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Does size matter? Influence of wood chip particle size on combustion efficiency and emissions

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ABSTRACT

Controlled combustion of woody biomass from prunings can valorize Mediterranean agroforestry residues, but the particle size of the woodchips could influence energy yield and emissions. This study evaluates the effect of particle size on fuel quality, boiler efficiency, and emissions during the combustion of woodchips from olive and citrus prunings. The residues were chipped with 20 and 40 mm screens; a 50/50 mixture was also prepared for each species. The classes were characterized (moisture, ash, C–H–N, LHV) and combusted in an 80 kW boiler with a multicyclonic filter; gases (CO, CO_2, NO_x, SO_2, O_2) and PM were continuously measured. Efficiency was calculated using the indirect method and analyzed with nonparametric tests; a PCA synthesized the emission profiles. Olive showed higher yields (73.1–78.1%) than citrus (54.2–69.3%) and lower concentrations of CO (1020–1879 vs 4229–9604 mg/Nm^3) and SO_2 (4.4–10.2 vs 55.6–192.7 mg/Nm^3), with lower NO_x (522–609 vs 749–871 mg/Nm^3). Within the tested size range (20 and 40 mm screens), nominal chip size did not significantly affect yield; however, mixed-size classes were associated with greater variability and, for citrus, greater dispersion of the emission profiles. PCA clearly separated the two species, highlighting greater emission stability in olive and greater variability in citrus.

1. Introduction

The use of woody biomass as a renewable energy source is receiving increasing attention in response to the need to reduce dependence on fossil fuels and lower greenhouse gas emissions. Controlled wood combustion is considered *carbon neutral* in the global carbon balance, as the carbon dioxide (CO_2) released during combustion is offset by the CO_2 absorbed by trees during their lifetime. In addition to its environmental benefits, the use of woody biomass in the energy sector offers significant economic and social advantages [1], linked to the development and strengthening of short supply chains based on readily available resources [2,3]. More recently, however, Europe has redefined the priority order in the use of woody biomass, placing energy production at the end of a hierarchy of possible uses—giving priority to the "material" use of biomass over its energy use, in accordance with the cascading use principle. This restriction arises from the need to align bioenergy policies with biodiversity conservation and climate change mitigation efforts two of the main environmental global challenges of our century and to avoid promoting unsustainable models [3]. Energy production based on lignocellulosic biomass can provide part of the solution to both crises, but only when biomass is produced sustainably [4]. Energy use should only be justified when no more sustainable alternatives are available, and subsidies should prioritize low-competition feedstocks that support both climate goals and biodiversity.

In this context, residual woody biomass from the agroforestry sector plays a key role. In Italy, only olive, citrus, and grapevines crops generate together more than four milliontons per year of lignocellulosic waste [5]. Using this waste for energy purposes not only addresses supply issues, such as risks related to indirect land use change (ILUC risks), but also prevents the common practice of open-field burning of such residues. This practice in addition to having no economic return for farmers is also in conflicts with current national environmental regulations (Italian Legislative Decree 3 April 2006, No. 152) due to the large amounts of pollutants released into the atmosphere during open burning. The easiest methos of utilizing pruned biomass for energy is by converting it into wood chips [6], which have become the most

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important commercial product for heat generation in power plants. According to Eurostat, wood chip production in the EU increased from 88 million m^3 in 2004 to 118 million me in 2019, before declining to 97 million m^3 in 2022 as a result of the COVID-19 pandemic [7]. This growing presence of wood chips in the market has prompted researchers to focus on the quality of this product. The main quality parameters defined by the standards and which determine classification into different quality grades include moisture content (MC), ash content (AC), nitrogen (N), chlorine (Cl), sulfur (S), heating value (HV) and Particle Size Distribution (PSD). A recent review [8] analyzes several parameters, such as MC, AC, volatile matter (VM), fixed carbon (FC), elemental composition, bulk density, and energy content of forest biomass, which can influence emissions and optimizing its utilization in energy and industrial valorization processes. Among the physical properties that can influence the energy performance of biomass, particle size is one of the most important. The particle size of wood chips is a crucial factor that can affect both combustion behavior and the emission of pollutants. Finer particles generally exhibit faster ignition and more complete combustion compared to larger ones because of their higher surface-to-volume ratio [9]; however their impact on emissions is pollutant-specific and operating-condition-dependent. In particular, smaller particles may increase fine particulate/fly-ash emissions through enhanced fragmentation, entrainment, and alkali release [10]. In some cases, they may also increase NO formation, whereas CO and unburned hydrocarbons often decrease because of improved burnout [9]. Despite its relevance, the detailed understanding of the influence of particle size on combustion performance and emission profiles is still limited. Vicente et al. (2016) [11] quantified emissions of particulate matter $PM_{2.5}$, defined as particulate matter with an aerodynamic diameter smaller than 2.5 μm, resulting from the combustion of woodchip biomass derived from residual pine and eucalyptus wood, considering pine stoichiometry and fuel leaching in the case of eucalyptus. Since wood chips represent a heterogeneous material that may include not only wood particles but also various impurities such as leaves, needles, soil clumps, or other mineral substances [12], which can impair combustion by reducing energy yield and increasing emissions and unburned particles, Kuptz et al. (2019) [13] subjected the biomass to mechanical screening to reduce fuel heterogeneity. The removal of needles, bark, and other impurities led to a decrease in AC and in critical chemical elements for combustion such as N, Cl, potassium (K), sodium (Na), and silicon (Si). Schön et al. (2017) [14] examined the emission behavior (carbon monoxide, CO; nitrogen oxides, NO_x; and PM) of various assortments of conifer wood chips derived from both stemwood and forest residues, analyzing specific fuel properties such as particle size distribution. However, their study did not consider the impact of this factor on energy yield. While several studies have examined the effect of particle size on industrial processes or on biomass derived from temperate forest species, the scientific literature on the influence of the size of pruning chips from Mediterranean species such as olives and citrus on combustion parameters and emissions is still limited.

