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Estimation of Emission Factors and Ignitability Index from the Physicochemical Characterization of *Ficus Benjamina* for Energy Purposes

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This work shows the physicochemical properties and assessment energetic quality assessments on the ignitability index and the emission factor of pruning from urban *Ficus benjamina* tree (Fb). Seven samples with different proportions and parts of the pruning were used. Such as; branches of different diameters, leaves, and their mixture. Proximate analysis, elemental analysis, and higher heating value analysis were conducted. From this information, the ignitability index and emission factor were estimated. The results showed that pruning of Fb has an average of 8.1 wt.% moisture, 75.15 wt.% volatile matter, 5.87 wt.% ash, 10.87 wt.% fixed carbon, 42.81 wt.% of carbon, 5.86 wt.% hydrogen, 1.01 wt.% nitrogen, 0.05 wt.% sulfur, and a higher heating value of 17.05 MJ kg^{-1}. Pruning of Fb has shown an ignitability index of 38.44, high CO and CO_2 emissions, and low levels of NOx and SO_2 emissions. When comparing the results obtained with the literature, pruning of Fb show potential to be explored as biofuels and energy generation systems.

1. Introduction

The increased energy demand and depletion of fossil fuel reserves, along with greenhouse gas emissions, have compelled the exploration of new energy sources (Roy & Kundu, 2023). Meanwhile, plant biomass emerges as an important alternative bioenergy source to traditional sources, due to its various attributes. The volume of waste generated from the maintenance of the urban green areas (both public and private) is abundant, continuous, not very studied, and its improper disposal causes severe disruptions to cities. Nonetheless, tree and shrub pruning could be harnessed by gasifier-generator facilities to generate between 10-1000 kW (O. Y. Ahmed et al., 2019), and for the production of solid biofuels (Akbari et al., 2019). In this context, *Ficus benjamina* (Fb) is the most common species in several cities in Peru. For example, of a total of 870 trees located in 11 urban parks, 480 are Fb (Patazca Farro, 2019). This tree belongs to the genus *Ficus* (Moraceae), with more than 800 species worldwide (Adhikari et al., 2023). It is characterized by its rapid growth, and generates about 16 kg of pruning per tree (Pérez-Arévalo & Velázquez-Martí, 2018). Therefore, pruning is essential to control the expansion and leafiness of its parts at least twice a year.

One of the methods for converting biomass into bioenergy, thermochemical conversion stands out. Some research demonstrate the thermochemical conversion of *Ficus* through pyrolysis (Nour et al., 2021; Tabal et al., 2021), as well as, the energy potential estimated of tree pruning of Fb from their physicochemical and calorific properties (Pérez-Arévalo & Velázquez-Martí, 2018). Some works in the literature utilize Fb as a feedstock, and generally focus on the use of branches and leaves for energy generation, but they do not address the lower branches (which support the leaves, among others). Also, no studies have been reported on the ignitability index

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and emission factor of Fb. These two properties are important because they ensure the potential use, and sustainability of the pruning for thermochemical conversion, and their subsequent use as fuel or bioenergy.

In this direction, research shows the influence of torrefaction temperature on the ignitability index for woods such as Teak and Melina, where the increase ranged from 40 to 63 (Adeleke et al., 2020). The same behavior was observed with the temperature increase during the torrefaction of sugarcane bagasse, where the ignitability index improved from 12.55 to 17.31 MJ kg^{-1} (Conag et al., 2017). The combustion emission factor, it was observed that biomass gasification emits significantly fewer pollutants (1.53 kg CO_2, 11.3 g CO, and 0.01 g soot per kg of biomass) compared to uncontrolled incineration (1.62 kg CO_2, 97.2 g CO, and 15.5 g soot per kg of biomass) (O. Y. Ahmed et al., 2019). Similar behavior was observed with a significant reduction in emissions with agricultural and forestry biomass utilized when compared to the use of anthracite, achieving reductions of 31-41% for CO, 30-39% for CO_2, 22-55% for NOx, 95-97% for SO_2, and 47-97% for soot (Maj, 2018). For that reason, this study explored the physicochemical properties, energy potential, ignitability characteristics, and emission factor of *Ficus benjamina* pruning (branches, leaves, twigs, and their mixtures), and evaluated their potential energetic such as biofuel or for energy generation.

