Journal of Environmental Management 357 (2024) 120844

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Fuel properties and incineration behavior of poultry litter blended with sweet sorghum bagasse and pyrolysis oil

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ARTICLE INFO

Keywords:
Waste biomass
Renewable energy
Flame image analysis
Ash indices

ABSTRACT

The incineration of poultry litter (PL) effectively reduces the volume of waste in line with the United Nations Sustainable Development Goal of "affordable and clean energy". However, mono-incineration is associated with considerable challenges due to the varying moisture, structural and chemical composition and low energy yield. The aim of the present work was to investigate the influence of sweet sorghum bagasse (SS) and pyrolysis oil (PO) on improving the fuel properties of PL and mitigating ash related burdens during incineration. The different biomass feedstocks were produced by combining PL with SS at 0.0% (T_0), 25% (T_1), 50% (T_2), 75% (T_3) and compared with 100% SS (T_4). In order to achieve high energy potential and low ash deposition, the parallel samples were additionally mixed with 10% PO to improve the energy value. The experimental results show that increasing the proportion of SS and adding PO to the mixtures increases the volatile matter and decreases the moisture and ash content. The addition of PO also increases the carbon and hydrogen content. The use of SS and PO thus increased the values of the ignitability index and apparently also the flammability by 30.0%–49.4% compared to pure PL. SS and PO shifted the HHV of the starting material from 16.90 to 18.78 MJ kg^{-1}. In addition, SS + PO improved the flame volume and red color intensity of the PL blends based on the image analysis method. However, the presence of SS and PO did not sufficiently improve the ash-related index values, which requires further investigation.

1. Introduction

Poultry litter (PL) waste is the end-product of commercial broiler chicken rearing in large poultry farms in rural sites. With the increasing population and massive demand for poultry meat and egg, the generation of PL is continuously increasing (Lynch et al., 2013; Ozdemir and Yetilmezsoy, 2020). Poultry litter is traditionally applied to farmland at small and mid-size farms (Chastain et al., 2012). However, as poultry production has become more concentrated and farm sizes have expanded, major environmental concerns have arisen about polluting water, land, and air (Prabakaran and Valavan, 2021). Large-scale accumulation of wastes out of the cropping season and poor PL waste management can cause health and welfare problems in flocks, fly breeding, air pollution, bad smells, and land and water contamination (Rahman et al., 2022). Currently, the disposal of PL includes direct land application in cropping season and energy applications such as pyrolysis, gasification, and combustion the rest of the time. However, due to the vast accumulation of waste, incineration is considered the fastest choice to dispose of PL.

Various energy recovery methods and techniques were investigated in the literature; among them, co-combustion with various renewable or nonrenewable fuels was indicated as the most effective from both technical and environmental points of view (Kumar et al., 2022). Compared with other disposals method, PL combustion has several advantages, including a remarkable decrease in waste volume, energy recovery for various applications, and destruction of toxic organic components and zoonotic pathogens (Gržinić et al., 2023). Furthermore, the PL incineration residue generates biomass ash, which can be used as a plant nutrient to partly replace chemical fertilizer (Fahimi et al., 2022). In this context, replacing fertilizer with biomass incineration ash has a remarkable environmental significance for reducing the carbon emission from fertilizer production, closing the nutrient loop, and the

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https://doi.org/10.1016/j.jenvman.2024.120844
Received 24 January 2024; Received in revised form 28 February 2024; Accepted 2 April 2024
Available online 4 April 2024
0301-4797/

harmless disposal of PL (Turp et al., 2021). Despite the significant environmental benefit of burning poultry litter, there are still many problems of incineration process that need to be further investigated.

To sustain the energy needs of the poultry industry, poultry waste could be a suitable energy source. In recent years, energy recovery from PL has attracted much attention because it is cost-effective, environmentally friendly, and easy to implement. Among thermal methods, direct incineration is the most efficient and sustainable technology due to its high reactivity and is considered the mature technology in thermal processing methods (Yurdakul et al., 2021). Direct incineration at various scales would provide a solution for poultry waste disposal and replace the costly fuel option. Although PL has a high content of lignocellulosic bedding litter and energy-rich manure like litter, previous direct incineration experiments have not yielded good results (Toptas et al., 2015; Onenc et al., 2018). This is due to the presence of moisture, ash, and the chemical composition of ash, which degrade fuel quality and reduce combustion performance, as well as ash deposits caused by alkaline minerals in the ash. Therefore, PL should be mixed with auxiliary fuels to achieve uniform combustion (Atimtay and Yurdakul, 2020). As an alternative renewable resource, biomass has a high content of organic compounds, which leads to a high calorific value that can help the combustion of poultry litter (Chastain et al., 2012). Blending PL with lignocellulosic biomass can increase the heating value of the blends. In addition, biomass has different combustion characteristics than PL, which has higher volatility and lower ash content than PL. Therefore, blending PL with biomass can lead to changes in the overall combustion process and improve combustion efficiency, which is associated with lower carbon monoxide emission and lower unburned carbon content in ash (Toptas et al., 2015).

The other problem with burning PL as mono-combustion is ash-related problems such as fouling and slagging in the boiler (Onenc et al., 2018), which limit the combustion performance of power plants and increase maintenance frequency and costs. The biomass fuel value of the PL is also listed in conjunction with the ash mineral composition. The co-combustion of PL and biomass may also solve the ash related problems by altering the content and composition of problematic minerals and improving ash indices. This is because mixing PL with biomass can change the elemental composition of the ash residue after combustion (Ozdemir and Demir, 2021). In general, lignocellulosic biomass has a higher calorific value than PL, and the ash residue from biomass ash combustion has a different ash composition. This results in an improved ash-related index value (Kraszkiewicz et al., 2017). Therefore, the co-combustion ash of PL and biomass fuel blends could have better fouling and slagging index property than PL.