Pruning biomass, often considered residual by-products, can represent a significant resource in Mediterranean agroforestry contexts, where residue management also poses a logistical and economic challenge. From this perspective, the energy use of these biomasses contributes both to the enhancement of the short supply chain and to the reduction of emissions associated with their elimination through uncontrolled combustion or spontaneous decomposition. Furthermore, the high seasonal availability and proximity to the point of use make these biomasses attractive from the perspective of energy and environmental sustainability. Proto et al. (2021) [2] evaluated both the emission performance and energy yield of different assortments of wood chips produced from agricultural residues, using wood particles smaller than 60 mm. The unique characteristics of these biomasses, in terms of nutrient content, anatomical structure, and variability in N, AC, and NO_x production, can significantly impact boiler performance and combustion quality [15–17]. Given the growing importance of these residues in the rural energy landscape, it is necessary to further investigate how different particle sizes, obtained by screening with increasingly large sieves, influence the chemical and physical properties of the fuel and the emissions produced during combustion. This aspect is particularly important for optimizing operating conditions in medium-scale biomass, which are increasingly widespread on farms and in local contexts driven by local circular economies.

In light of these considerations, this study aims to evaluate the effect of woodchip particle size distribution on selected fuel properties and combustion emissions, comparing two different Mediterranean species – olive and citrus – largely representative of the agricultural landscape of southern Italy. The aim is to contribute to a better understanding of the factors that influence the energy efficiency and environmental sustainability of biomass systems fueled by pruning residues, providing useful insights for the management and valorization of these materials in the context of the ecological transition. Specifically, the specific objectives of this study are: (*i*) to verify how different woodchip size affects the N and AC, and the energy yield of woodchips for each of the two wood species analyzed; (*ii*) to determine the extent to which fuel particle size affects emissions of CO, CO_2, NO_x, sulfur dioxide (SO_2), PM and oxygen (O_2) during combustion; (*iii*) identify, for each species, the most suitable granulometric class to guarantee a good compromise between the chemical-physical quality of the fuel and the environmental efficiency of the combustion process. The results of this research are expected to provide essential insights for optimizing the use of woody biomass as a fuel, improving energy efficiency, and reducing pollutant emissions. Additionally, the findings may inform the development of practical guidelines for the design and management of biomass combustion systems and may also provide useful indications for improving fuel classification and quality criteria for pruning-derived wood chips, particularly with respect to particle-size uniformity and combustion behavior.

2. Materials and methods

2.1. Biomass type

Wood chip samples were obtained from pruning residues of citrus and olive trees, materials typically regarded as waste by local agroforestry enterprises. This choice represents the most widespread and characteristic perennial crops of marginal agricultural areas across the Mediterranean Basin. These residues, primarily derived from mature tree pruning, are usually considered vegetal waste but can be valorized as biomass for energy production or other applications. The biomass was used as collected from pruning operations, without removing bark or other naturally associated woody fractions; however, visible non-biomass contaminants such as soil and other foreign materials were excluded before chipping. These wood residues were collected from several farms in the Calabria region (southern Italy) and transported to the Wood Technology Laboratory of the Department of AGRARIA, Mediterranean University of Reggio Calabria, where the chipping process was carried out. Chipping was conducted using a Peruzzo T3 branch chipper, a robust and versatile machine powered by a 9.7 kW gasoline engine. The chipper processes a wide range of woody materials and operates at capacities ranging from 3 to 8 m^3/h. Two different screen sizes (20 mm and 40 mm holes) were installed to produce wood chips of

Table 1
Sample classification according to species and particle size.

Sample Code	Species	Screen Size (mm)	Description
C20	Citrus	20	Chips from Citrus, 20 mm screen
C40	Citrus	40	Chips from Citrus, 40 mm screen
CMix	Citrus	20 + 40	50% C20 + 50% C40
O20	Olive	20	Chips from Olive, 20 mm screen
O40	Olive	40	Chips from Olive, 40 mm screen
OMix	Olive	20 + 40	50% O20 + 50% O40

distinct particle sizes (Table 1).

2.2. Characterization, combustion and emissions sampling

Biomass characterization was carried out in the LASER-B (Laboratory of Experimental Renewable Energies from Biomass) of CREA-IT of Monterotondo (Rome), to investigate the physical and chemical parameters of the different types of chipwood studied. The moisture content was measured by means of a Memmert UFP800 oven, according to the UNI EN ISO 18134-1: 2015 [18] and expressed in wet basis.Wood chips were dried at 105 ± 2 °C and the humidity was determined considering the weight loss of the sample after 24 h. The AC was determined using a Lenton EF11/8B muffle furnace according to the UNI EN ISO 18122: 2016 [19]. About 1 g of each samples was placed in the ceramic crucible at thermal ramp (6 °C/min up to 250 °C and then 10 °C/min from 250 °C to 550 °C) into the furnace. The higher heating value (HHV) was determined by Paar 6400 calorimeter, according to the UNI EN ISO 18125: 2018 [20], and the lower heating value (LHV) was calculated from the HHV considering the hydrogen content. The elemental composition was evaluated by using a Costech ECS 4010 CHNS-O elemental analyzer according to the UNI EN ISO 16948: 2015 [21] to determine the C, H, and N content.

Biomass burning was carried out at CREA-IT by using the boiler GSA-80 (D'Alessandro Termomeccanica Series GSA 80kWth) with a multicyclonic filter, supplied by the boiler manufacturer, as abatement system for PM. The unit is a mechanically fed, auger-fed biomass combustion system for solid fuels. Biomass is extracted from the hopper by motorized devices and conveyed through a screw-feeding system to a fire-pot, where combustion occurs with primary and secondary air supply. The flue gas is discharged through a chimney with an internal diameter of 200 mm and a height of 9 m. Flue-gas sampling was carried out at a height of 6 m above the combustion chamber. During combustion and emissions sampling all the parameters useful for the energetic yield computation were also recorded and sampled. Measurements of macropollutants were carried out in compliance with UNI EN 14791:2017, 14792, and 15,058 standards [22–24]. The boiler stack was equipped with a port to accommodate the sampling probe (HP1 Dadolab, Cinisello B., MI, Italy) used for flue gas analysis. A 180 °C heated lines was connected to a multiparametric gas analyzer capable of measuring NO_x, SO_2, CO, CO_2, and O_2. For this multi-gas analysis, a Horiba PG-250 portable gas analyzer was used. The HP5 Dadolab probe and the ST5 Dadolab isokinetic sampler were utilized to collect the total PM, following the European standards EN 13284–1:2017 [25]. PM was collected on 47 mm glass microfiber filters and quantified via gravimetric analysis with a Mettler Toledo AL104 Analytical Balance, maintained in a temperature- and humidity-controlled room at 20 °C and 50% relative humidity.

