Bioresource Technology Reports 33 (2026) 102483

Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports

Bioenergy potential of pampa grass waste: Combustion properties and economic-environmental considerations

S. Pérez [a,*], J. Fernandez-Ferreras [b], I. Fernandez [a]

[a] Department of Energy Engineering, Universidad de Cantabria, Spain
[b] Department of Chemistry and Process and Resources Engineering, Universidad de Cantabria, Spain

ARTICLE INFO

Keywords:
Sustainability
Calorific value
Adiabatic flame temperature
Biomass yield
Energy density
Emission factors

ABSTRACT

The EU is addressing the invasive *Cortaderia selloana* (*CS*) due to its high management costs and large waste generation. This study evaluates *CS* waste as a feedstock for bioenergy production through direct combustion. Thermochemical parameters, including heating values, moisture and ash content, bulk density, adiabatic flame temperature (AFT), and fuel value index, were analyzed to assess combustion performance. Biomass yield, energy output, and the economic and environmental feasibility of *CS* combustion were also evaluated. Results show that optimal combustion requires a moisture content below 31.70 %. The average dry biomass yield was 10.21 ± 1.22 Mg ha^{-1} yr^{-1}, equivalent to 166 GJ ha^{-1} yr^{-1}. The process becomes economically viable when electricity prices exceed 107 € MWh^{-1}. Emission analysis revealed low CO, CO_2, and SO_2 levels but elevated NO_x emissions. Overall, *CS* waste represents a sustainable bioenergy resource and an environmentally friendly strategy for non-chemical control of this invasive species.

1. Introduction

Biomass is being extensively studied as a renewable energy resource owing to its environmental advantages and its role as a reservoir of fixed carbon. Biomass waste offers sustainable energy alternatives while supporting circular waste management. Its high energy potential, balanced against environmental and economic costs, is crucial for regional energy sustainability (Zhu et al., 2025). Lignocellulosic biomass combustion provides renewable energy, contributes to land restoration, promotes biodiversity, and supports socio-economic development in marginalized areas. Additionally, it supports climate change mitigation through its near-neutral carbon cycle. These benefits align with several United Nations' Sustainable Development Goals, specifically goal 7 (affordable and clean energy), goal 8 (decent work and economic growth), goal 12 (responsible consumption and production), goal 13 (climate action) and goal 15 (life on land) (United Nations Development Programme, 2025), which should guide the development and implementation of sustainable bioenergy strategies.

In developing countries that rely heavily on petroleum imports, interest in biomass-based renewable energy is driven by the large-scale production potential enabled by favorable land availability and climatic conditions.

Thermochemical processes for obtaining energy from dry biomass efficiently and economically convert biomass into electrical and/or thermal energy (Anyaoha, 2022). Combustion is the simplest and most used process to generate heat and/or electricity, despite its relatively low efficiency typically ranging from 20 % to 30 %. However, current advances in biomass combustion enhance efficiency, including low-temperature Chemical Looping, the use of sustainable oxygen carriers, and oxy-biomass circulating fluidized beds, which offer higher efficiency, lower costs, and reduced emissions (Vasileiadou, 2025). Compared to other conversion methods such as pyrolysis and gasification, direct biomass combustion requires fewer infrastructure modifications when transitioning from fossil fuels to biomass.

Cortaderia Selloana (Schult. & Schult. f.) Asch. & Graebn., (*CS*), commonly known as pampas grass, is an invasive plant native to South America that colonizes marginal areas, riverbanks, industrial zones, road edges, etc., throughout the world (Fig. 1) (Domènech and Vilà, 2007).

The spread of *CS* has had detrimental effects on local ecosystems, outcompeting native vegetation, disrupting the natural balance, and causing respiratory allergies (Rodríguez et al., 2021). Different national and regional initiatives have been implemented to control or eradicate this invasive species (Ministerio para la Transicion Ecológica y el Reto

* Corresponding author.
E-mail address: perezrs@unican.es (S. Pérez).

https://doi.org/10.1016/j.biteb.2025.102483
Received 11 September 2025; Received in revised form 5 December 2025; Accepted 10 December 2025
Available online 18 December 2025

Demográfico, 2025). The European Union has allocated significant funding €3.5 million for the 2018–2022 period and an additional €3.8 million for 2023–2028 to support a regional network to control *CS* inland spread and raise public awareness. Despite these efforts, *CS* remains prevalent along the northern coasts of Spain, Portugal, and France.

In Spain, presence of pampas grass has been documented by several studies (Domènech and Vilà, 2007). In the region of Cantabria (northern Spain), current *CS* control measures focus primarily on annual felling of affected areas which generates large volumes of waste that must be removed to prevent its spread. However, the high operational costs associated with these management strategies led to the abandonment of these efforts, resulting in the widespread propagation of pampas grass throughout the community's territory. Therefore, alternative strategies that valorise *CS* waste, such as its use as a feedstock for bioenergy production (e.g., via combustion), are appealing. These approaches can simultaneously reduce management costs and provide added environmental and economic value.

Although the valorization of invasive species like *Arundo donax* has been explored through composting for fertilizer production on a commercial scale (Pelegrín et al., 2018), research on the energy potential of CS waste remains limited despite its widespread global distribution.

There are studies that analyze the use of *CS* for the biological treatment of municipal wastewater (Daverey et al., 2019). However, research on the energy valorization of CS residues is still scarce. Some authors have investigated the fast pyrolysis of *CS* wastes, focusing on the yield and composition of the resulting fractions (Pérez et al., 2021). In the present work, we contribute to advancing scientific knowledge by exploring the use of *CS* wastes as a raw material for energy production through combustion, which is currently the most common process at an industrial scale in biomass power plants. The findings of this study will enhance current understanding of the valorization of CS residues as a renewable feedstock for energy generation.