Growing poultry production results in a significant amount of PL, mainly consisting of manure and litter materials, whose safe and efficient disposal becomes a problematic challenge. Literature indicates that the higher heating value (HHV) of animal origin waste reaches 19.0 MJ kg^{-1} (Maj, 2022), which makes it a promising renewable energy source. Moreover, due to the high prices of fossil fuels, there is a great interest in the combustion of PL in special furnaces developed for space heating in poultry houses. This is because the circular economy approach and the regulation on the use of manure of farmed animals as a fuel in combustion plants promote the use of PL as fuel for direct combustion to heat poultry houses on site (Turzyński et al., 2022). However, PL is considered a difficult fuel because it decomposes quickly and the HHV drops from 19.0 to 9.0–13.5 MJ kg^{-1} within a few days due to the higher moisture content (Choudhury et al., 2020), which hinders combustion (Dalólio et al., 2017) and cause ash-related problems when mono combustion applied (Ozdemir and Demir, 2021). To this end, premixing or pretreatment must be performed to improve the properties for combustion in a power plant or direct combustion on a farm for space heating. Some biofuel feedstocks are characterized by high HHV, low ash content, low ignition point, and optimal fouling, slagging, and high ash melting temperatures, making them combustion friendly. In general, it is recommended to blend more than two feedstocks after analyzing combustion characteristics to optimize combustion problems (Yurdakul et al., 2021) and minimize gas emissions and ash-related problems (Kraszkiewicz et al., 2017). Previous research indicates the synergistic effect of additional biomass fuels on PL in relation to combustion parameters such as flame characteristics and ash element index (Anyaoha, 2022; Ozdemir et al., 2022).

Several structural and chemical factors crucially influence PL's fuel, combustibility, and ash properties. In the presented study, the simple, practical method has been tested to improve the combustion characteristics, possible combustion-related challenges, and ash-related problems of PL by combining energy crop sweet sorghum bagasse and a novel byproduct pyrolysis oil obtained from PL pyrolysis. This research investigated the combustion behaviors of PL, sweet sorghum bagasse, their mixture, and pyrolysis oil addition by standard physico-chemical fuel analysis. Moreover, the incineration properties of blended PL mixtures were assessed by a new approach image analysis. Furthermore, the ash composition analysis was performed to determine the ash-related index values for comparing blended fuel for the tendency to fouling and slagging in the boiler system.

2. Materials and methods

2.1. Experimental materials

The materials used for the experimental studies are shown in Table 1. The litter samples were collected from chicken farms in Sakarya province, Turkey, while the litter was removed from the chicken houses. 15 subsamples of 10 kg each from different poultry houses were collected to represent the PL batches in the region for experimental use. The bedding materials were sawdust and litter consisting mainly of poultry droppings and feathers and with a moisture content of about 15–30%.

The sweet sorghum bagasse used in this work is *Sorghum bicolor* (L.) Moench, variety Gulseker. After dejuicing, the by-product bagasse was obtained from a local farmer in Sakarya province, Turkey. The bagasse sample was then air-dried until the moisture content was below 10%, and the homogenized samples were then ground in a laboratory mill (Perten 3100) and sieved through a 2 mm mesh for subsequent analysis. Proximate analysis, ultimate analysis, and calorimetry analysis were performed on the three homogenized samples to determine the combustion characteristics of the PL and biomass samples.

The pyrolysis oil comes from the gasification plant, which uses a rapid pyrolysis process at 600 °C for poultry waste. The condensable

Table 1
Properties of raw poultry litter, sweet sorghum bagasse and pyrolysis oil sample.

Parameters	Poultry litter	Sweet sorghum	Pyrolysis oil
Lignin %	5.23	3.31	–
Hemicellulose %	29.49	27.75	–
Cellulose %	22.65	22.91	–
Moisture content (%)	22.45	10.06	3.50
Ash content (%)	12.46	5.55	0.42
Volatile matter (%)	72.74	81.95	–
Fixed carbon %	14.80	12.50	–
C %	45.29	45.05	68.70
H %	4.70	4.70	8.20
N %	5.20	1.45	7.20
O %	44.80	47.01	16.00
HHV MJ kg^{-1}	16.25	18.37	34.59
Ca	2.88	2.49	0.15
Mg	0.57	1.17	0.06
Si	1.17	0.85	–
K	3.48	2.06	0.44
P	2.03	0.92	0.02
Na	0.62	0.36	0.23
Al	0.05	0.97	0.04
Fe	0.04	0.59	0.11
Zn	0.06	0.29	0.02
S	0.71	0.65	0.56
Cl	0.48	0.13	0.21

vapor is cooled in the condenser and collected in a tank at the bottom. The material on the surface is then collected separately to obtain crude bio-oil.

In the study, the different biomass pellets were prepared by combining PL with SS at the ratio of 0.0% SS (T_0), 25% SS (T_1), 50% SS (T_2), and SS 75% (T_3) and compared with 100% SS (T_4). As a second factor, parallel sets of these samples were additionally mixed with 10% pyrolysis oil to achieve a high energy potential and low ash deposition to improve the energy value of PL pellets.

2.2. Proximate and ultimate analysis

The moisture content was determined as a difference between sample weights before and after drying using the oven drying method. The PL and bagasse samples were dried at 60 °C until the constant weight and after 105 °C for 24 h for proximate and elemental analysis. The ash content was determined using the ASTM D1102 protocol by calculating the mass of the residue after sample combustion in a muffle furnace at 550 °C in open crucibles. The mass of the residual ash in the crucible was then compared with the initial mass of the sample. The volatile matter content was determined according to ASTM E870. A test sample was burned at 950 °C for 7 min in capped crucibles. The percentage of the volatile matter was calculated based on the loss in mass. Then, the fixed carbon was estimated by difference.

The ultimate analysis of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) of samples was performed using a CHN628 Analyzer according to the method ASTM D5373-14. Total oxygen (O) was determined by subtraction.