During the combustion campaign, stack sampling was carried out under comparable operating conditions. Isokinetic measurements were performed over 15-min intervals at the sampling port located 6 m above the combustion chamber on a circular flue duct with an internal diameter of 0.20 m, using a single-point configuration. Across the available sampling records, the dry normalized flue-gas flow rate (QVn) averaged about 316 $Nm^3\ h^{-1}$, while the corresponding moist normalized flow rate averaged about 359 $Nm^3\ h^{-1}$. The mean stack-gas temperature was approximately 119 °C, with an average gas velocity of about 2.93 m s^{-1}. The tests were conducted under reasonably comparable boiler operating conditions, while the observed differences in emissions were mainly associated with fuel type and chip-size class.

The primary and secondarily air supply was regulated using the boiler's built-in manual control system, which does not provide a direct airflow value in volumetric terms. To ensure comparability among tests, the same primary-air setting was maintained throughout the entire experimental campaign.

To provide additional operational detail for each combustion test, the mass of fuel consumed together with the net boiler operating time and the net hot-air generation time are reported in Table 2. These data complement the concentration-based emission results and help contextualize the differences observed among the tested biomass classes.

2.3. Combustion efficiency

The determination of combustion efficiency was performed using the indirect method described in the UNI EN 303–5:2012 [26]. The indirect measurement of boiler efficiency requires the quantification of the energy entering the system and all energy flows classified as losses, i.e., the Heat Loss in Dry Flue Gases (P_1), Heat Loss due to Water Content in Fuel and Hydrogen Combustion (P_2), Heat Loss due to Moisture in Combustion Air (P_3), Heat Loss due to Unburned Carbon (P_{ad}) and the Heat Loss due to Radiation to the Environment (P_R).

$$\text{Efficiency} = 100 - P_1 - P_2 - P_3 - P_{ad} - P_R$$

For solid and liquid fuels, the parameters that need to be measured include the Carbon (C) %, H_2 %, S %, O_2 %, N_2 %, H_2O %, AC %, and LHV. The combustion gas analysis involve measurements of O_2 %, CO_2 %, CO %, Gas temperature at the air outlet (t_g), Air temperature at the inlet (t_a).

The value P_1 is calculated using the mass of dry flue gases produced per kilogram of fuel, their temperature, and their specific heat capacity, together with the inlet air temperature. This estimation does not consider the hydrogen content of the fuel nor the water vapour generated during combustion. The weight of dry flue gases G_g is derived from the combustion gas analysis and the burnt carbon and sulfur per kg of fuel.

$$G_g = \frac{4CO_2 + O_2 + 700}{3(CO_2 + CO)}\left(\frac{C}{100} + \frac{S}{267}\right) + \frac{S}{160}$$

$$P_1 = \frac{G_g \bullet c_{pg} \bullet (t_g - t_a) \bullet 100}{LHV}$$

Where c_{pg} is 0.24 kcal/kg °C, and LHV of the fuel is expressed in kcal/kg.

The second value P_2 refers to the thermal loss associated with the water vapour generated by the combustion of hydrogen contained in the fuel, as well as the heat carried by the inherent moisture present in the fuel.

$$P_2 = \frac{\left(\frac{H_2}{100} \bullet 8.936 + H_2O\right) \bullet c_{pSH} \bullet (t_g - t_a) \bullet 100}{LHV}$$

where:

- $\frac{H_2}{100} \bullet 8.936$ is the weight of water produced from hydrogen (H_2) combustion in the fuel.
- H_2O is the percentage of water in the fuel by weight.
- c_{pSH} is the specific heat of superheated vapour, set to 0.45 kcal/kg °C.

The third value P_3 represents the thermal loss associated with heating the water vapour present in the combustion air. The amount of water vapour in the incoming air is assumed to correspond to full saturation at 15 °C. The weight of the comburent air is the weight of air per kg of fuel,

Table 2
Combustion-test operating data by sample class.

Sample	Burned biomass [kg]	Net boiler operating time [hh:mm:ss]	Net hot-air generation time [hh:mm:ss]
C20	5.00	01:00:00	00:11:33
C40	12.20	02:06:00	00:40:59
CMix	20.30	01:30:00	01:15:57
O20	23.00	01:57:00	01:32:24
O40	30.35	02:15:00	01:59:15
OMix	17.00	01:00:00	00:51:39

calculated by adding the weight of dry flue gases G_g to the air required for hydrogen combustion in the fuel, and subtracting the fuel weights:

$$G_A = G_g + \frac{7.936}{100} \bullet \left(H_2 - \frac{O_2}{8}\right) - \left(\frac{C + S + N_2}{100}\right)$$

While the P_3 is:

$$P_3 = \frac{G_A \bullet 0.0013 \bullet c_{pSH} \bullet (t_g - t_a) \bullet 100}{LHV}$$

P_{ad}: The heat loss in ash deposits in boiler is calculated as:

$$P_{ad} = \frac{G_{ad} \bullet C_{ad} \bullet LHV_{carbon}}{G_{fuel}}$$

Where:

- G_{ad} is the ash weight
- C_{ad} is the unburned carbon content
- LHV_{carbon} is the lower heating value of pure carbon
- G_{fuel} is the weight of the fuel burnt

The mass of chipwood fuel (G_{fuel}) was determined by weighing the fuel before each test. Each experimental run was then carried out until complete fuel depletion, i.e., until the entire pre-weighed fuel batch had been consumed; alternatively, any unburned fuel remaining after the test was collected and weighed.

Heat Loss due to External Radiation (PR) corresponds to the thermal loss associated with heat dissipation through the boiler walls. According to biomass boiler test protocols, this term should ideally be determined from direct heat-flux measurements or from external surface-temperature measurements. However, such measurements were not available in the present study. Therefore, PR was treated as an approximate boiler-dependent surface-loss term. This choice was supported by technical literature indicating that radiation and convection losses for boilers operating at full load are typically of the order of 3%, whereas much lower values (e.g., 0.2–0.5%) are generally reported for much larger boiler sizes than the tested GSA-80 unit (80 kW nominal, 94 kW furnace input) [27,28]. On this basis, PR was assumed to be of the order of 3% of the fuel energy input. Because the same boiler and operating layout were used throughout all tests, this term was considered approximately constant across fuel samples and therefore not expected to affect the relative comparison among fuels, although it may influence the absolute efficiency values.