2. Materials and methods

2.1 Biomass preparation

Tree pruning of Fb were collected from various urban square public and green areas along a high-traffic avenue in Chiclayo city, Peru. The pruning was separated into leaves (L), branches (B) with a diameter of 12±3 mm, and twigs (T) with a diameter of 2±0.5 mm. The leaves were pre-treatment (surface impurity removal) and naturally dehydrated before being dried in a Binder FD 115 model oven at 105±5 °C for 24 h to remove any remaining moisture. The branches and twigs were cut into 100 mm pieces and similarly dried in the oven at 105±5 °C for 24 h. They were subsequently crushed and sieved to obtain homogeneous samples (0.075 mm - 0.3 mm). Seven samples with different weight percentages were prepared and labeled as B, L, T, L40T30B30, L70T20B10, B50T50, and L50B50. Posteriorly, the samples were stored in airtight bags for further analysis.

2.2 Proximate and ultimate analysis

The determination of the moisture (M), volatile matter (VM), and ash (Ash) were carried out according to the ASTM D3173, D3175, and D3174 technical standards respectively, and for triplicate. 10 g was weighed for each sample; this was dried at 105°C±5 °C for 4 h. Moisture was determined by the weight difference. From these samples, 1 g was weighed and placed in covered crucibles for 7 min in a preheated Thermolyne Eurotherm 2116 muffle at 950±10 °C, where the volatile matter was determined through weight difference. Also, for ash analysis, 1 g of each dried sample was weighed. The uncovered crucibles with the samples were placed in the muffle and heated at 750±20 °C for 6 h. The fixed carbon (FC) content was determined using Eq. 1.

The carbon (C), hydrogen (H), and nitrogen (N) contents were determined using the CKIC 5E-CHN2200 elemental analyzer following the ASTM D5373 procedure. The sulfur (S) content was analyzed using the CKIC 5E-IRSII module according to the ASTM D4239 procedure. The oxygen (O) content was determined by difference, as per Eq. 2. Also, all values are expressed in wt.% on a dry basis and in triplicate.

$$FC\ (\%) = 100 - (M\ \% + VM\ \% + Ash\ \%) \tag{1}$$

$$O\ (\%) = 100 - (C\ \% + H\ \% + N\ \% + S\ \% + Ash\ \%) \tag{2}$$

2.3 Calculation of Emission Factors

The emission factors (CO, CO_2, CH_4, NOx, and SO_2) of the tree pruning of Fb were estimated using the indicator method for emission estimation based on elemental analysis (Maj, 2018). The equations are given in Table 1.

Table 1: Equations used for the calculation of emission factor of the pruning of Ficus benjamina

Emission Factor	Eq.	N°
For chemically pure coal, Ec	$Ec = 0.88*C$	(3)
For CO (EF_{CO}), kg kg^{-1}	$EF_{CO} = 0.06*(28/12)*Ec$	(4)
For CH_4 (EF_{CH4}), kg kg^{-1}	$EF_{CH4} = 0.005*(16/12)*Ec$	(5)
For CO_2 (EF_{CO2}), kg kg^{-1}	$EF_{CO2} = (44/12)*[Ec - (12/28)*EF_{CO} - (12/16)*EF_{CH4} - 0.009*(26.4/31.4)]$	(6)
For NOx (EF_{NOx}), kg kg^{-1}	$EF_{NOx} = 0.122*(46/14)*Ec*N/C$	(7)
For SO_2 (EF_{SO2}), kg kg^{-1}	$EF_{SO2} = 0.02*S*(1 - r)$	(8)

Where r is the fraction of total sulfur content in the ash, r is considered negligible (Alves et al., 2020).