To determine the calorific values, PL and bagasse samples were milled at 1 mm, oven-dried at 60 °C, and then at 105 °C for 24 h, respectively. Following the wet weight determination, the higher heating value (HHV) was determined directly on a 1 g pill in a bomb-type calorimeter (IKA, C 200) at the reference temperature (25 °C). After complete combustion had taken place in 6 min, the calorific value was read out on the screen of the calorimeter in Kcal Kg^{-1}. The lower calorific value (LHV) was estimated by an analytical formula using the HHV measurements and the moisture content of the feedstock samples as follows.

$$\mathrm{LHV} = \mathrm{HHV}\left(1\text{-}\frac{\mathrm{MC}}{1000}\right) - Ps\left(\frac{\mathrm{MC}}{1000}\right)\Delta Hv \quad (1)$$

where MC represents moisture content at 60 °C (g kg^{-1}), Ps is sample weight (1.00 ± 0.01 g) and Hv is the heat of water vaporization (2.54 MJ kg^{-1}).

The ignitability index (Ii) was determined using Eq. (2).

$$Ii = \frac{HHV - 81 \times FC}{VM + MC} \quad (2)$$

where CV is the calorific value in Kcal kg^{-1}, FC is the fixed carbon (%), VM is the volatile matter (%) and MC is the moisture content (%).

2.3. Flame image analysis

A laboratory combustion method described by Polesek-Karczewska et al. (2018) was used to visualize the incineration properties of the tested samples. A dry pellet sample of about 250 g was placed on a perforated flat grate and placed in the combustion chamber. The biomass samples were ignited by hot air (approx. 350 °C) supplied from the underside of the grate. The flame combustion phase during the entire combustion process was recorded with a high-resolution camera placed in front of the combustion system.

The image files corresponding to the different variants of the combustion processes were recorded as 450 × 800 pixel images and these images were analyzed using Image-J software to determine the combustion quality. The RGB color space is commonly used in flame image processing. The Image-J program makes it possible to determine the dominant color intensity by RGB profile analysis of a specific area in the image. Before determining the red color intensity, the RGB color space is converted to dark scale to reduce the reflection of the unburned color space of the image. To create equal areas on the image, a certain number of pixels were set to 1 cm and rectangular areas of 1 cm height were created using grids. The mean values of the red color intensity were calculated for each of these areas.

2.4. Ash composition and combustion indices

Inorganic composition of the biomass samples was subjected to the ash constituent analysis using an Inductively Coupled Plasma-Mass Spectrometry (ICP-MS Optima 2200 PerkinElmer, USA) device after acid digestion of solid ash residue in nitric acid, hydrochloric acid digestion in a microwave oven as described in an ASTM D3682 method. Prior to digestion, the biomass and ash samples were completely combusted in a muffle furnace at an incineration temperature of 550 °C. To estimate the problems associated with the mineral composition of biomass such as aerosol emissions, ash melting behavior of PL and mixtures, the aerosol emission index, ash melting index, base to acid ratio, slagging index, fouling index, slag viscosity index, bed agglomeration index and boiler corrosion tendency index are calculated using the procedure described in previous studies (Garcia-Maraver et al., 2017; Ozdemir and Demir, 2021), which is based on the chemical analysis of the fuel, the chemical reactions between the ash-forming elements and the interactions between the different groups of elements. The fuel indices were often used to predict the melting behavior of the ash based on its chemical composition.

Particulate emissions index evaluated by using the sum of following aerosol forming elements concentration in biomass pellets as presented in equation (3).

$$PEI = K + Na + Zn + Pb \quad (3)$$

Ash melting behavior of the biomass samples are estimated as molar basis of the elements using the following equation (4).

$$AMB = \frac{Si + P + K}{Ca + Mg} \quad (4)$$

Fouling or dry deposition of ash particles on heat transfer surfaces that indicates fouling tendency was calculated using equation (5).

$$FI = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3 + TiO_2} \times (Na_2O_3 + K_2O) \quad (5)$$

The biomass slagging tendency evaluation index was predicted by using equation (6). When BSI is below 0.7, then softening temperature is below 1000 °C and when BSI is above 1.7, softening temperature is higher than 1200 °C.

$$BSI = \frac{MgO + Al_2O_3 + Fe_2O_3}{CaO + P_2O_5} \quad (6)$$

The bed agglomeration index indicates ash agglomeration during combustion processes in a fluidized bed reactor and estimated using equation (7).

$$BAI = \frac{Fe_2O_3}{Na_2O + K_2O} \quad (7)$$

Finally, the melting temperatures of the ash are evaluated using temperature sensitivity analysis and given as: Deformation Temperature (DT), Spherical Temperature (ST), Hemispherical Temperature (HT) and Flow Temperature (FT) according to the ASTM D 1857 method.

2.5. Statistical analysis

A multifactorial analysis of variance (ANOVA) was used to evaluate the effects of the two main factors pyrolysis oil and sweet sorghum bagasse on the combustion characteristics of poultry litter and their interactions on dependent variables. In addition, regression analysis was used as an exploratory tool to assess the proportion of variability explained in the dependent variables. The biomass energy indicators were subjected to a correlation analysis. The above analyzes were performed within the statistical software package StatsDirect (V2.7.2, StatsDirect, Ltd., Altrincham, Cheshire, UK) at values of P = 0.05.

3. Results and discussion

3.1. Material properties

The parameters of the proximate analysis, i.e., the content of moisture, ash, volatile matter, and fixed carbon in the biomass, are a decisive factor that determines the energy content, the energy recovery rate, and the suitability of the feedstock for combustion. The moisture content of the prepared mixtures was significantly affected by the addition of pyrolysis oil and SS to the poultry litter (Table 2). Adding pyrolysis oil did not significantly affect the ash and volatile matter content, but the SS and interaction effect was significant.

The moisture content of SS bagasse was 7.08%, and the addition of SS to PL significantly reduced the moisture of the mixtures. This moisture concentration is much lower than the reported values for the PL and biomass-PL blend (Kumar et al., 2022; Turzyński et al., 2022), which meet the ISO standards for fuel pellets below 10.00%. Moisture content is generally reduced during compression of the pelletizing process (Kumar et al., 2022), and the determined moisture content was 7.24% and 7.58% for pellets with and without pyrolysis oil, respectively (Fig. 1). Similar compositions were evaluated in other pellet studies with different types of energy crop biomass and blended with PL (Ozdemir and Demir, 2021). Wzorek et al. (2021) reported a higher initial moisture content in PL and lignocellulosic crops, but this was reduced in their biomass pellets. It is also reported that, at a moisture content of 11%, the ignition temperature for an adequate thermal process would be 580 °C for 2 s. In comparison, this value increases to 620 °C for 8 s at a moisture content of 20% of the litter because a high moisture content of the litter means higher energy consumption to release the energy content of the poultry litter and a loss in the energy balance (Dalólio et al., 2017).