Therefore the aim of this study was to evaluate the suitability of *CS* waste as feedstocks for direct combustion, analysing technical, economic and environmental aspects. Firstly, this research quantifies key parameters such as annual biomass yield (t ha^{-1} yr^{-1}), Higher Heating Value (HHV) (MJ kg^{-1}), Lower Heating Value (LHV) (MJ kg^{-1}), energy density (MJ m^{-3}), energy yield (MJ ha^{-1}), bulk density (kg m^{-3}), moisture content (MC), ash content (%), Adiabatic Flame Temperature (AFT), Fuel Value Index (FVI) to assess the technical viability of *CS* combustion. Secondly, based on the evolution of electricity prices over the past 12 years, the economic viability of offsetting *CS* management costs through energy production was analyzed. Finally, the environmental benefits of the combustión of *CS* waste were evaluated by estimating the equivalent fossil fuel volume and associated emission reductions. In Spain, CO_2 emissions from industry and the residential sector were 64,073.90 and 65,784.80 million tons of CO_2 equivalent respectively (Spanish National Institute of Statistics, 2023). The valorisation of the *CS* waste generated during its control by means of their combustion will contribute to make their management more attractive as well as, reducing the use of fossil fuels to produce electric energy whereas avoiding the use of chemical products (herbicides) in *CS* control, thereby reducing the negative impact on the environment.

The valorisation of the waste generated during CS control through combustion can make control measures more economically attractive while reducing reliance on fossil fuels and avoiding the use of herbicides, thus minimizing environmental impact. This integrated approach contributes to the development of sustainable waste management strategies, enhances energy recovery, and supports ecological restoration in areas affected by invasive species.

2. Materials and methods

2.1. Study area and climatic conditions

This work was conducted in the region of Cantabria, northern Spain, located at 43°28′N latitude and 3°48′W longitude. The area is characterized by variable topography and soils predominantly classified as Acrisols, Cambisols, and Umbrisols. *Cortaderia Seollana (CS)* specimens used in this study were established in soils composed of 36 % sand, 32 % silt and 28 % clay, sampled at a depth of 30 cm. The soil had a pH of 5.78 and an organic matter content of 4.50 %, as determined through laboratory analysis. Climatic conditions of the study area during the study period were atypically dry, with a total accumulated rainfall of 615.50 mm, markedly lower than the 10-year average of 1055 mm, the annual average temperature was 14.80 °C, the annual average maximum temperature was 17.80 °C whereas the annual average minimum temperature was 12.23 °C, the annual average relative humidity in air was 74.9 %, the annual average wind speed was 11.4 km/h, hydric deficiency was 99 and Mediterranean Index was 2.40. This indicates that the study period was drier than-average one which likely impacted on biomass growth.

Once the study area was selected, the research procedure shown in Fig. 2 was followed:

The following subsections provide a detailed explanation of each stage.

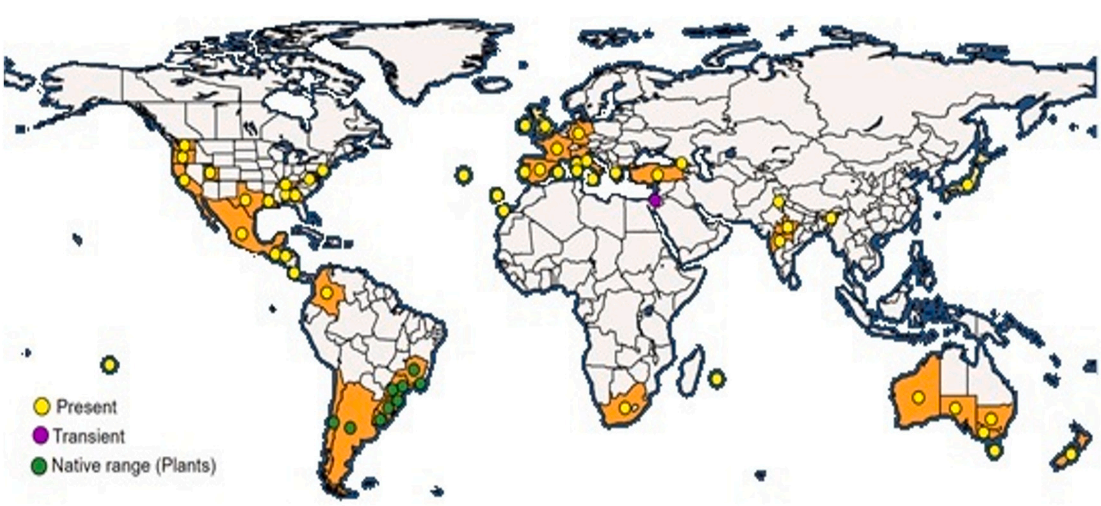

Fig. 1. Global Distribution of *Cortaderia Selloana* (Domènech and Vilà, 2007).