2.4 Higher Heating Value

The higher heating value (HHV) was determined using the LECO AC600 semi-automatic calorimeter, by ASTM D5865 standard. All values are expressed in MJ kg^{-1}, on a dry basis.

2.5 Ignitability Index

The ignitability index (Ii) was determined using Eq. 9 (Gajera et al., 2023), where HHV is in kcal kg^{-1}.

$$\mathrm{Ii} = \frac{\mathrm{HHV} - 81 * \mathrm{FC}}{\mathrm{VM} + \mathrm{M}} \tag{9}$$

2.6 Data Analysis

Data were statistically analyzed with R software. A one-way ANOVA and the Duncan post hoc test were used to identify significant differences ($p < 0.05$). When the assumptions of the distribution of normality and homogeneity of variance with the Shapiro-Wilk test and Levene tests, respectively, were not met, the nonparametric Kruskal-Wallis test with Holm's post hoc test was used.

3. Results and discussion

3.1 Proximal analysis

From Table 2, it can be observed that there is a statistically significant difference in moisture ($p < 0.05$).

Table 2: Proximate and ultimate analysis of tree pruning of Ficus benjamina

Biomass	**Proximate analysis (wt.% dry basis)**				**Ultimate analysis (wt.% dry basis)**				
	Moisture	VM	Ash	FC	C	H	N	S	O
B	6.40±0.1g	77.59±0.2a	3.39±0.03g	12.62±0.2a	42.36±0.02c	6.15±0.2a	0.64±0.0f	0.045±0.0a	47.42
T	7.40±0.0f	77.09±0.1b	4.53±0.02e	10.98±0.1d	43.62±0.05a	5.84±0.02b	0.97±0.0d	0.058±0.0a	44.98
L	9.44±0.0a	69.66±0.2e	8.85±0.04a	12.05±0.2b	43.59±0.01a	5.86±0.04b	1.28±0.0a	0.051±0.0a	40.36
B50T50	7.67±0.1e	76.99±0.2b	3.75±0.1f	11.59±0.3c	42.36±0.2c	5.85±0.02b	0.85±0.0e	0.043±0.0a	47.13
L40T30B30	8.39±0.0d	76.84±0.0b	6.44±0.04d	8.33±0.1f	42.48±0.4bc	5.55±0.05c	1.04±0.1c	0.048±0.0a	44.44
L50B50	8.53±0.0c	73.19±0.1d	6.71±0.02c	11.57±0.1c	42.72±0.2b	5.93±0.04b	1.14±0.0b	0.044±0.0a	43.46
L70T20B10	8.90±0.0b	74.71±0.2c	7.43±0.02b	8.95±0.2e	42.53±0.1bc	5.86±0.09b	1.16±0.0b	0.060±0.0a	42.96

The values are expressed as Means ± SD. Different letters express significant differences ($p < 0.05$) by column.

The moisture content of tree pruning of Fb ranged from 6.40 wt.% (B) to 9.44 wt.% (L). The same values were found in the *Acacia auriculiformis* pruning, 8.15 wt.% (A. Ahmed, Hidayat, et al., 2018), *Acacia cincinnata* pruning, 7.78 wt.%, *Acacia holosericea* pruning, 8.22 wt.% (A. Ahmed, Abu Bakar, et al., 2018), and in the Para grass (*Urochloa mutica*), 7.23 wt.% (Ahmad et al., 2017), which are fast-growing invasive species that produce abundant biomass. But, the moisture to leaves with twigs (70 wt.% leaves) was 13.0 wt.% (Jaideep et al., 2021). The discrepancy in moisture content is due to the transportation and hygroscopic nature of each biomass, its place of origin, age, and tree parts selected. The different parts of tree pruning of Fb and their mixtures showed moisture content below 10 wt.%. For this reason, these pruning can be utilized and their energy quality improved through torrefaction (Akbari et al., 2019), or by pyrolysis or gasification (González-Arias et al., 2020).