The high content of ash and its mineral composition in poultry litter is a significant obstacle to its valorization for mono-combustion since these compounds have detrimental effects on PL combustion and create burning and ash-related deposits, slagging, and agglomerations (Onenc et al., 2018). Results obtained from the proximate analysis in dry basis for ash content, volatile matter, and fixed carbon confirm our hypothesis both pyrolysis oil and SS proportions reduced ash content and increased volatile matter, thereby tending to the suitability for combustion due to high volatile matter, low ash content and low fixed carbon. According to the data, the PL used in the experiments has 64% volatile material content, demonstrating reasonable combustibility. The SS addition to PL significantly contributed to volatile matter increments 67, 68, and 71.50% with 25 (T_1), 50 (T_2), and 75% (T_3) SS addition. Pyrolysis oil addition further increased the volatile matter to 68, 70, and 73%, respectively. Similarly, SS and pyrolysis oil significantly reduced ash content from 12.85% to 7.10% on a dry matter basis, indicating that much of the material resulting from burning are products that do not react to the fouling, slagging, and agglomeration during combustion. Fixed carbon was reduced from 15.47 to 12.71% by the addition of SS and pyrolysis oil, which is relevant from a thermochemical perspective since a lower fixed carbon content of the biomass means lower ignition temperature (Yurdakul et al., 2021).

Low moisture and ash content and a relatively high volatile matter content have been shown to correlate positively with PL combustion and significantly improve the process and energy conversion during combustion. Therefore, low ash and moisture content, and high volatile matter content are recommended for an efficient combustion process and to control the operating parameters in an incinerator. It is evident from Fig. 1 that both sweet sorghum bagasse and pyrolysis oil addition to PL pellet significantly improve the proximate analysis parameters. With increasing SS in the blend, the ash content of pellets decreases gradually from 13.40 to 5.60%, whereas the volatile matter content increases progressively from 64.07 to 74.35%. A decrease in ash content and an increase in volatile matter could increase the energy value and improve combustion performance (Li et al., 2016), since a high volatile matter content improves the biomass combustion rate during the devolatilization phase (Kantarli et al., 2016). Thus, poultry manure combustion and bioenergy recovery can be enhanced by bioenergy crop by-products such as SS and the gasification by-product PO to control poultry litter combustion.

The ignitability index is used as an indicator of the likely performance of biomass in the boiler conditions. Fig. 2 shows the variation in ignition index values along the SS content in PL with and without pyrolysis oil in biofuel pellets. The SS addition to PL shifted the ignitability indices of the pellet in a 25% mixture and remained almost constant (41.94–42.02) with a further increase of SS in the mixture. Accordingly, the PO addition to PL:SS blends significantly improved the ignitability index from 41.75 to 43.74. However, all the estimated ignitability index values were above 35, which is in the range of efficiently useable in a boiler (Gajera et al., 2023) because high volatile content promotes rapid burning and more flaming combustion (Li et al., 2016). In this regard, the high volatile content of SS is beneficial for rapid ignition at low temperatures to avoid the prevalent problems with ash at higher temperatures.

3.2. Elemental compositions

The energy potential of solid biomass is determined by ultimate energy parameters analysis, which includes the mass participation for C, H, N, S, and O. Elemental analysis results of PL, SS, and PO are tabulated in Table 1. Ultimate analysis shows that, in general, PL and SS have lower C and N content but higher O content than the PO. The H and S contents were comparable. Biomass with high C and H content and low N and O concentration requires lower temperatures and shorter ignition period and thus gives higher energy during the thermochemical processes and is therefore favorable (Dalólio et al., 2017; Anyaoha, 2022). It can be observed from the elemental composition presented in Table 1 that there were no significant differences in the elemental composition of PL and SS, except for their N contents, where PL has exceptionally

Table 2
Analysis of variance (mean squares) for the effect of pyrolysis oil (Factor A) and sweet sorghum bagasse (Factor B) addition on proximate analysis parameters in poultry litter.

Source of variation	df	Moisture	Volatile matter	Ash content	Fixed Carbon	Heating value	Ignitability index
Pyrolysis oil (A)	1	0.8721***	0.0376^{ns}	0.0974^{ns}	3.5308***	25,696.1***	0.7140***
Bagasse (B)	4	0.7537***	48.1007***	46.9476***	4.9623***	29,128.9***	1.7743***
A × B	4	0.7943***	1.1423***	0.9789***	0.1852^{ns}	1728.7**	0.6686***
Residual	21	0.0490	0.0566	0.0702	0.1735	269.1	0.0833
Total	29						

ns, *, **, ***: non-significant, and significant at $P < 0.05$, 0.01 and 0.001 probability levels, respectively.