2.4. Statistical analysis

The statistical analysis was conducted in Python version 3.12 environment. A one-way ANOVA with a Kruskal-Wallis test was performed to understand the influence of the specie and the size on combustion efficiency. A Principal Component Analysis (PCA) was also performed to reduce the variables able to describe and group the emission behavior of the different chip wood samples.

3. Results

In Table 3 the main data coming from laboratory analysis and emission recording are reported. Regarding the analysis of C, H, N, LHV and AC are reported the means of triplicate. For the emissions of CO, NO_x, CO_2, SO_2, O_2, are reported the means of the recorded data captured every 10 s. The other parameters are obtained in a single value from instrumentation or calculations.

3.1. Correlation analysis

The analysis of the correlations between biomass characteristics, combustion parameters, and emissions reveals a complex interplay of physical, chemical, and thermodynamic processes that govern the behavior of biomass during combustion. These relationships are deeply rooted in the properties of the biomass and the mechanisms underlying its thermal decomposition and oxidation, and they reflect the intricate balance required to achieve efficient combustion with minimal emissions. The positive correlation between the biomass burn rate and chimney temperature can be explained by the increased energy release as the combustion rate rises. The combustion of C and H within the biomass is highly exothermic [29], releasing heat that raises the temperature of the flue gases. This relationship highlights the direct impact of combustion intensity on heat transfer within the system. As mentioned in [30], the heat content of natural fuels is related to their oxidation state, with C atoms generally playing a dominant role and outweighing minor variations in hydrogen content. Based on literature values for different wood species, Tillman, 1978 [31], also identified a linear relationship between HHV and C.

The chemical composition of the biomass—particularly the concentrations of C and H—shows a strong positive correlation with the LHV, emphasizing their role as primary energy carriers. The oxidation of C and H releases the majority of the energy during combustion, directly influencing the calorific value of the fuel. Biomasses with high C and H content therefore exhibit superior combustion performance and energy output. A higher concentration of these elements leads to more complete combustion, which maximizes heat release and results in a greater conversion of C into CO_2 rather than incomplete combustion products such as CO. Since efficiency is defined as the useful energy output relative to the energy input by the fuel [32], an increased proportion of these high-energy elements in the biomass enhances efficiency by improving the combustion process and minimizing losses. This relationship is mirrored in the correlations between efficiency and these variables (Fig. 1). Fig. 1 highlights several associations among fuel properties, flue-gas composition, and performance indicators. In particular, carbon and hydrogen contents, together with LHV, are positively associated with energy yield, suggesting that fuels with higher energetic quality tend to produce higher thermal output. Likewise, higher CO_2 concentrations and lower O_2/CO levels are broadly consistent with more efficient combustion conditions. Fig. 1 captures the overall pattern of associations among the analyzed variables, providing a general framework for interpreting the links between biomass characteristics and combustion performance. For MC and stack temperature: the observed negative association is consistent with the additional energy required to evaporate water in wetter biomass, which can reduce the sensible heat available to raise flue-gas temperature [33]. At the same time, stack temperature may also reflect differences in burn intensity and phase, rather than fuel moisture alone. Consequently, wet biomass not only lowers combustion efficiency but also impacts downstream processes, such as the temperature-dependent kinetics of

Table 3
Characterization and emission parameters.

Sample	C20	C40	CMix	O20	O40	OMix
C [%]	39.1	41.0	40.6	45.3	45.5	45.9
H [%]	6.11	5.9	6.09	6.84	6.71	7.23
N [%]	0.35	0.36	0.4	0.27	0.25	0.21
LHV [MJ/kg]	18.1	18.1	17.7	18.6	18.7	18.7
Ash [kg]	0.3	0.4	0.68	0.26	0.41	0.2
Ash [%]	3.1	3.42	3.31	2.4	2.5	1.51
Moisture [%]	9.01	9.55	8.73	8.5	8.34	8.49
CO_2 [%]	4.17	2.39	2.15	5.19	5.05	6.66
O_2 [%]	15.9	17.7	18.2	15.1	15.1	13.4
NO_x [mg/Nm^3]	748.7	870.8	806	581.4	521.8	609.2
SO_2 [mg/Nm^3]	183.27	192.68	55.62	10.23	4.41	4.44
CO [mg/Nm^3]	8941.8	9603.9	4228.7	1878.7	1440.7	1020.0
Stack T [°C]	94.6	91.8	124.0	116.0	144.1	144.7
PM [mg/Nm^3]	15.3	83.3	110.4	55.1	63.9	65.5
Burning rate [kg h^{-1}]	5.0	5.8	13.5	11.9	13.4	17.0
Yield [%]	65.4	69.3	54.2	77.1	73.1	78.1