The volatile content, the twigs and the B50T50 and L40T30B30 mixtures show similar volatile contents ($p > 0.05$). The volatile content of tree pruning of Fb ranged from 69.66 wt.% (L) to 77.59 wt.% (B). The same values have been reported, with 73.28 wt.% for *Acacia auriculiformis* branches (A. Ahmed, Hidayat, et al., 2018), 71.23 wt.% for pine needle leaves (Roy & Kundu, 2023) and 68.75 wt.% for *Ficus nitida* wood (Tabal et al., 2021). However, different behavior with higher values was observed in the study of branches, leaves, and different compositions of Fb branches with leaves, ranging from 83.07 to 87.35 wt.% (Pérez-Arévalo & Velázquez-Martí, 2018), and in the pruning of the lechero tree *(Euphorbia laurifolia*), ranging from 75.75 to 85.27 wt.% (Velázquez-Martí et al., 2018).

The ash content, tree prunings of Fb show a statistically significant difference ($p < 0.05$), ranging from 3.39 wt.% (B) to 8.85 wt.% (L). The very same behavior was observed in lechero tree pruning, ranging from 3.7 wt.% (branches) to 10.37 wt.% (leaves) (Velázquez-Martí et al., 2018). For the L50B50 mixture, the very same ash content was observed in the avocado branches and leaves mixture, which was 6.3 wt.% (Tauro et al., 2022). From Table 2, it can be seen that the branches, twigs, and B50T50 mixture contain around 5 wt.% of ash, which is suitable for energy conversion. While, leaves and the L40T30B30, L50B50, and L70T20B10 mixtures contain a higher amount of ash (5-10 wt.%), primarily due to the presence of leaves. The high ash content is influenced by factors such as cultivation conditions, environmental factors, and climatic conditions. It is important to mention that a high ash content not only reduces the energy quality but may also cause operational failures in the boiler when used as fuel (Tauro et al., 2022).

Furthermore, biomass with a high ash content is not suitable for composting and biomethanation, but it can be utilized through gasification (Gupta et al., 2018).

The fixed carbon content, tree pruning of Fb shows a statistically significant difference ($p < 0.05$) except for the B50T50-L50B50 mixture ($p = 0.90$), which has similar content. In addition, the fixed carbon varied from 8.33 wt.% (L40T30B30) to 12.62 wt.% (B), compared to reported values for Fb leaf and branch mixtures varying from 4.94 wt.% to 9.3 wt.% (Pérez-Arévalo & Velázquez-Martí, 2018), and for the *Ficus* trunk, which is 16.85 wt.% (Tabal et al., 2021). It is highlighted that an increase in solid carbon content enhances the calorific value, thereby improving biomass quality for bioenergy purposes (Voća et al., 2021). Therefore, tree pruning of Fb exhibit potential qualities for thermochemical conversion and attributes to their use as a biofuel or for energy generation.

3.2 Ultimate analysis

From Table 2, it can be observed that tree pruning of Fb contains an average of 42.81 wt.% of C, 5.86 wt.% of H, 1.01 wt.% of N, 0.050 wt.% of S, and 44.39 wt.% of O. The C, H, N, and O contents are same to those observed in pruning the lechero tree (Velázquez-Martí et al., 2018), and for the trunk of the *Ficus* tree (Tabal et al., 2021). In addition, the twigs and leaves of Fb have a similar C content ($p = 1$). Therefore, there is a significant difference between the branches and leaves ($p < 0.05$). In terms of H content, tree pruning of Fb range from 5.55 wt.% to 6.15 wt.%, with branches having a higher H content. It was also observed that the twigs, leaves, and the mixture of B50T50, L50B50, and L70T20B10 have a similar H content ($p>0.05$). It is essential to maintain low levels of both N and S to mitigate the risk of environmental contamination through the generation of NOx and SO_2 emissions (Ahmad et al., 2021). Branches, twigs, and the B50T50 mixture showed low N content, less than 0.98 wt.% (Ahmad et al., 2017). On the other hand, the S content of the tree pruning of Fb is less than 0.24 wt.% (Ahmad et al., 2017). It was also observed that the pruning of Fb has the same S content ($p>0.05$).