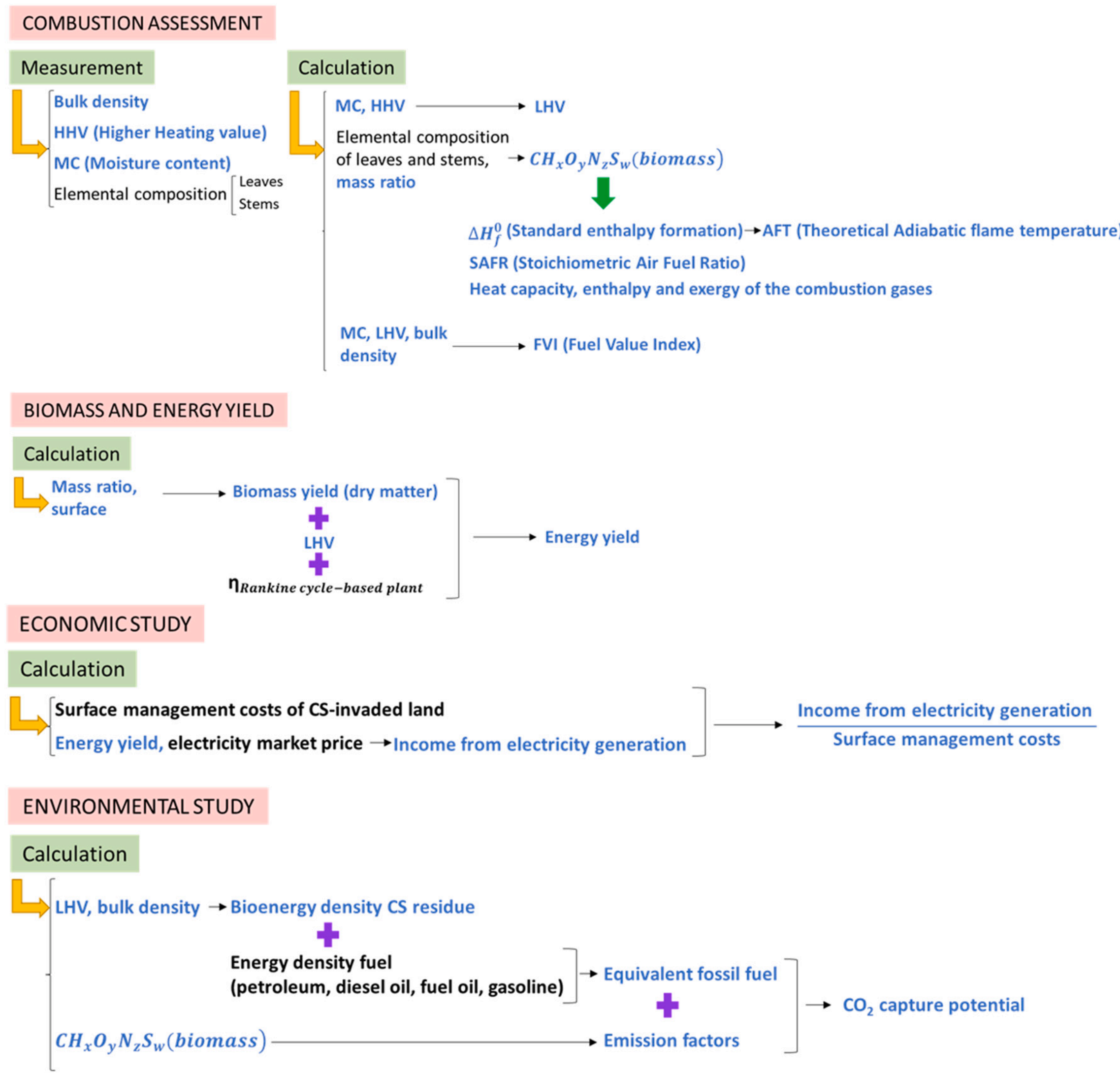

Fig. 2. Research process flowchart.

2.2. Combustion experiments of CS

The experimental determination of the calorific value of substances provides a realistic measurement of combustion performance, as it accounts for the influence of impurities, moisture content, and inefficiencies often overlooked in theoretical calculations based on elemental composition. Samples of *CS* biomass were separated into stems and leaves for combustion analysis. Four samples of each plant component were collected, stored in polyethylene bags to preserve their MC and transported to the laboratory. Once in the laboratory, the samples were cut to reduce their size (< 5 mm) and analyzed to determine HHV, LHV, MC (wet basis), ash content (dry basis) and bulk density. Moisture content was determined according to the ISO 18134-2 standard (International Organization for Standardization, 2017a). Ash content on a dry matter basis was measured following ISO 18122 (International Organization for Standardization, 2022), by incinerating the sample at a controlled temperature of 550 ± 10 °C and measuring the residual mass. The HHV was obtained using an IKA 5000 bomb calorimeter in accordance with the ISO 18125 (International Organization for Standardization, 2017b). The LHV (MJ kg^{-1}was calculated from the HHV by applying Eq. (1), which considers the latent heat of vaporization of water (2.44 MJ kg^{-1}).

$$LHV = HHV - 2.44*0.01*(H_b + H_a) - 2.44*0.01*9*H_d \quad (1)$$

where H_d represents the hydrogen content in dry sample (%), H_b represents the moisture content in sample (%) and H_a represents atmospheric humidity during combustion (neglected here due to pure O_2 atmosphere during combustion). The H_d value used was 5.76 %, based on elemental composition data from (Pérez et al., 2021) and considering the stem-to-leave ratio determined in this study. LHV is a key parameter to evaluate the energetic potential and flammability or ability to generate and propagate fire of biomass buels. Bulk density was obtained following ISO 17828 (International Organization for Standardization, 2025) using a graduated cylinder. The Eq. (2). was used to calculate the bioenergy density of the total *CS* waste:

$$Bioenergy\ density\ (MJ\ m^{-3}) = Bulk\ density(kg\ m^{-3}) \bullet LHV(MJ\ kg^{-1}) \quad (2)$$

2.2.1. Theoretical adiabatic flame temperature (AFT)

AFT is the highest temperature theoretically obtained during combustion under idealized conditions of no heat loss. AFT serves as an indicator of combustion efficiency and is of particular relevance to evaluate power plant performance and provides crucial parameters for industrial applications (Ditl and Šulc, 2024). AFT directly affects energy production and its increase improves energy efficiency (Daverey et al., 2019). The highest AFT values are provided by stoichiometric combustion conditions. For ratios lower or higher than stoichiometric, the AFT decreases (Reyes et al., 2024). In real biomass combustion systems, moisture content (MC) is significant, and an excess of oxygen is utilized to achieve complete combustion, resulting in an AFT reduction. Understanding how AFT varies with moisture and air excess is crucial for combustion optimization and for co-firing *CS* waste with other biomass types. For this purpose, it was assumed that the chemical reaction of biomass combustion is the one described in Eq. (3). This approach assumes energy conservation between the enthalpy of reactants and products.

$$CH_xO_yN_zS_w(biomass) + \left(1+\frac{x}{4}+w-\frac{y}{2}\right) O_2 \rightarrow CO_2 + \frac{x}{2}\ H_2O + \frac{w}{2}SO_2 + \frac{z}{2}N_2 \tag{3}$$

To determine the standard enthalpy of formation of the waste, $\Delta H_f^0(Biomass)$, Eq. (4) and Eq. (5) were implemented.

$$HHV = -\Delta H_r^0 = -\left[\Delta H_f^0(CO_2) + \frac{x}{2}\Delta H_f^0(H_2O) + \frac{w}{2}\Delta H_f^0(SO_2) - \Delta H_f^0(Biomass)\right] \tag{4}$$

$$\Delta H_f^0(Biomass) = \Delta H_f^0(CO_2) + \frac{x}{2}\Delta H_f^0(H_2O) + \frac{w}{2}\Delta H_f^0(SO_2) - \Delta H_r^0 \tag{5}$$

where HHV is the high heating value in dry basis, ΔH_r^0 is the standard enthalpy reaction and ΔH_f^0 is the standard enthalpy formation.