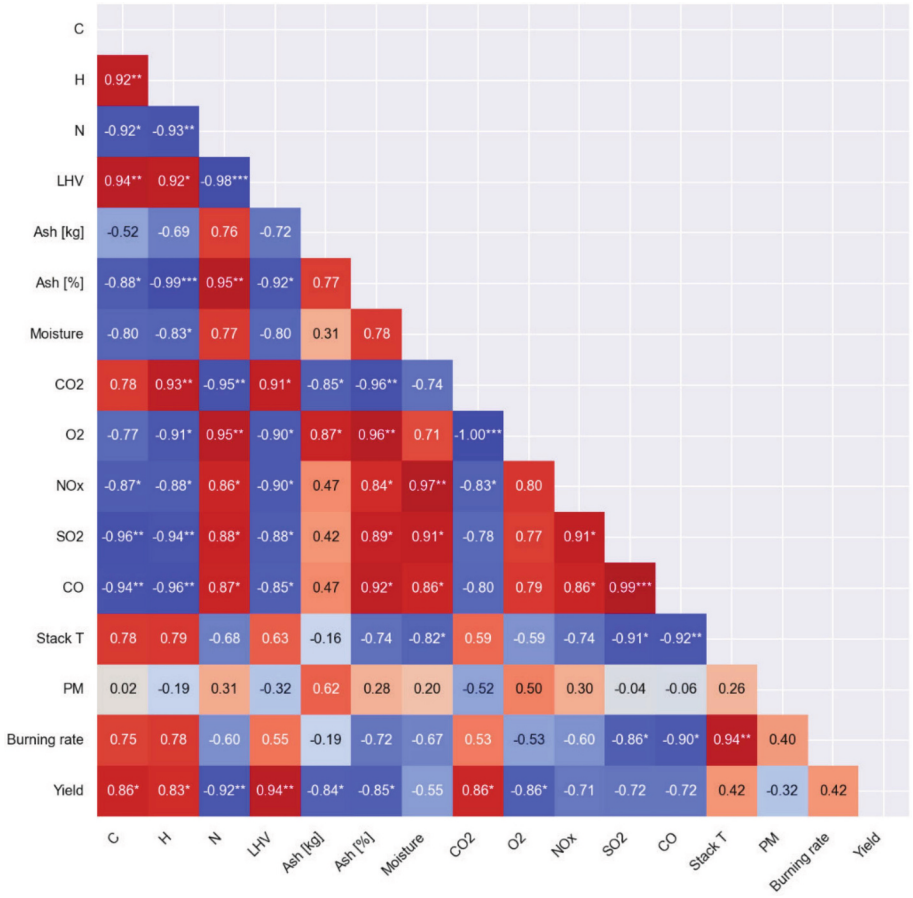

Fig. 1. Pearson correlation matrix of biomass properties, flue-gas composition, and process-performance variables. Positive correlations are shown in red and negative correlations in blue, with color intensity proportional to the correlation magnitude. The matrix provides an overall view of the interrelationships among fuel composition, combustion indicators, and performance parameters. Values were calculated after power transformation of the variables. Asterisks indicate statistically significant correlations (*$p < 0.05$, **$p < 0.01$, *$p < 0.001$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pollutant formation. The influence of moisture content extends further, as higher MC was associated in the present dataset with increased CO and SO_2 emissions. A positive association between MC and NO_x was also observed in Fig. 1; however, this relationship should be interpreted cautiously, since NO_x emissions in biomass combustion are primarily governed by fuel-N conversion. Higher moisture content in biomass slows down the combustion process, leading to poor ignition and lower combustion temperatures. This temperature reduction hinders the complete oxidation of reaction intermediates, ultimately affecting combustion efficiency and emission quality. Additionally, burning high-moisture fuels generates larger volumes of flue gas, which in turn requires larger flue gas treatment systems [34]. In small- to medium-scale biomass boilers, thermal NO_x formation is generally limited by the relatively low combustion temperatures, and NO_x emissions are therefore mainly associated with fuel-N conversion [35,36]. Higher fuel moisture may further lower combustion temperature, thereby affecting the overall NO_x emission pattern [37]. However, the relationship between moisture content and NO_x is not straightforward. Although higher moisture can delay combustion and modify the conversion pathways of nitrogen-containing intermediates such as NH_3 and HCN, NO_x emissions in biomass combustion are generally governed primarily by fuel-N content rather than moisture alone [37]. Some studies nevertheless suggest that moisture may still influence the overall NO_x pattern, either by affecting the partitioning of nitrogen species [37] or by increasing emission factors under specific combustion conditions [38,39]. Additional studies have also reported that high moisture content can prolong devolatilization and modify combustion dynamics [33,40,41]. In this sense, literature-based mechanisms involving residence time, oxidizing conditions, and radical chemistry have been proposed to explain how moisture may indirectly affect NO_x formation [42–44]. However, these mechanisms cannot be resolved within the present study and are mentioned here only as possible interpretative context. Biomass nitrogen remains the main factor influencing NO_x formation, since fuel-bound N is the dominant source of NO_x in biomass combustion [45,46].This elevated N contributes to increased NO_x emissions during combustion, as nitrogen compounds are oxidized to form NO_x, a major pollutant [33]. Additionally, biomass with high N often contains higher concentrations of inorganic elements like K, Cl, phosphorus (P), and calcium (Ca), which play a significant role in ash formation [47,48]. High ash content negatively impacts combustion efficiency by reducing the heating value of the fuel, as ash represents the non-combustible fraction. Studies have shown that every 1% increase in ash concentration can decrease the heating value by approximately 0.2 MJ/kg [46]. The combustion efficiency of biomass is also adversely affected by high AC, as it slows down the burning rate, leading to incomplete combustion and increased unburned char [49]. This results in lower flame temperatures, as heat is absorbed by non-combustible materials, reducing the overall combustion temperature and affecting the conversion rate of nitrogenous compounds into NO_X [50,51]. Incomplete combustion further increases the amount of unburned C in the ash, reducing overall combustion efficiency [52].

PM deserves a separate comment, since it was determined by isokinetic gravimetric sampling and was not included in the PCA, which was restricted to the time-resolved gaseous emissions. PM

concentrations ranged from 15.3 to 110.4 mg/Nm^3 across the tested biomass classes. The lowest value was observed for C20, whereas the highest PM concentration was measured for CMix. Overall, the citrus classes showed a wider spread in PM values, with a marked increase from the 20 mm class to the 40 mm and mixed classes. In contrast, olive-derived samples showed more moderate differences, with PM values remaining within a narrower range. Under the tested conditions, these results suggest that PM emissions were influenced not only by biomass type, but also by chip-size heterogeneity. In particular, the mixed classes appeared to be associated with less stable combustion and/or greater entrainment of fine particles, especially in citrus biomass. At the same time, because PM was obtained as a single gravimetric value for each test, these observations should be interpreted as indicative trends rather than as a fully resolved statistical comparison.