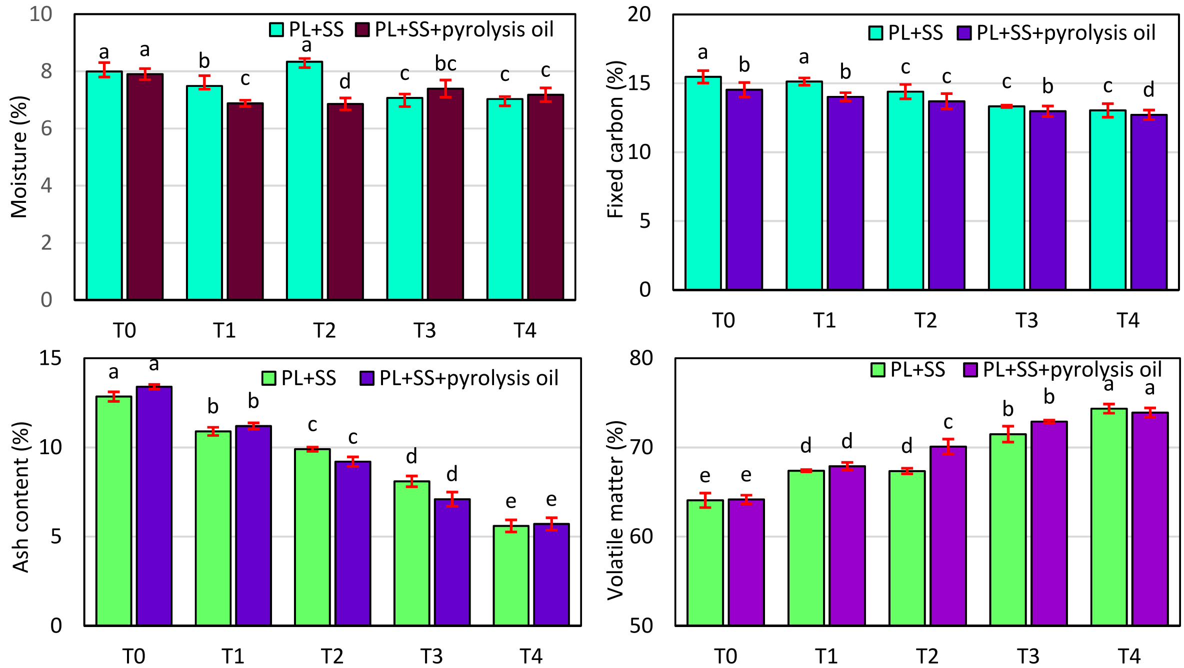

Fig. 1. Effect of pyrolysis oil and sweet sorghum bagasse (SS) addition on moisture, ash fixed carbon and volatile matter content in poultry litter. Different letters indicate significant difference at the 5% level according Duncan's new multiple range test.

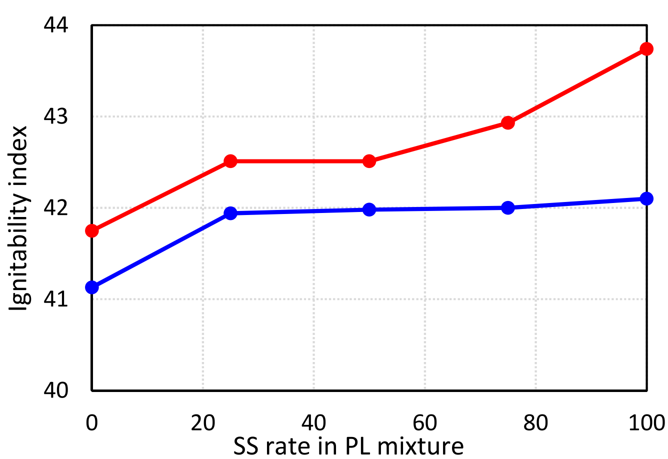

Fig. 2. The ignitability index of poultry litter amended with sweet sorghum bagasse (blue line) and 10% pyrolysis oil (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

higher N content compared to the SS. In addition, PO has significantly more C, H, and N but a low O content compared to both PL and SS.

Apart from the ultimate analysis, the inorganic composition of biomass significantly affects the incineration performance and creates various combustion problems in combustion systems (Kraszkiewicz et al., 2017). Inorganic components in PL generally have more problematic mineral constituents such as silica, potassium, and phosphorus compared to the well-known coal, which has more aluminum, iron, and calcium than biomass (Yurdakul et al., 2021). It can be seen that PL contains much higher K, P, Si, Na, Ca, S, and Cl than SS and PO (Table 1). Considering combustion in a fluidized bed reactor, pretreatment or co-combustion feedstock arrangement is essential for optimal ash mineral composition to minimize ash-related problems of poultry litter biomass. Pyrolysis oil produced from the PL had substantially lower K, Mg, Al, and S concentrations than PL. Thus, SS and PO are promising candidates for improving mineral composition to minimize the content of problematic minerals while, in contrast, increasing the energy density of biomass pellets.

3.3. *Calorific value*

The combustion of PL alone is an obstacle with some problems connected to the high moisture and ash contents and low heating values. Therefore, co-combustion with lignocellulosic biomass and energy-rich pyrolysis oil can help upgrade PL's energetic value. The calorific values of raw materials for PL, SS and PO were significantly different, ranging from 17.93 (PL) to 34.39 (PO) MJ Kg^{-1} (Table 1), compared to the reported values (Ozdemir and Demir, 2021). Fig. 3 shows the relationship between the addition of SS and PO to the PL mixtures and the LHV and HHV levels obtained in the samples. The regression equations were validated to see if they could be used to describe the effect of SS and PO on the energetic properties of PL blends. The results showed that the higher proportion of SS and PO at 10% in the PL:SS mixture had a higher heating value. It can be seen from Fig. 3 that the heat content increases as a function of the increase in the proportion of SS in the poultry litter mixture. By increasing the proportion of SS from 25 % to 100 %, the HHV values increased from 4295 ± 12 kcal kg^{-1} to 4404 ± 9 kcal kg^{-1} (Fig. 3). The R^2 (the proportion of total variance explained by the equations) ranged from 0.8326 to 0.8966 (Fig. 3). The increasing trend in LHV and HHV values can be attributed to the chemical structure of both SS and PO materials because PL contains relatively high moisture and ash minerals, which reduce the LHV.