Stoichiometric Air Fuel Ratio (SAFR) was calculated based on the idealized combustion reaction of *CS* waste (Eq. (6)) and considering a molecular weight of air od 28.97 g/mol.

$$SAFR = \frac{\left(1+\frac{x}{4}+w-\frac{y}{2}\right)\bullet 28.97}{12+x+16\bullet y+14\bullet z+32\bullet w} \tag{6}$$

The coefficients x, y, z, and w in the molecular formula of the waste (Eq. (3)) were determined based on the elemental composition reported by (Pérez et al., 2021), incorporating the leaf-to-stem ratio obtained in this work.

The specific heat capacity, enthalpy and the exergy of the combustion gases were evaluated for an excess air ratio of 150 % and a gas temperature of 1323 K, based on the method described by (Coskun et al., 2009).

2.2.2. Fuel Value index (FVI)

The heating value reflects the energy content of a fuel. However, in practical applications, the presence of ash and MC can hinder the achievement of maximum energy efficiency during biofuel utilization (Pegoretti Leite de Souza et al., 2021). To account for these limitations, the Fuel Value Index (FVI) of the waste was calculated. The FVI estimates the effective bulk energy output (Eq. (7)), taking into account the detrimental effects of ash and moisture content.

$$FVI = \frac{LHV\ (MJ\ kg^{-1}) \bullet Bulk\ density(kg\ m^{-3})}{MC(\%) \bullet Ash\ Content\ (\%)} \tag{7}$$

2.3. Biomass and energy yield of CS

Annual biomass production was assessed to estimate the biomass yield of this species, noting its high regrowth capacity after cutting, a feature also highlighted by previous studies. For this assessment, an approximately 15 m^2 plot of *CS* was cleared in October 2021 and harvested in October 2022 and October 2023. Plants were cut at ground level and immediately weighed to determine their fresh biomass. No agricultural practices (e.g., fertilization) were applied during this period. Multiple plants distributed throughout the plot were harvested (Fig. 3). From each plant, leaves and stems were separated and weighed individually to determine the fresh weight of each component and to calculate the stem-to-total plant weight ratio (leaves + stems). Simultaneously, four subsamples from each component were collected to determine average moisture content (MC) and dry weight. These data enabled the estimation of biomass yield (Mg ha^{-1} yr^{-1}) of *CS* as a primary biomass resource. By integrating the biomass yield with the Low Heating Value (LHV) (Section 2.2), the energy yield (GJ ha^{-1} yr^{-1}) of *CS* was calculated for both fresh (maximum MC) and dry (minimum MC) conditions.

2.4. Economic and environmental assessment

2.4.1. Economic assessment

An economic assessment was conducted based on the costs associated with *CS* control, considering four treatments scenarios (see Table 1) that vary according to terrain slope and the method of removal (manual or mechanical) (Ministerio para la Transicion Ecológica y el Reto Demográfico, 2025). It is important to highlight that all proposed

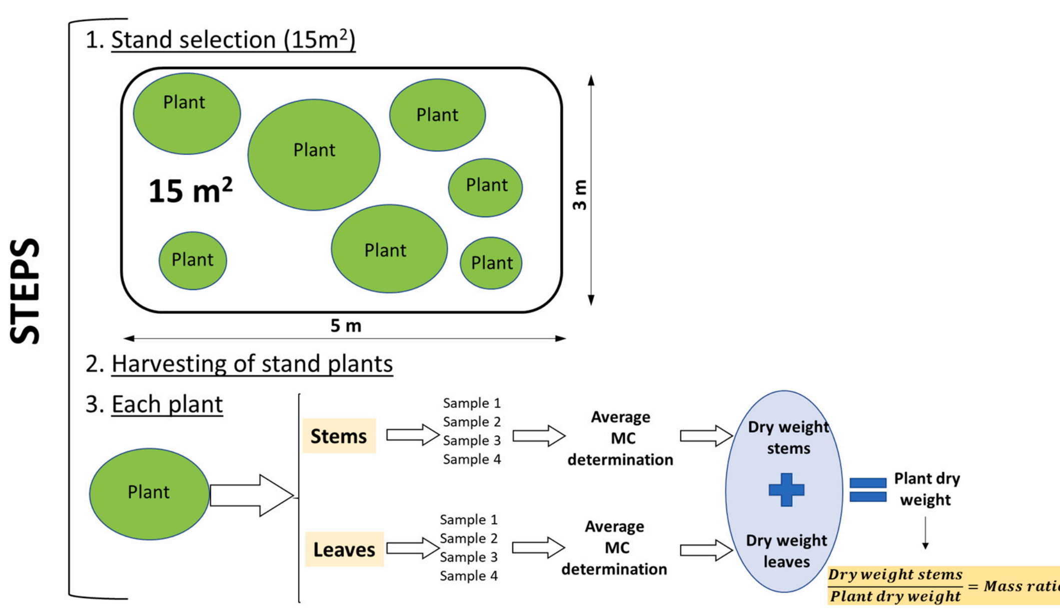

Fig. 3. Procedure to determine *CS* biomass yield.

Table 1
Surface management costs of *CS*-invaded land.

	Type of treatment	Management costs (€ ha^{-1})
T1	Manual scraping, percentage < 50 %	6160
	Manual scraping, percentage > 50 %	7632
T2	Brush cutter scraping, slope < 50 %	3116
	Brush cutter scraping, slope > 50 %	3750
T3	Mechanized scraping 10 % < slope < 20 %	1016
T4	Mechanized scraping with a spider excavator and chain brush cutter.	2299

treatments are not chemical in nature, which makes them environmentally preferable by avoiding the use of chemical products (e.g., herbicides) for control. Income from electricity generation was estimated based on the electricity market price set by the Designated Electricity Market Operator of the Iberian Peninsula. An operational cost of €45 MWh^{-1} has been considered, based on data from the International Renewable Energy Agency (IRENA). For the calculations, a ± 20 % sensitivity in the average electricity selling price was assumed.