3.3 Analysis of Higher Heating Value (HHV)

From Table 3, it can be observed that there is no statistically significant difference in the HHV of the B, T, B50T50, and L40T30B30 but there is a difference in HHV between L, L70T20B10, and L50B50. The HHV of the tree pruning of Fb ranged from 16.19 (L50B50) to 17.66 MJ kg^{-1} (L). The HHV values found in this study for the branches of Fb are similar to the reported values for *Ficus* wood, 16.82 MJ kg^{-1} (Tabal et al., 2021). Another study reported HHV values of Fb ranging from 18 to 19 MJ kg^{-1} for the leaves, the branches, and their mixtures (Pérez-Arévalo & Velázquez-Martí, 2018). Furthermore, the HHV of dried leaves from jackfruit, raintree, mango, and eucalyptus trees varied from 16 to 22 MJ kg^{-1} (Gupta et al., 2018), the corn residues were 16.8 MJ kg^{-1} (Tippayawong et al., 2018), and the pruning the lechero tree, it ranged from 18.31 to 18.68 MJ kg^{-1} (Velázquez-Martí et al., 2018). Therefore, the HHV of the pruning of Fb falls within the range of the species used as biofuels.

Table 3: HHV, Ignitability Index and emission index of tree pruning of Ficus benjamina

Biomass	HHV, MJ kg^{-1}	Ii, Kcal kg^{-1}	Emission factors, kg ton^{-1}				
			EF_{CO}	EF_{CH4}	EF_{CO2}	EF_{NOx}	EF_{SO2}
B	17.34±0.1b	37.17±0.3	51.80±0.0	2.47±0.0	1268.46±0.0	2.18±0.09	0.0092±0.0008
T	17.35±0.02b	38.5±0.1	53.20±0.0	2.53±0.0	1302.74±0.0	3.32±0.10	0.012±0.0009
L	17.66±0.09a	41.05±0.4	53.20±0.0	2.53±0.0	1302.74±0.0	4.38±0.03	0.010±0.003
B50T50	17.18±0.1b	37.42±0.1	51.80±0.0	2.47±0.0	1268.46±0.0	2.92±0.12	0.0087±0.002
L40T30B30	17.25±0.2b	40.53±0.4	52.27±0.81	2.49±0.04	1279.88±19.8	3.60±0.18	0.0096±0.004
L50B50	16.19±0.2d	35.65±0.3	52.27±0.81	2.49±0.04	1279.88±19.8	3.92±0.07	0.0089±0.0008
L70T20B10	16.60±0.2c	38.78±0.6	52.27±0.81	2.49±0.04	1279.88±19.8	3.98±0.03	0.012±0.0008

The values are expressed as Means ± SD. Different letters express significant differences ($p < 0.05$) by column.