SS contain a low proportion of minerals but a high proportion of volatiles, which are mainly composed of cellulose, hemicellulose, and lignin and contain more stored biomass energy in their structure than PL (Ozdemir and Demir, 2021). Therefore, positive regression lines were observed between the heat values and the proportions of SS in PL. In addition, the HHV values of PL:SS blends were further increased in the 0.5–2.6 % range when the blends were mixed with 10 % PO in fuel blends. The calorific value of biomass negatively correlates with moisture and ash content but positively correlates with volatile matter and fixed carbon contents (Maj, 2022). The determined concentrations of volatile matter, fixed carbon, moisture, and ash content are in the range of the values reported for poultry litter (Fahimi et al., 2022), and the

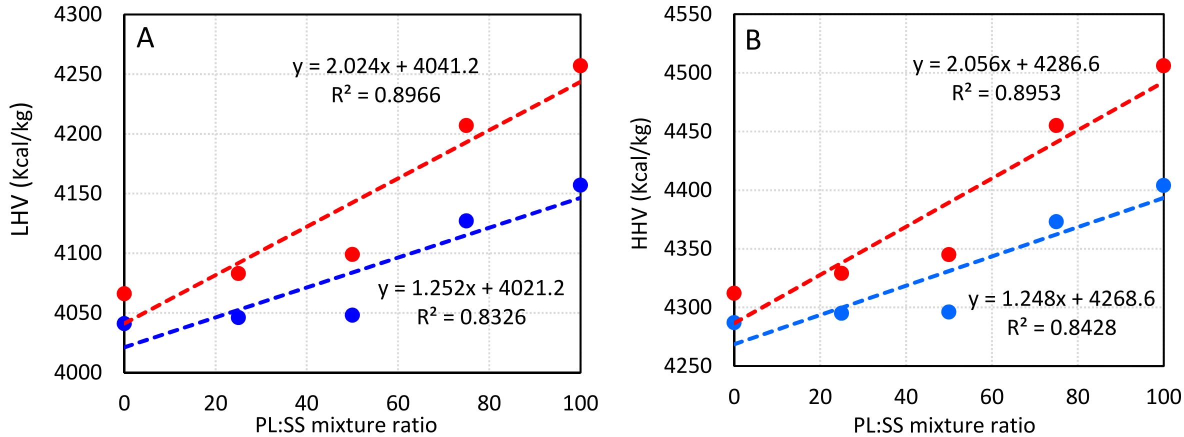

Fig. 3. LHV (A) and HHV (B) of poultry litter with increasing proportion of sweet sorghum bagasse (blue line) and 10% pyrolysis oil blend (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

addition of lignocellulosic biomass to the mixture (Ozdemir et al., 2018) to improve the LHV and HHV of mixtures in line with reported studies (Gutiérrez et al., 2020). The positive contribution of pyrolysis oil to biomass pellets was also reported by Riva et al. (2020) in their biochar thermochemical experimental tests.

3.4. Flame image analysis

The finding of the flame image analysis for pure poultry litter, pure sweet sorghum bagasse, and their mixture are shown in Fig. 4, which is different from pyrolysis oil. The lower row shows the combustion images corresponding to the 10% pyrolysis oil addition to pure PL, sweet sorghum bagasse, and their 50 + 50% mixture. Compared to the pure PL, the size and brightness of the flame area and red color intensity of images were increased with an increasing percentage of SS in the mixture. The flame area and red color intensity were further increased by the addition of PO to the biomass pellets. These results confirm our hypothesis that sweet sorghum bagasse and pyrolysis oil have more potent effects on PL combustion. The volatile flame's area and red color intensity for SS and PO are larger and more robust than pure PL.

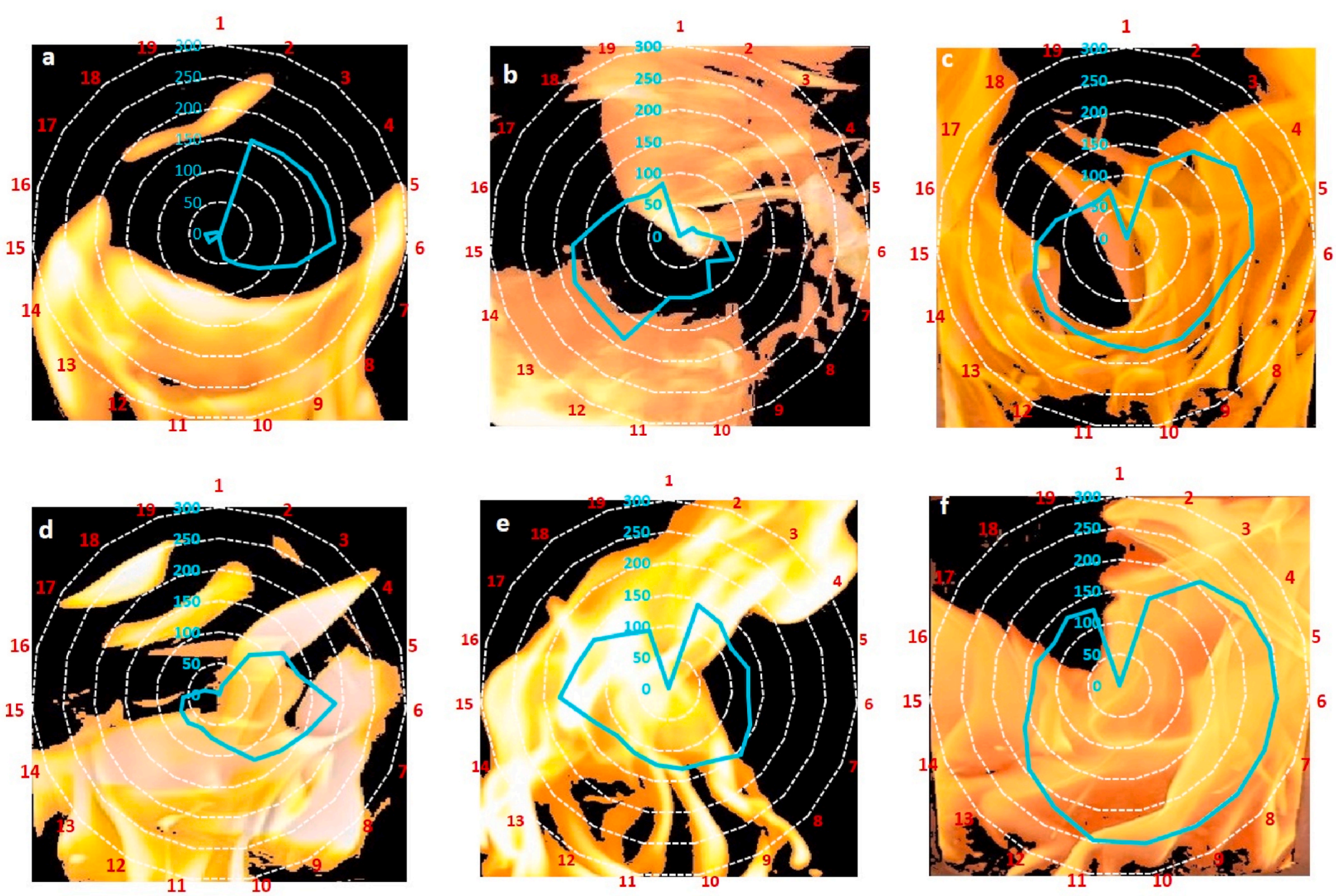

Fig. 4. Image analysis and red color intensity for the pellet (a) PL (T_0), b) SS (T_4), c) PL:SS (T_2), d) (T_0+PO, e) T_4+PO and, f) T_2+PO. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