2.4.2. Environmental assessment

2.4.2.1. Equivalent fossil fuel of CS waste. The fossil fuel equivalent volume per cubic meter of *CS* waste was calculated (Eq. (8)), as the ratio between the energy density of the CS waste and that of various reference fossil fuels: petroleum (37.03 GJ m^{-3}), diesel fuel (36.27 GJ m^{-3}), fuel oil (39.93 GJ m^{-3}), and gasoline (32.62 GJ m^{-3}) (Protásio et al., 2013).

$$\text{Equivalent fossil fuel } (m^3) = \frac{Bioenergy\ density_{Residues}}{Bioenergy\ density_{fuel}} \tag{8}$$

2.4.2.2. CO_2 capture potential of CS waste. The potential reduction in CO_2 emissions achieved by substituting *CS* waste for fossil fuels was also estimated. This calculation used the emission factors of the same reference fossil fuels: petroleum (3.43 10^{-3} kg CO_2 m^{-3}), diesel fuel (36.27$10^{-3}$ kg CO_2 m^{-3}), fuel oil (39.93 10^{-3} kg CO_2 m^{-3}) and gasoline (32.62 10^{-3} kg CO_2 m^{-3}) (Protásio et al., 2013). The estimation was performed using Eq. (9).

$$CO_2 \text{ capture potential } \left(kg_{CO_2}\right) = \text{Emission factor} \bullet \text{Equivalent fossil fuel} \tag{9}$$

2.4.2.3. Emissions from CS waste combustion. Estimating gas emissions is critical to evaluate the environmental feasibility of biomass in bioenergy applications (Alves et al., 2020; Maj, 2018; Pashakolaie et al., 2025). In this work, emissions of CO_2, CO, NO_x and SO_2 were estimated following the methodology outlined by other autors (da Silva et al., 2023; Maj, 2018).

The emission factor corresponding to pure carbon (E_C) is calculated using Eq. (10).

$$E_C = C \bullet U_c \tag{10}$$

where C is the carbon mass fraction and U_c denotes the oxidized carbon fraction during combustion, assumed to be 0.88 for biomass.

The emission factor for carbon monoxide (E_{CO}) is determined by Eq. (11).

$$E_{CO} = \frac{MM_{CO}}{MM_C} \bullet E_c \bullet C_{CO-C} \tag{11}$$

Where MM_{CO} and MM_C correspond to the molar masses of carbon and monoxide and carbon. The $C_{CO\text{-}C}$ ratio indicates the fraction of carbon released as CO during combustion, taken as 0.06 for biomass materials.

The emission factor of methane (E_{CH4}) is given by Eq. (12).

$$E_{CO2} = \frac{MM_{CO2}}{MM_C} \bullet \left(E_c - \frac{MM_C}{MM_{CO}} E_{CO} - \frac{MM_C}{MM_{CH4}} E_{CH4} - \frac{26.4}{31.4} E_{NMVOC}\right) \tag{12}$$

where MM_{CO_2} and MM_C correspond to the molar masses of carbon dioxide and carbon. E_{NMVOC} refers to the emission factor of non-methane volatile organic compounds (VOCs), taken as 0.009 for biomass materials.

The emission factor of methane (E_{CH4}) is given by Eq. (13).

$$E_{CH4} = \frac{MM_{CH4}}{MM_C} \bullet E_c \bullet C_{CH4-C} \tag{13}$$

where MM_{CH4} and MM_C are the molar masses of methane and carbon. $C_{CH4\text{-}C}$, which is the carbon fraction emitted as CH_4 in combustion processes, is 0.005 for biomasses.

The emission factor of nitrogen oxide (E_{NOx}) is given by Eq. (14).

$$E_{NOx} = \frac{MM_{NOx}}{MM_N} \bullet E_c \bullet \frac{N}{C} \bullet N_{NOx-N} \tag{14}$$

where MM_{NO_2} and MM_N represent the molar masses of nitrogen dioxide and nitrogen. N and C denote the elemental mass fractions of nitrogen and carbon. The $N_{NOx\text{-}N}$ ratio indicates the proportion of nitrogen released as NO_x during combustion, taken as 0.122 for biomass fuels.

The emission factor of sulfur dioxide (E_{SO2}) is given by Eq. (15).

$$E_{SO2} = \frac{MM_{SO2}}{MM_S} \bullet \frac{S}{100} \tag{15}$$

where MM_{SO2} and MM_S are the molar masses of sulfur dioxide and sulfur and S represents the sulfur fraction in biomass combustion.

3. Results and discussion

3.1. Combustion results

Table 2 gathers the results of the proximate analysis for both components of the *CS* plant (stems and leaves), including total ash content at different MC: at harvest, after intermediate drying, and after approximately 30 days of natural drying. As expected, both the HHV and LHV on a wet basis were strongly influenced by MC, increasing more than fourfold between the highest and lowest MC in the case of leaves. This high moisture content after harvesting is consistent with values reported in the literature for similar biomasses. For example, (Eufrade-Junior et al., 2020) reported moisture contents ranging from 46 % to 48 % for *Eucalyptus urophylla*, while (Bentini and Mantelli, 2013) documented values of 66 % for sorghum, 23 % for switchgrass, and 41 % for giant reed. There is a negative correlation between moisture content and combustion efficiency. Higher moisture levels hinder ignition and delay the onset of combustion, causing a quicker and more direct transition to flameless combustion (Lai et al., 2024). This would justify the need for natural pre-drying prior to compaction for transportation.

In terms of MC, the LHV of *CS* leaves obtained in this study was comparable to that reported by (Pérez et al., 2021) (16.7 versus 17.7 MJ kg^{-1}), whereas the LHV for stems was lower (15.11 versus 18.00 MJ kg^{-1}). This difference may be attributed to differences in methodology; (Pérez et al., 2021) calculated the LHV analytically based on elemental composition, while in this study, it was determined experimentally. Ash content, a parameter that negatively impacts fuel quality, was found to be higher in leaves (4.40 %) than in stems (2.45 %). The ash content of CS stems aligns closely with the value reported by (Pérez et al., 2021) (2.50 %). However, the ash content of the leaves was lower than that reported by (Pérez et al., 2021) (4.40 % versus 7.50 %), and more consistent with the values reported by (Lanning and Eleuterius, 1989). This difference may stem from the growing conditions; both this study and that of Lanning and Eleuterius were conducted in natural environments with abundant resources, whereas (Pérez et al., 2021) collected

Table 2
Proximate analysis for both components of the *CS* plant (stems and leaves) and the total ash content at different MC.