3.2. Influence of biomass type on combustion efficiency

A further key result from the analysis is that, using a one-way ANOVA with a Kruskal-Wallis test, it was found that citrus biomass combustion exhibits a statistically significantly lower combustion efficiency compared to olive ones (Fig. 2), with a *p*-value of 0.049. This suggests that citrus may not be as efficient as olive in terms of energy production during combustion. Moreover, it was observed that the variability in the combustion efficiency for citrus is notably greater, indicating a less predictable and more heterogeneous combustion process. This higher variability in the combustion performance of citrus biomass can be attributed to the inherent physical and chemical properties of citrus wood chips, which can cause fluctuations in heat release and combustion efficiency. This result is consistent with findings from Proto et al., 2021 [2], who also observed a similar trend in the combustion of citrus versus olive biomass. Their study indicated that citrus wood chips showed a lower and more variable combustion efficiency compared to olive wood, which was attributed to differences in the chemical composition and structural characteristics of the two biomasses. The significant effect of species type on combustion efficiency suggests that certain biomasses, such as olive, may inherently possess favorable properties for energy production, likely due to a more favorable chemical composition and lower lignin content, which improves combustibility [53]. Wood density could be also a factor influencing the energetic efficiency of wood combustion since it is strongly correlated with its calorific value [54]. In turn wood density depends on many factors as specie, humidity and plant portion. For example Hassanpoor Tichi et al., 2020 [55] show for citrus brunches near the canopy a wood density value definitely lower than density values commonly found also in other work for breast height wood [56,57]. Olive biomass, characterized by a relatively high bulk density, generally provided a more consistent and higher energy output. In contrast, citrus biomass, with its lower energy density and higher moisture variation, led to a more erratic combustion process and reduced overall thermal efficiency. This pattern reflects a broader trend observed in the literature [58,59], where olive biomass is often found to have superior combustion characteristics, including higher energy yields and more predictable combustion behavior, compared to citrus biomass.

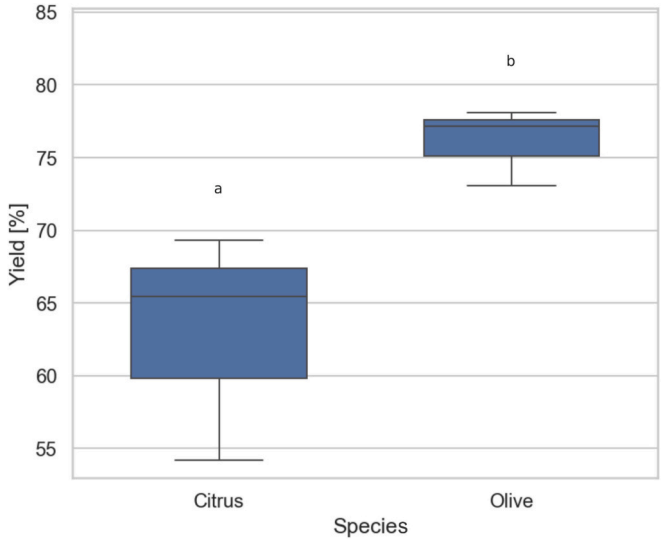

Fig. 2. Boxplots of Yield [%] by species (*Citrus* vs *Olive*). A nonparametric comparison was used: Kruskal–Wallis for the overall test and Mann–Whitney for the pairwise contrast. Groups that do not share a letter differ significantly.

3.3. Influence of biomass size on combustion efficiency

In contrast to the results observed with biomass type, when performing a one-way ANOVA testing the factor of chip size, no significant differences in energy yield were found. Under the tested conditions, no statistically significant differences in combustion efficiency were found among the evaluated chip-size classes. However, this result should be interpreted within the limits of the present experiment, which compared only two screened size classes and one mixed class. However, an interesting observation arises when a mix of different chip sizes is used: the variability in energy yield increases (Fig. 3). This finding suggests that chip-size uniformity may influence combustion stability under the tested conditions; however, the present dataset does not allow broad generalization beyond the evaluated size classes and boiler configuration. The increased variability observed when a mixture of chip sizes is used suggests that the combustion process becomes less predictable when there is a lack of homogeneity in the fuel's particle size. While chip size within an acceptable range likely does not directly influence energy yield, maintaining a consistent size may help ensure more uniform combustion. Boilers are designed to operate most efficiently when the fuel is presented in a consistent manner, allowing for more stable combustion characteristics. Therefore, within the tested size range, mixed chip classes appeared to be associated with greater variability, whereas no statistically significant effect of nominal size alone was observed. This finding is in line with other studies that emphasize the importance of fuel uniformity in biomass combustion systems, highlighting that more consistent fuel characteristics lead to better efficiency and lower emissions [60–62]. Nonetheless, the influence of chip size remains secondary to the overall system configuration and operational conditions, which ultimately dictate the combustion efficiency. Trojanowski et al., 2024 [63] examined the combustion-related emissions and

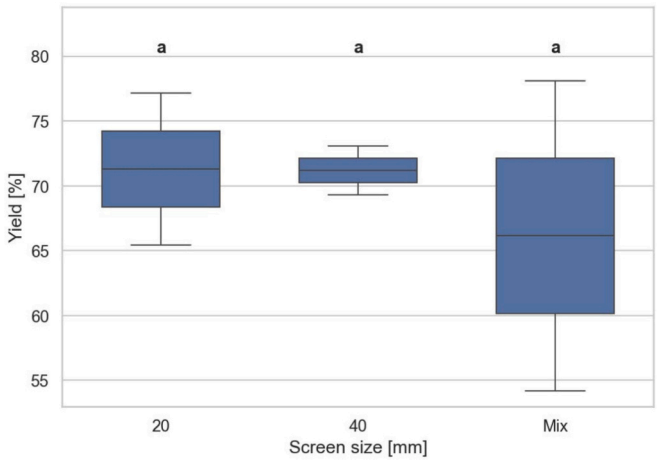

Fig. 3. Boxplots of Yield [%] by screen size (20 mm, 40 mm, Mix). A nonparametric Kruskal–Wallis test followed by Dunn's post-hoc comparison was applied. Groups sharing the same letter are not significantly different.

efficiency performance of five different woodchip types. The researchers found that variations in fuel properties, including particle size distribution, influenced combustion efficiency and emissions. This suggests that uniformity in chip size can lead to more predictable and efficient combustion outcomes. Further research investigated the effect of woodchip size distribution on combustion in a small-scale fixed-bed biomass boiler. The study concluded that a more uniform chip size distribution resulted in more stable combustion temperatures and reduced the release of volatile compounds, thereby enhancing combustion efficiency [64]. Additionally, a study on the storage of wood chips evaluated the effects of different chip sizes on storage properties. The findings indicated that coarse chips had significantly lower moisture content and energy losses after storage compared to fine chips. This highlights the importance of considering chip size and uniformity not only during combustion but also during storage to maintain fuel quality [65].