It should be noted that SS alone and in combination with PO exhibit a shorter time to ignition compared to PL. Therefore, the ignition delay times of the prepared pellets were 75, 29, and 38 s for pure PL, SS, and their 50 + 50% mixture, respectively. When 10% pyrolysis oil was added to the pellets, the ignition delay times were shortened to 49, 28, and 33 s, respectively. Previous studies on biomass combustion have shown that the ignition delay time is directly related to the volatile matter content of solid fuels (Ozdemir et al., 2022). The variations in ignition delay time observed in the present study can be attributed to the volatile matter content and the composition of PL, SS, and PO in the different mixing ratios. In this, regard, the ignition delay time of PL improved by 39%, 56%, and 63% when mixed with SS, PO, and SS + PO, respectively. These results are consistent with the phenomenon that more volatiles provided by SS and PO affect dehydration, devolatilization, and positive contribution to burning. Accordingly, the red color intensity appears more remarkable in the mixture of SS and PO, as shown in Fig. 4, indicating the continuous combustion process of volatile matter release, volatile matter combustion, and charring. The high flame area and red color density in the co-combustion of SS and PO could be explained by the high combustion efficiency of the carbon-rich biomass compared to poultry litter, which was observed in a similar study (Polesek-Karczewska et al., 2018).

Flame image analysis indicates the synergistic effects between PL, SS and PO during the combustion process at blending ratios of 50%, which promote the flame area and red color intensity (Fig. 4). The rapid flame and red color intensity increase in PL:SS blends are more likely caused by the extensive devolatilization of volatile matter during combustion, which is contributed by SS, as discussed above. The higher levels of C, H, and lignocellulosic content in SS blends as opposed to pure PL pellets could be one reason for the wide flame area and stronger red color intensity. Biomass main components, hemicellulose, cellulose, and lignin, as well as C and H contents, play an essential role in the ignition and combustion behaviors; therefore, flame area and red color intensity can be explained by the synergistic effects between volatile matter, C, H and cellulose, hemicellulose and lignin contributed by SS and PO. Wzorek et al. (2021) and Yurdakul et al. (2021) also observed the synergistic effects between animal manure, including PL and lignocellulosic biomass during combustion. They explained that the devolatilization of biomass residue occurred earlier than PL, and the combustion of the released biomass volatiles provide extra heat to promote the devolatilization and ignition of PL. The strong correlation between the ignitability index and red color intensity (r = 0.87**) supports the benefits of SS and PO to the combustion efficiency of PL. In biomass, cellulose, hemicellulose, and lignin provide a higher bound oxygen content that promotes complete combustion and reduces unburned hydrocarbons (Anyaoha, 2022). The higher latent heat of vaporization also contributes to improved fuel vaporization and enhances combustion efficiency reflected by flame volume and red color intensity.

To better understand the changing biomass fuel parameters on flame red color intensity, Pearson correlations were performed using proximate composition parameters and ignition index values obtained from prepared biofuel pellets. Fig. 5 shows the significant positive contribution of volatile matter and organic matter content on flame red color intensity. HHV and ignitability index (Ii) also positively affect red color intensity. On the other hand, the ash content and fixed carbon contributed by PL had significant adverse effects on the red color intensity.

The degree of association differs in terms of investigated parameters in Fig. 5. Ash content correlates negatively with HHV (Ozdemir and Demir, 2021), while volatiles are positive. In addition, ash and moisture content negatively correlate with volatile matter. The findings shed more light on the fact that the solid biofuel's composition significantly affects the combustion's quality. Accordingly, measuring the intensity of the red color is a practical technique to determine ignitability and provides a clear means of demonstrating how the fuel mixture influences the quality of combustion. Hence, utilizing the RGB approach to analyze the flame image can be a useful way to determine the quality of combustion.

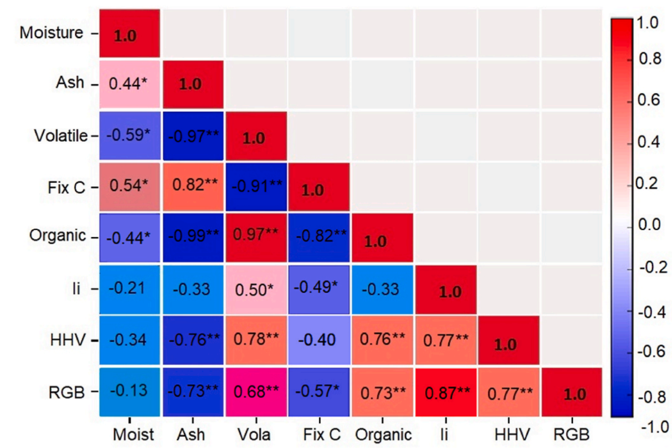

Fig. 5. Pearson correlation between proximate composition parameters and red color intensity of flame (**$p < 0.01$, *$p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.5. Ash composition and indices

The PL combustion ash had a pH in the range of 9.5–13.5, reflecting the generally alkaline nature due to the major ash components K, Ca, Na, Mg, HCO_3, and CO_3 in PL ash, which may lead to the formation of an ash layer on the burner and heat exchanger. In the current study, reducing ash content or changing the mineral composition of PL was investigated by index values to indicate ash-related problems. Various fouling and slag formation predictive indexes proposed in the literature, such as particulate emission index, ash melting behavior, biomass slagging index, fouling index, and agglomeration index presented in Table 3, were used in the present study to indicate ash-related problems.