	MC (%)		HHV (wet basis) (MJ kg^{-1})		HHV (dry basis) (MJ kg^{-1})	LHV (wet basis) (MJ kg^{-1})	Ash content (dry basis) (%)		Bulk density (kg m^{-3})	
	Average	Std dev	Average	Std dev	Average	Average	Average	Std dev	Average	Std dev
Leaves	54.61	±4,20	8.25	±0.17	18.18	6.78	4.03	±0.88	482	±19
	39.28	±3,40	10.69	±0.34	17.62	9.60	4.40	±0.71	361	±11
	5.64	±1,30	17.01	±0.12	18.02	16.73	4.35	±0.96	232	±21
Stems	54.68	±3,80	7.69	±0.22	16.97	6.21	2.94	±0,64	340	±17
	25.22	±2,90	12.43	±0.10	16.62	11.67	2.50	±0.78	218	±19
	7.21	±3,20	15.50	±0.40	16.70	15.18	2.45	±0.89	166	±15
Total waste	54.63	±5.70	8.09	±0.27	17.84	6.62	3.72	±1.10	442	±27
	35.32	±4.50	11.18	±0.36	17.33	10.18	3.86	±1.10	321	±25
	6.08	±3.50	16.58	±0.41	17.65	16.29	3.81	±1.30	214	±20

Std dev: standard deviation.

biomass from urban areas. *CS* plants growing in natural habitats typically produce more lignin and have lower silica content compared to those growing in urban setting, which may contribute to reduced ash content. The ISO 17225-4 standard for solid biofuels (International Organization for Standarization, 2021) recommends a maximum ash content of 3 %. In the present study, the ash content of *CS* leaves exceeded this threshold, whereas that of stems remained within acceptable limits. This suggests that fuel quality could be improved by harvesting during growth stages when stem biomass predominates. However, since leaves typically constitute a larger portion of the total biomass by weight, it would be advisable to co-process CS biomass with other low-ash feedstocks to ensure compliance with ash content standars. Despite not meeting the standard, the ash content of *CS* leaves remains lower than that of several other herbaceous energy crops currently used for bioenergy (Monti et al., 2008). For example, (Monti et al., 2008) reported ash contents ranging from 6.20 % in *Miscanthus sinensis x Giganteus* to 11.70 % in *Cynara cardunculus L.*, suggesting that CS still represents a comparatively cleaner biomass option.

Bulk density influences handling, storage, transportation costs and combustion efficiency (Ezzati and Mohammadi, 2024; Sanongraj et al., 2023), and is positively correlated with MC. The bulk density (dry basis) of *CS* waste was 219 kg m^{-3} for leaves and 154 kg m^{-3} for stems, resulting in an overall average of 201 kg m^{-3} for the total biomass waste. These values are consistent with those reported for similar lignocellulosic materials such as sugarcane bagasse (160 kg m^{-3} (Mythili et al., 2013) and elephant grass (230 kg m^{-3}) (Braga et al., 2017) and significantly lower than those reported for jackfruits seeds (546.80 kg m^{-3} (Alves et al., 2020). This value falls within a similar range to that reported in other studies for non-lignocellulosic residues, such as open-dump solid waste processed as refuse-derived fuel (Sanongraj et al., 2023). Additionally, bulk density influences combustion duration, with denser particles generally exhibiting longer burn times.

Bioenergy density, defined as the energy content per unit volume, is a key parameter when the logistical and economic feasibility of biofuel use is evaluated. Higher energy density implies lower transportation and storage costs and higher efficiency in energy delivery. For *CS* waste, a bioenergy density (dry basis) of 3.48 GJ m^{-3} was obtained. This value was slightly higher than those reported for comparable biomass resources, such as sugarcane bagasse (2.30 GJ m^{-3}) (Mythili et al., 2013) and elephant grass (3.29 GJ m^{-3}) (Braga et al., 2017), although lower than that obtained for jackfruit seeds (8.67 GJ m^{-3}) (Alves et al., 2020). An increase in energy density enhances the physical characteristics of the fuel for combustion and co-combustion, thereby improving energy generation efficiency (Jifara Daba and Mekuria Hailegiorgis, 2023). The results of this study indicated that *CS* waste can be effectively integrated into existing biomass supply chains to produce energy without significantly compromising energy density.

The elemental composition of the total CS waste was calculated based on the relative proportions of leaves and stems in the total waste, as determined in this study (stem weight = 0.28 × total waste weight; leaf weight = 0.73 × total waste weight). Considering the elemental composition of both stems and leaves, together with their respective proportions in the total waste, the elemental composition of the total waste was estimated. It was C (47.21 wt%), H (5.70 wt%), N (1.60 wt%), S (0.20 wt%) and O (38.30 wt%). This composition is required to determine the coefficients of the molecular formula of *CS* waste which is critical to calculate the theoretical air requirement during combustion process.

The resulting molecular formula of *CS* waste was determined to be $CH_{1.449}O_{0.608}N_{0.029}S_{0.002}$ (23.70 kg $kmol^{-1}$), being the standard enthalpy of formation of the total waste calculated from its HHV (dry basis) $\Delta H_f^0(\text{Biomass})\left(\text{kJ mol}^{-1}\right) = -148.65$. The calculated stoichiometric air–fuel ratio (SAFR) was 1.30. This ratio was considerably lower than those of conventional fossil fuels such as coal (7.10), natural gas (17.20), and gasoline (14.70) (Nussbaumer, 2003), due to a relatively low carbon, higher hydrogen and oxygen content compared to fossil fuels. The specific heat capacity, enthalpy, and exergy of the combustion gases were determined to be 1.40 kJ·kg^{-1} K^{-1}, 1427.10 kJ·kg^{-1} - flue gas, and 518.27 kJ·kg^{-1} - flue gas, respectively. The obtained values are slightly higher than those reported for lignite coal (Coskun et al., 2009). This can be attributed to the assumption of an almost dry moisture content in the *CS* residues and to differences in the elemental composition of the fuels.

3.1.1. Fuel Value Index (FVI)

Fig. 4A illustrates the variation of FVI as a function of MC. No significant differences in FVI were detected between stems and leaves at any MC level. Considering the leaf-to-stem ratio obtained in this study, the FVI of the total *CS* waste ranged from 14 MJ m^{-3} at maximum MC to 154 MJ m^{-3} at minimum MC, highlighting the significant influence of MC on the fuel quality. These findings demonstrate the highly beneficial effect of in-field drying in improving the combustibility of *CS* waste. Further research could assess seasonal fluctuations in MC to identify the most suitable harvest period.

