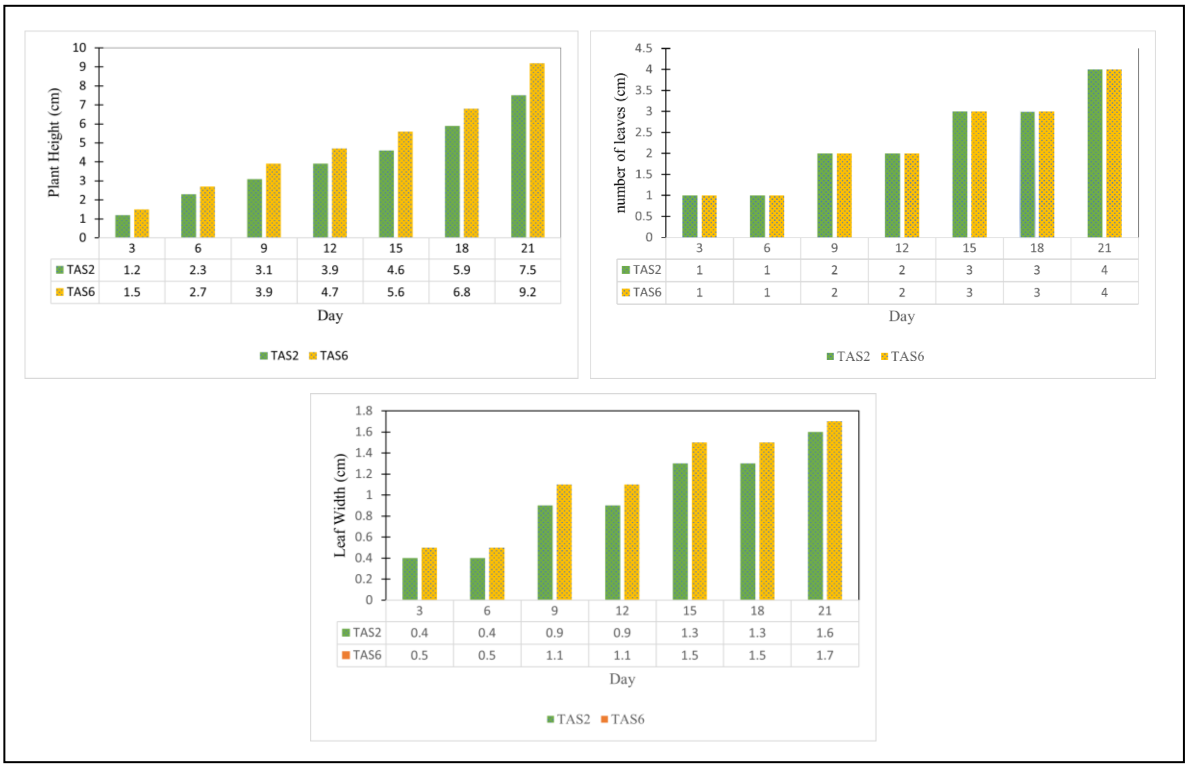


Fig. 3. Observation graphs for plant height, leaf number, and leaf width

Observations of chilli plant growth were conducted for 21 days at three-day intervals for three primary parameters: plant height, leaf number, and leaf width, under two different treatments: TAS2 and TAS6. All observation results are summarised in a single graph to facilitate comparisons between parameters and treatments.

In general, chilli plant growth in both treatments increased consistently throughout the observation period. However, TAS6 treatment showed better results than TAS2 for most observed parameters. For the plant height parameter, chilli plant growth on TAS6 was consistently higher than on TAS2 from the beginning of the observation. The initial slight difference in plant height on day 3 became increasingly larger towards the end of the observation period. On day 21, the chilli plants in TAS6 reached optimal growth, with a height of approximately 9.2 cm, while those in TAS2 reached only about 7.5 cm. This indicates that soaking biochar in bio-oil for 6 hours can increase nutrient availability and improve soil structure, thereby supporting better plant growth than soaking for 2 hours. For the leaf count parameter, both treatments showed a similar pattern of leaf increase, rising from 1 leaf at the start of the observation to 4 on day 21. There was no significant difference between TAS2 and TAS6 at all observation points. This indicates that the duration of biochar soaking in bio-oil did not significantly affect leaf number during the early growth period of chilli plants. Meanwhile, for the leaf width parameter, treatment TAS6 again showed better results than TAS2. The difference in leaf width became apparent on day 9 and was increasingly noticeable until day 21. At the end of the observation period, TAS6 produced leaves with a width of 1.7 cm, slightly larger than TAS2, which only reached 1.6 cm. This increase indicates that the higher nutrient content absorbed by TAS6 contributed to more optimal leaf morphology development.

Overall, TAS6 had a greater effect on plant height and leaf width than TAS2. However, for the number of leaves, both treatments showed similar results. These findings indicate that the duration of biochar soaking affects nutrient absorption efficiency, particularly in vertical growth and leaf development, but does not significantly influence leaf number formation during the early vegetative phase of chilli plants.