The predominant components of elements with a low melting point, such as Na, K, S, or Cl, have a high concentration in PL ash. In addition, the minerals contain a high proportion of K and Ca, which are important in the reaction between silicon dioxide (SiO_2) and sulfur (S) to form alkali silicate and alkali sulfates, which can lead to ash deposits in burners and affect combustion rates and pollutant emissions. SS contains a lower ash, potassium, and phosphorus content than PL. In addition, pyrolysis oil contains less ash and mineral elements in small quantities, resulting in a lower ash content.

The high temperature typically enhances the conversion of ash material to the gas phase and, consequently, the emission of inorganic particles. The increasing sum of K, Na, Zn, and Pb in the fuel form volatile ash-forming emissions during combustion, and these ash-forming vapors start to nucleate or condense on the exchanger tubes. In the current study, index values of all tested fuel pellets were above >10,000,

Table 3
Slagging and ash deposition index of poultry litter (PL), sweet sorghum bagasse (SS), and their combination with pyrolysis oil (PO).

Biomass	PEI	AMB	BSI	FI	BAI
Pl (T_0)	43,515	2.36	0.31	296.91	0.03
SS (T_4)	26,410	1.54	0.43	22.14	0.05
PL:SS 50% (T_2)	33,264	1.86	0.38	157.43	0.04
T_0+PO 10%	41,428	2.31	0.32	283.56	0.03
T_4+PO 10%	24,562	1.52	0.43	22.02	0.05
T_2+PO 10%	31,756	1.85	0.38	151.84	0.05
Desired range	***>1000***	***<0.6***	***>0.72***	***<0.6***	***>0.15***

Particulate emission index (PEI), ash melting behavior (AMB), biomass slagging index (BSI), fouling index (FI), and bed agglomeration index (BAI).

indicating a high potential for aerosol emission. PL has more K and Na than SS which reduced the aerosol emission potential in PL:SS combination. However, SS and PO addition to PL did not reduce the index values below the desired range of <1000 (Table 3). It is evident from the index formula that Ca, Si, and P influence the K release to the gaseous phase. Therefore, a well-defined mixture of Ca, Si, and K may mitigate the formation of the aerosols.

The ash melting behavior of biomass samples is determined by the (Si + P + K)/(Ca + Mg) molar ratio. It is generally assumed that the presence of Si in combination with K and P lowers the ash melting temperature. In contrast, the opposite is observed when the concentration of Ca and Mg increases (Kraszkiewicz et al., 2017). Based on this index, the ash melting temperatures decrease with increasing index values. The indices for PL, SS, and PL:SS have high values of 2.36, 1.54, and 1.86 (mol/mol), respectively, so low ash melting temperatures should be expected. The ash fusion analysis results showed the values DT 1116, ST 1128, HT 1133, and FT 1165 °C for the PL. Similarly, the melting temperature determined for the SS was DT 1136, ST 1157, HT 1173, and FT 1243 °C.

Low-melting minerals such as K_2O and Na_2O in biomass ash vaporize during combustion, forming eutectic compounds that cause slagging and fouling (Garcia-Maraver et al., 2017). PL had the highest fouling index value (FI < 40) and was classified as extremely high due to the presence of potassium, sodium, and phosphorus in ash. On the other hand, the index value of SS was in the medium range (FI 0.6–40). The FI results of the 50 + 50% PL: SS mixture thus reduced the index value. However, neither SS nor PO in the mixture met the low tendency to ash fouling (Table 3). This finding is consistent with previous results suggesting that poultry litter is more susceptible to slagging or fouling (Ozdemir and Demir, 2021).

The presence of a high concentration of K both in PL and SS promoted the agglomeration tendency of blends. This is partly due to the higher combustion temperatures above 600–1000 °C leading to the melting K and formation of SiO_2 and K_2O, which is a dominant part of the slag and promotes the formation of silicate and alkali sulfates in bed agglomeration (Maj, 2022).

It is worth saying that blends of PL with the SS or PO considerably decreased the amount of ash; however, there were very few changes in the mineral composition of major plant nutrients and minor elements. Utilizing ash in agriculture could be a viable way to responsibly retrieve plant nutrients during the crop-production cycle, in line with the European Union's circular economy Action Plan, which promotes the use of waste materials as fertilizers (Turp et al., 2023).

4. Conclusion

As the global chicken meat industry grows, poultry production facilities generate a significant amount of litter waste. The direct combustion of waste to create electricity allows for faster disposal. However, before combustion the structural and compositional barriers of litter need to be eliminated, either by changing the fuel's properties or the ash's composition. This study proposes sweet sorghum bagasse and poultry litter-derived pyrolysis oil to mitigate the combustion of poultry litter. The studies showed that increasing the SS content from 25% to 75% significantly increased the C, H, fixed carbon, volatile matter, and calorific values in the PL mixtures. Moreover, the ash and moisture content decreased. Adding 10 % pyrolysis oil biofuel to pellets further improved the fuel parameters.

The image analysis of the flame features and the RGB color intensity results show that flame size and red color intensity successfully differentiate the biomass burning behavior. The proportional addition of SS and PO to the mixtures significantly improved the flame characteristics and red color intensity. On the other hand, the synergistic effects of SS and PO on ash composition and ash characteristics were relatively small and did not correspond to the desired ranges. Considering the findings of proximate and ultimate composition, ash indexes and flame image analysis the best ratio of successful combustion was 45:45:10 PL:SS:PO, respectively.

Poultry waste has the potential to produce clean energy as defined by the Kyoto Protocol and EU policy on the use of biomass for energy purposes. Additionally, by-products from sweet sorghum bagasse and biocrude oil from pyrolysis plants exhibit promising characteristics as a renewable energy potential for the co-combustion candidate to PL. However, further studies are needed to improve the ash index values to find a proper use for market development.

CRediT authorship contribution statement

Umit Pehlivan: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Writing – review & editing. **Saim Ozdemir:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Hasan Ozer:** Writing – original draft, Validation, Data curation, Investigation, Resources. **Omer Hulusi Dede:** Writing – review & editing, Visualization, Validation, Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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