The FVI values obtained for CS waste were comparable to those found for shrub biomass used as fuelwood (Cardoso et al., 2015), suggesting that CS waste exhibits acceptable quality for its use as a renewable bioenergy feedstock.

3.1.2. Theoretical adiabatic flame temperature (AFT)

Contrary to common perception, calorific value alone does not determine fuel quality. The theoretical maximum efficiency of a power cycle is governed by Carnot's principle, which depends on the temperature gradient between a maximum temperature (AFT) and a minimum temperature (ambient temperature). As indicated by (Eq. (10)), higher AFT leads to improved thermal efficiency. The AFT is influenced by both the composition of the fuel and its calorific value, as the composition determines the theoretical air requirement for combustion, as explained above.

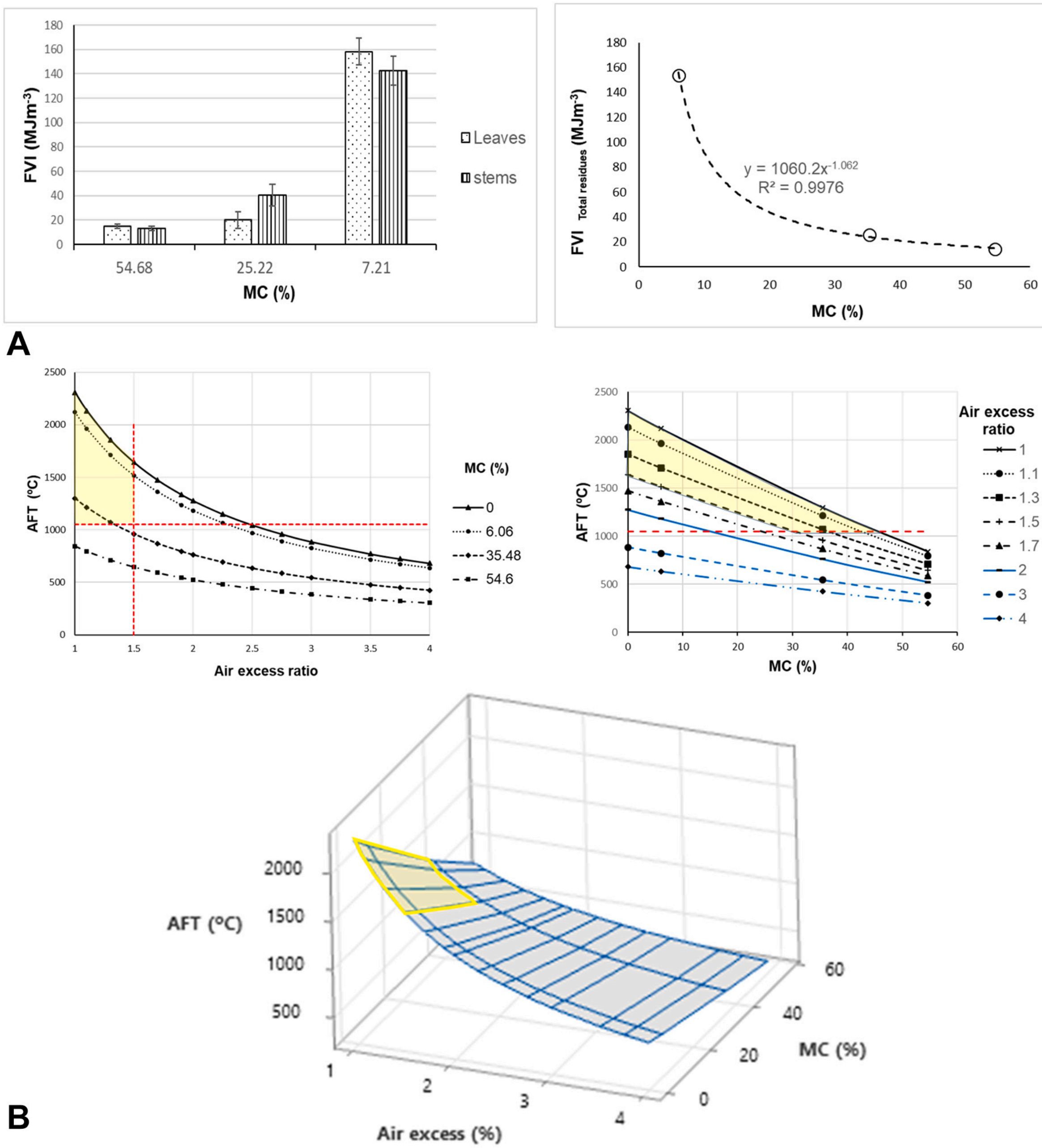

Fig. 4. Combustión results; (A), Effect of MC on the FVI of *CS* waste; (B) Variation of AFT vs excess air in combustion and MC of the *CS* waste.

$$\eta_c = 1 - \frac{T_2}{T_1} = 1 - \frac{T_2}{AFT} \quad (10)$$

where T_1 and T_2 are maximum (AFT) and minimum temperature respectively between at which the power cycle operates.

In practical biomass combustion systems, excess air is typically employed to ensure complete combustion. However, the results gathered in Fig. 4B show that AFT decreased with increasing levels of excess air and increasing MC of *CS* waste. The AFT values ranged from 2307 °C at 0 % MC and 0 % excess air (stoichiometric conditions) to a minimum of 306 °C at 54.60 % MC and 300 % excess air. These values are consistent with those reported for other biomass types. The results revealed a higher negative influence of excess air on the AFT at lower MC. For completely dry biomass (MC = 0 %), the AFT dropped from 2307 °C to 682 °C, whereas for the maximum MC (54.60 %) it varied from 843 °C to 306 °C for minimum and maximum excess air, respectively. This implied a difference of 1626 °C and 537 °C respectively, thus the absence of moisture tripled the effect of excess air on AFT. Similar trends have been also observed in other studies (Ditl and Šulc, 2024).