3.4 Ignitability index and emissions factors

From Table 3, it can be observed that the ignitability index varied between 35.56 (L50B50) and 41.05 (L) for the tree pruning of Fb. The very same value was observed for mustard straw residues (35.6), which value increased to 50.49 after torrefaction at 300 °C for 1 h (Gajera et al., 2023). In comparison, Teak and Melina woods had higher values than those observed. Additionally, their ignitability index increased further through torrefaction at 320 °C for 1 h, reaching 56.2 for the Teak wood and 63.29 for Melina wood (Adeleke et al., 2020). In consequence, the tree pruning of Fb exhibits a suitable ignitability index for potential use as fuel in boilers or thermal power plants. Moreover, this value found in the study can be further increased through thermochemical processes, considering that the tree pruning of Fb exceeds the value of 35 (Adeleke et al., 2020). Also, some researchers suggest that the minimum ignitability index should be above 14.5 MJ kg^{-1} (or 35) to be used as an energy source in a boiler (Conag et al., 2017). When selecting combustion systems and considering the clean conversion of biomass into bioenergy and its efficiency as a bioenergy source, it is important to consider combustion emissions such as CO, CO_2, CH_4, NOx, and SO_2 (Alves et al., 2020). Table 3 presents an estimation of gas emissions generated by the tree pruning of Fb. The CO emission factor for the pruning of Fb ranges from 51.80 kg ton^{-1} (B and B50T50) to 53.20 kg ton^{-1} (T, L), while other biomass sources such as forestry and agricultural residues vary between 48.33 and 56.34 kg ton^{-1} (Maj, 2018). For instance, jackfruit shells and seeds generate 50.28 and 51.46 kg ton^{-1} of CO, respectively (Alves et al., 2020). Anthracite coal generates 82.01 kg ton^{-1} of CO (Maj, 2018). The CO_2 index of the tree pruning of Fb, it ranged from 1268.46 (B and B50T50) to 1302.74 kg ton^{-1} (T and L), which is higher than the average CO_2 index of jackfruit shells and seeds, which is 1217.95 kg ton^{-1} (Alves et al., 2020). However, it was lower than the CO_2 index of larch needles and anthracite coal, which generate 1379.53 and 1969 kg ton^{-1}, respectively (Maj, 2018). The variation in CO and CO_2 levels between the tree pruning and other biomass sources and anthracite coal is due to the carbon content. That is, the tree pruning of Fb contains an average of 42.81 wt.% carbon, while jackfruit shells and seeds contain an average of 41.29 wt.% carbon (Alves et al., 2020). Larch needles contain 45.73 wt.% carbon (Maj, 2018). Therefore, higher carbon content leads to higher levels of CO and CO_2 emissions. About, the methane index, the tree pruning of Fb emits an average of 2.5 kg ton^{-1}. This level is lower than that emitted by open burning, with an emission index of 4.6 kg ton^{-1}, while decomposition generates 33.3 kg ton^{-1} (O. Y. Ahmed et al., 2019). In terms of the NOx index of the tree pruning of Fb, ranged from 2.18 kg ton^{-1} (B) to 4.38 kg ton^{-1} (L), with leaves generating the highest NOx emissions. It's worth noting that anthracite emits 4.09 kg ton^{-1} of NOx (Alves et al., 2020). Nevertheless, the NOx index of leaves is lower than that of seeds (8.71 kg ton^{-1}) and jackfruit peels (4.66 kg ton^{-1}) (Alves et al., 2020), as well as, oat grain, which has an index of 5.39 kg ton^{-1} (Maj, 2018). Therefore, a high NOx emission index would harm the environment and contribute to acid rain. The emission level of SO_2 in the pruning of Fb, it ranged from 0.0087 (B50T50) to 0.012 (T, L70T20B10) kg ton^{-1}, which is significantly lower than the SO_2 index of anthracite, which is 5.20 kg ton^{-1} (Alves et al., 2020).

4. Conclusions

This research demonstrated that tree pruning of *Ficus benjamina* (Fb) exhibits bioenergy and biofuel potential due to several identified attributes. One notable attribute is their higher heating value (average 17.05 MJ kg^{-1}), similar to other potential biomass sources for bioenergy generation. This value is associated with other characteristics found in the tree pruning of Fb, such as low moisture content (below 10 wt.%), which is important for thermochemical conversion processes like pyrolysis. They also have a high volatile content and low ash content (less than 5 wt.%), making them suitable for potential biochar production. Another attribute of the tree pruning of Fb is the estimation of the ignitability index and gas emission factors. The ignitability index varied from 35.56 to 41.05, which is considered appropriate values and similar to those found in the literature for other species used in the thermochemical conversion. They also exhibit low levels of NOx emissions (except for the leaves) and low levels of SO_2 emissions. Additionally, *Ficus benjamina* exhibits other important characteristics for bioenergy, such as rapid growth (continuous pruning), abundance, renewability, and widespread cultivation in urban areas of Peru and various countries.

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