3.4. Emission grouping

To provide a more direct visualization of the gaseous emissions, the mean values and standard deviations of the main flue-gas parameters recorded during the combustion tests are shown in Fig. 4. This representation complements the correlation analysis and allows a more immediate comparison of the emission levels and within-group variability among the tested biomass classes. Overall, citrus samples showed higher mean concentrations of NO_x, CO, and SO_2, whereas olive samples were associated with higher CO_2 levels. In addition, variability was generally greater in the citrus classes, particularly for CO and SO_2, while olive classes showed lower dispersion and more stable emission profiles.

To further investigate the relationship between biomass type and chip size on emissions, a PCA was performed using the macro-pollutants sampled from the flue gases. The resulting PCA plot visually illustrates how emissions vary by biomass type (olive vs. citrus) and by chip size categories (20 mm, 40 mm, and mixed sizes). The analysis provides a clear separation of emission profiles based on these factors, revealing distinct trends in the combustion behavior of each biomass type and particle size. The PCA was performed on the pooled time-resolved emissions dataset obtained from six combustion tests. Gas concentrations (CO, CO_2, SO_2, NO_x, and O_2) were recorded every 10 s, and each point in the score plot therefore represents one individual measurement record, grouped according to biomass type and chip-size class. Fig. 5 should thus be regarded as an exploratory multivariate overview of the emissions dataset, highlighting general clustering patterns.

Fig. 5 provides an exploratory multivariate overview of the emissions dataset. Olive-derived emissions cluster relatively tightly in the central-left region of the PCA plot, suggesting lower overall variability in their emission characteristics. This clustering suggests that the emissions produced from olive biomass combustion are relatively consistent across different chip sizes (20 mm, 40 mm, and mix), with minimal variability regardless of particle size distribution. The limited separation among olive size classes is accompanied by a general association with CO_2 in the PCA space.The CO_2 levels in olive biomass emissions are notably higher than those of citrus, reflecting the combustion of dense, C-rich material [66]. Even when chip size varies, olive biomass emissions remain closely

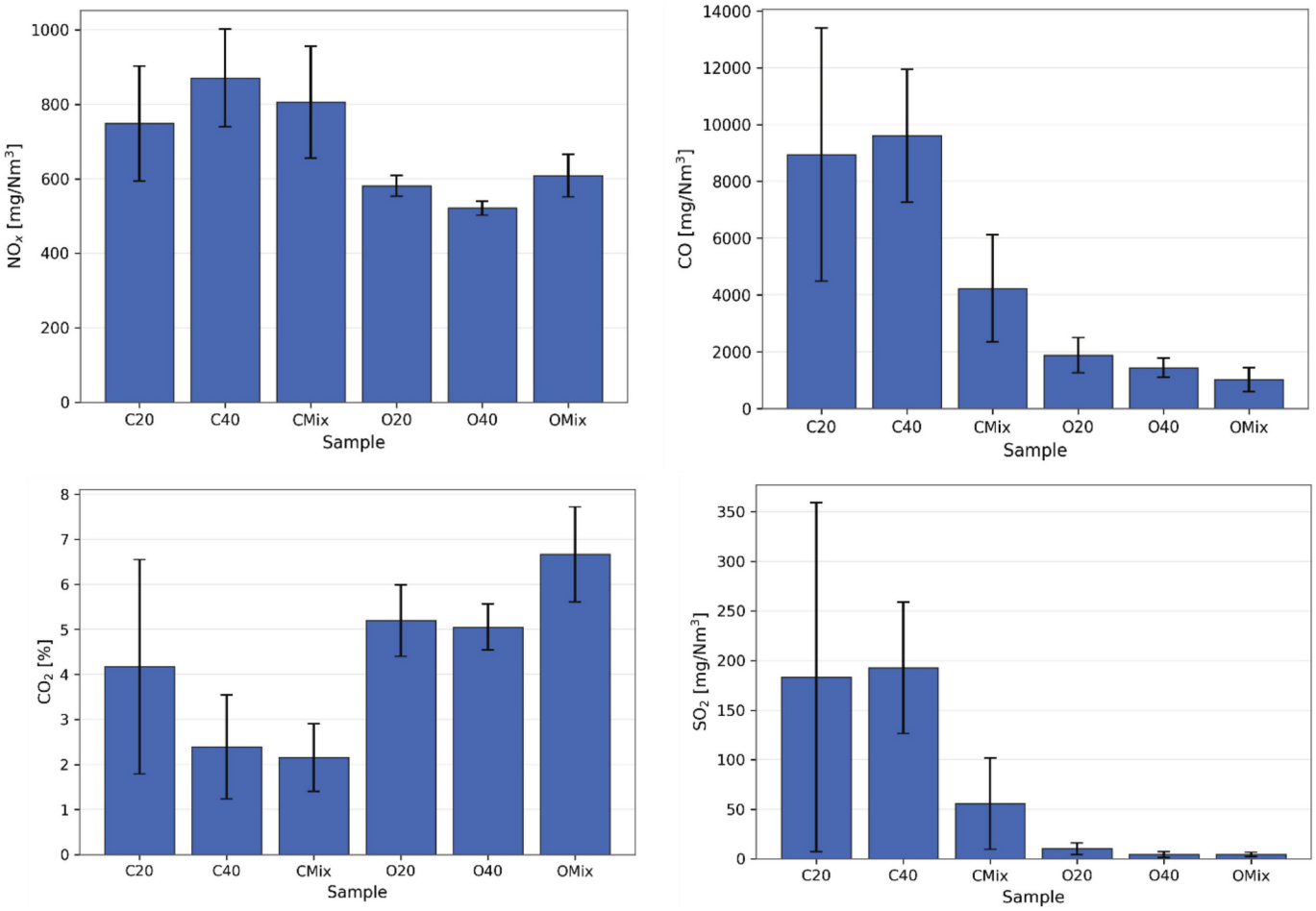

Fig. 4. Mean values (± standard deviation) of NO_x, CO, CO_2, and SO_2 for each sample class (C20, C40, CMix, O20, O40, OMix), calculated from time-resolved flue-gas measurements recorded every 10 s during the combustion tests. The figure provides a direct comparison of the main gaseous emission parameters across biomass type and chip-size class.