3.4. Results of an XRF analysis of TA, TAS2, and TAS6

To determine the mineral and nutrient content in TA and the changes induced by the addition of biochar from TAS2 and TAS6, analysis was conducted using XRF. The XRF analysis results were used to evaluate the effect of biochar on increasing mineral content and soil fertility potential. The XRF test data included TA, TAS2, and TAS6, as shown in Table 4.

Table 4. XRF Analysis Results from TAS, TAS2, and TAS6

Compound (%)	TA	TAS2	TAS6
SiO_2	13.157	16.986	18.246
K_2O	0.315	0.500	0.639
Fe_2O_3	3.336	0.426	0.491
P_2O_5	0.170	0.359	0.370
CaO	1.118	0.187	0.251
Cl	0.0615	0.153	0.191
MgO	0.00002	-	0.090
SO_3	0.081	0.107	0.151
MnO	0.064	0.0367	0.0422

The SiO_2 content increased gradually, from 13.157% in Tas to 16.986% in TAS2 and 18.246% in TAS6. This increase in silica concentration indicates that the longer the biochar is soaked in bio-oil, the greater the accumulation of SiO_2 in the soil. Silica is known to strengthen plant cell walls, improve nutrient uptake, and promote growth [39]. This decrease is consistent with the observation results, which showed that TAS2 and TAS6 had better plant height and leaf width than Tas. The K_2O element also increased, from 0.315% (TAS1) to 0.500% (TAS2) and 0.639% (TAS6). Potassium is an essential element in regulating stomata, activating enzymes, and translocating photosynthetic products. The increase in K_2O levels in TAS2 and TAS6 supports wider leaf growth and more robust plant conditions, consistent with vegetative observations [40]. Conversely, the Fe_2O_3 content decreased from 3.336% at Tas to 0.426% at TAS2 and slightly increased to 0.491% at TAS6. Although lower than the initial soil, this value is still sufficient for chlorophyll formation, and excessive Fe reduction also helps prevent potential metal toxicity [41]. This change is related to the more stable growth of TAS2 and TAS6, which do not show signs of stress. The P_2O_5 content increased from 0.170% (Tas) to 0.359% (TAS2) and 0.370% (TAS6). Phosphorus plays a vital role in energy formation (ATP), cell division, and root development. Increased phosphorus in TAS2 and TAS6 supports stronger root growth, which subsequently affects plant height and leaf number [42]. For the element CaO, there was a decrease from 1.118% in Tas to 0.187% in TAS2, but it increased again to 0.251% in TAS6. Although the CaO value was lower than TA, the increase in TAS6 indicates the reactivation of basic elements from the biochar that had been soaked for a longer time. Calcium continues to play a role in maintaining the stability of plant tissues [43]. This trend is evident from the leaves of TAS2 and TAS6, which do not show symptoms of Ca deficiency. Microelements such as Cl, SO_3, and MgO also show a gradual increase from Tas to TAS2 to TAS6. The increase in these elements also supports photosynthesis and enzyme activity, thereby improving growth performance in TAS2 and especially TAS6. Meanwhile, MnO decreased slightly but remained within the optimal range for plant enzymatic function.

Overall, the increase in major nutrients such as SiO_2, K_2O, P_2O_5, MgO, and SO_3 in TAS2 and TAS6 positively correlated with better observations of plant height, leaf number, and leaf width compared to Tas. Thus, biochar soaked in bio-oil for 2 hours and 6 hours was shown to improve soil quality and significantly support the vegetative growth of chilli plants.

4. Conclusion

The research results indicate that activating rice husk biochar by soaking it in bio-oil significantly improves soil quality and vegetative growth of cayenne pepper plants. Proximate and ultimate analyses of rice husks confirm that this biomass has great potential as a pyrolysis feedstock, characterised by carbon content (33.89 wt.%), cellulose (33.80 wt.%), and lignin (19.84 wt.%), which supports the formation of high-quality biochar. Based on observations of chilli plant growth on day 21, the chilli plant heights for 2-hour and 6-hour soaking were 7.5 cm and 9.2 cm, respectively. Soaking durations of 2 and 6 hours showed the most optimal growth compared to other soaking durations. This also affected leaf width, with 2 and 6 hours of soaking resulting in leaf widths of 1.6 cm and 1.7 cm, respectively. XRF analysis of soil amended with biochar that had been soaked for 6 hours showed an increase in essential mineral content compared to untreated soil. Soaking biochar in bio-oil for up to 6 hours, compared to soil without biochar and bio-oil, increased SiO_2 by 38.70%, K_2O by over 100%, P_2O_5 by over 100%, Cl by over 100%, SO_3 by 86.42%, and MgO by over 100% which contribute to improved soil structure, increased nutrient absorption, and better vegetative growth. Overall, this research demonstrates that rice husk biochar soaked in bio-oil for 2–6 hours has excellent potential as an organic fertiliser derived from agricultural waste, improves soil fertility, and supports sustainable agriculture by utilising agricultural waste to create value-added products. Thus, this approach can be a strategic alternative to reduce dependence on chemical fertilisers while increasing the productivity of horticultural crops such as chilli pepper.

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