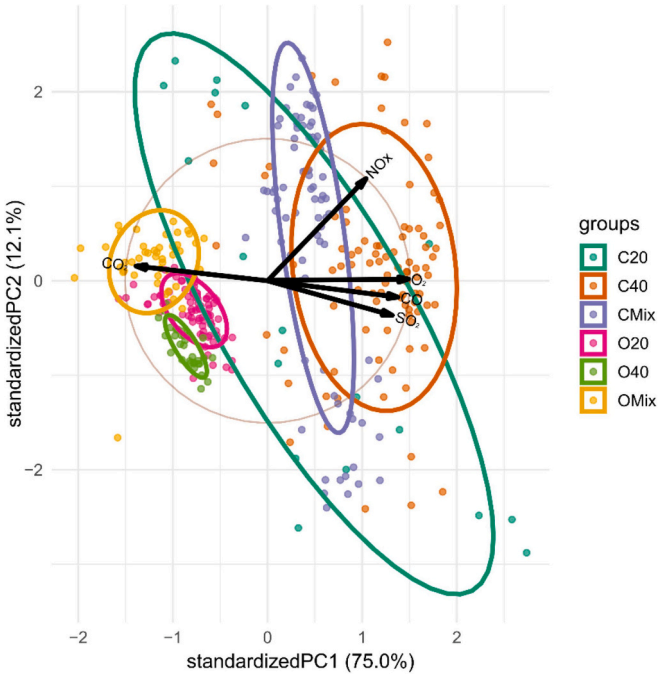

Fig. 5. PCA biplot of the emissions data standardized (z-score). Points are grouped as C20, C40, CMix, O20, O40, OMix; ellipses illustrate within-group dispersion. PC1 (75.0%) and PC2 (12.1%) together explain 87.1% of the variance. Black arrows show variable loadings, indicating the direction and strength of association with the principal components.

grouped, suggesting that particle size has limited influence on the emission profile for this biomass type. There is a slight observable difference between the Omix size category and the homogeneous O20 and O40 categories, with the mix group showing a marginally different spread. However, this difference is minimal and may suggest that the uniformity in combustion characteristics for olive biomass overrides the influence of particle size heterogeneity. In contrast, emissions from citrus biomass display a broader distribution in the PCA plot, indicating greater variability in their emission profiles. This variation could stem from the more heterogeneous combustion properties of citrus biomass, which tends to generate lower concentrations of CO_2, but higher levels of NO_x compared to olive biomass. Higher NO_x emissions align with findings in literature, such as [2], which suggest that biomass with lower C content and higher volatile matter, like citrus, may produce more NO_x during combustion due to N-rich compounds and incomplete combustion reactions. Within the citrus group, the 20 mm chip size category stands out as the most variable in terms of emissions, showing a dispersed spread across the PCA plot. This heightened variability is likely attributable to environmental and operational conditions during sampling, which could have introduced inconsistencies. This variability emphasizes the importance of controlled sampling conditions when analyzing biomass emissions. The other two citrus categories, citrus mix and citrus 40 mm, also show noticeable spread but are more distinct from each other in emission profiles.

4. Conclusions

In conclusion, high N in biomass is often linked to proteinaceous or mineral-rich residues, which contribute to increased ash formation and decreased combustion efficiency. The complex relationship between N, AC, and combustion characteristics underscores the importance of carefully selecting biomass feedstocks and employing advanced combustion technologies to maximize energy output while minimizing operational challenges in biomass-fired systems. These findings highlight the importance of appropriate fuel preparation and combustion management when using pruning-derived biomasses with variable AC and N. Optimized boiler designs, tailored to manage slag formation and ash accumulation, are essential for handling high-ash biomass. Additionally, combustion control strategies, including optimizing air-to-fuel ratios, can help reduce NO_x formation and enhance combustion efficiency. Overall, these correlations underscore the central role of fuel quality in determining combustion performance and emission behavior. MC, AC, and N emerge as critical factors that hinder efficiency and increase pollutant emissions, while C and H content drive energy output and combustion completeness. The observed relationships highlight the thermodynamic and chemical constraints of biomass combustion and offer insights into optimizing the process. By reducing MC and AC, managing N levels, and maximizing C and H content, it is possible to achieve cleaner and more efficient energy production. This interplay of variables illustrates the delicate balance required to design systems capable of leveraging biomass as a sustainable energy source while mitigating its environmental impact. These findings underscore the importance of biomass composition and combustion conditions in determining yield. The strong influence of species type on yield suggests that citrus biomass may be inherently more favorable for energy production than olive, likely due to differences in chemical composition. The trend observed in particle size, where more homogeneous sizes yield higher energy output, implies that particle size optimization could enhance combustion efficiency. However, the lack of statistical significance for size effects alone suggests that other interacting factors (e.g., species type and combustion settings) play important roles. These findings underscore the complex interplay of biomass composition, particle size, and combustion conditions in determining yield. The significant effect of species type on yield confirms that biomass characteristics play an important role in combustion performance. This insight supports the idea that feedstock selection is critical for optimizing biomass boiler efficiency. The observed trend in particle size where more uniform sizes enhance yield, aligns with studies that highlight the importance of particle size in achieving consistent combustion and efficient energy release. Homogeneity in size allows for steady flame propagation and minimizes issues associated with unburned fuel residues, which can occur with larger or mixed particle sizes. However, the lack of significant size effect alone, without considering species and combustion settings, indicates that other factors interact with particle size to impact yield. This suggests that the most efficient combustion is achieved through both particle size optimization and feedstock selection. The PCA analysis reveals that olive biomass is characterized by stable, consistent emissions dominated by high CO_2 levels, with limited impact from particle size variation. In contrast, citrus biomass shows greater emission variability, with a marked tendency for higher NO_x emissions and lower CO_2 concentrations. These findings provide a nuanced understanding of how biomass type and particle size can influence the emission profiles in biomass combustion systems, highlighting the importance of optimizing both feedstock selection and particle size distribution to control emissions effectively. The results suggest that feedstock selection is more influential than nominal chip size within the tested range, with olive biomass showing higher yield and more stable emission profiles than citrus. In addition, mixed chip-size classes were associated with greater variability, indicating that more homogeneous fuel preparation may improve combustion stability, especially for citrus biomass.

CRediT authorship contribution statement

Andrea R. Proto: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Adriano Palma:** Writing – original draft, Methodology, Investigation. **Enrico Paris:** Writing – review & editing, Writing – original draft, Investigation. **Salvatore F. Papandrea:** Writing – review & editing, Writing – original draft, Investigation. **Francesco Gallucci:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition.

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.

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Data availability

Data will be made available on request.

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