Moisture content also had a significant negative effect on the AFT. At a constant excess air ratio of 1.50, the AFT decreased from 1641 °C at 0 % MC to 645 °C at 54.60 % MC. Similar trends have been reported in the literature, where increasing MC reduces AFT and destabilizing the combustion process (Nhuchhen et al., 2018). In fact, some studies have considered the addition of auxiliary fuels, such as natural gas, when biomass MC exceeds 60 %, in order to maintain combustion stability.

AFT is also a key parameter influencing NO_x emissions (Glaude et al., 2010). According to (Pershing and Wendt, 1971) when AFT is below 2480 K, approximately 75 % of NO_x emissions originate from the fuel bound nitrogen. This proportion increased by about 10 % when AFT rises to 2580 K. In this case, all AFT values remained below 2580 K, indicating that most NO_x emissions (75 %) would stem from the nitrogen content of the *CS* waste itself. The nitrogen content of *CS* leaves is relatively high (1.60 %) compared to that of stems (0.60 %). However, due to the higher mass proportion of leaves in the total biomass, the overall nitrogen content of *CS* waste is higher than in other feedstocks (Alves et al., 2020). This suggests that blending *CS* waste with other high nitrogen fuels would not effectively reduce NO_x emissions. In the work developed by (Al Omari et al., 2019) it was reported that there was an increase in CO emissions as AFT decreased. This suggests that both high MC and high excess air during combustion promote incomplete combustion and elevated CO emissions.

To achieve high combustion efficiency with minimal unburned pollutant concentrations to nearly zero, the optimal operation conditions are low excess air levels (less than 1.50) and high combustion temperatures (Nussbaumer, 2003).

The minimum flame temperatures in biomass power plants using agricultural and forestry waste range from 900 to 1200 °C (J. Werther et al., 2000) assuming an average temperature of 1050 °C, a performance region (Fig. 4B, yellow area) can be defined in which both energy efficiency and emissions are optimized. According to the results of this study, achieving this temperature threshold would require the *CS* waste to have a moisture content below 31.70 %.

On the other hand, AFT decreases with ash content since the ash content is lower in stems (Table 2), a higher proportion of stems in the *CS* waste would result in higher AFT values. Consequently, the optimization of the harvesting period to maximize the proportion of stems could be beneficial to improve fuel quality and combustion performance of *CS* waste.

3.2. Biomass and energy yield

Table 3 displays the biomass yield results obtained for *CS*. In this study, the estimated average biomass yield was 10.21 ± 1.22 Mg ha^{-1} yr^{-1} (dry matter). This result falls within the range reported in the literature for herbaceous energy crops. For example, in Mediterranean environments, average dry matter yields of 14 Mg ha^{-1} yr^{-1} have been exhibited for *Cynara Cardunculus* in Spain and Italy, respectively (Gominho et al., 2018). In Poland, *Helianthus salicifolius* and various grass genotypes yielded 9.10 Mg ha^{-1} yr^{-1} under annual fertilization. Other studies conducted in the USA and the Mediterranean area obtained biomass yields of 14–15 Mg ha^{-1} yr^{-1} dry matter for *Miscanthus x giganteus*, which exceed the yield found in this work (Burner et al., 2015; Monti et al., 2015). In Brazil, *Mimosa scabrella* and *Ateleia glazioviana* yielded 18.60 and 5.10 Mg ha^{-1} yr^{-1}, respectively (Schwerz et al., 2020). These variations are due not only to species differences, but also to local soil and climatic conditions. *CS* is a species with significant potential for biomass production under the conditions of this study and it could be used as a complementary resource to other established energy crops. Biomass yield is highly influenced by factors such as soil characteristics, environmental conditions, fertilization, herbicides, irrigation, pests and diseases pressure, genotypic variability, harvest timing, location, etc., so average yield values can differ significantly between locations. These significant yield variations of the same species of short rotation energy crops in studies conducted in different places and conditions are gathered in the scientific literature. For example, some authors report average yields ranging from 10.60 Mg ha^{-1} yr^{-1} to 4.20 Mg ha^{-1} yr^{-1}, both for *Salix* spp. on a dry matter basis (Rosso et al., 2013). These findings highlight the need for further studies across various environments and management regimes (fertilization, climate, etc.) to better understand the *CS* biomass yield.

Table 3
Comparison of the biomass yield of *CS* with other species used for energy generation purposes.

Sample	Annual biomass yield (Mg ha^{-1} yr^{-1} dry matter).	Referencia
Cortaderia Selloana	10.21	Present study
Cynara cardunculus	14	(Fernández et al., 2005; Gominho et al., 2018)
Miscanthus x giganteus	14–15	(Burner et al., 2015; Dierking et al., 2016; Monti et al., 2015)
Miscanthus sacchariflorus	9.10	(Stolarski et al., 2018)
Mimosa scabrella	18.60	(Schwerz et al., 2020)
Ateleia glazioviana	5.10	(Schwerz et al., 2020)
Salix spp	10.60–4.20	(Rosso et al., 2013)

The use of *CS* waste as a renewable energy source could be particularly advantageous in Mediterranean climates with mild winters, where low temperatures are the primary challenge for their growth. Furthermore, the utilization of *CS* for energy production would reduce the need for herbicides used for its control, thereby mitigating the negative impact of these substances on the environment. The stem/total plant mass ratio found was 0.28, meaning that 72 % of the biomass consisted of leaves and 28 % of stems. This ratio is subject to variation depending on the plant's stage at the time of harvest. For example, plants of *CS* harvested before flowering will have a significantly lower stem proportion, while harvesting during flowering results in ratios similar to those observed in this study.

The average annual bioenergy yield obtained for the total *CS* waste varied from 133 GJ ha^{-1} yr^{-1} to 166 GJ ha^{-1} yr^{-1} for fresh and dry biomass respectively. Considering a 25 % electrical conversion efficiency for a Rankine cycle-based power plant, this translates into an installed power potential of 1.10 to 1.30 kW ha^{-1} r. These energy yield values are within the range (from 137 to 175 GJ ha^{-1} yr^{-1} for fresh biomass) found for herbaceous species in Poland (Stolarski et al., 2018). In Italy, significantly higher energy yields were achieved (from 500 to 1400 GJ ha^{-1} yr^{-1} on a dry basis) for different species of *Cynara cardunculus* under three different fertilization regimes (Ierna et al., 2012). In Lithuania, values close to 300 GJ ha^{-1} yr^{-1} for *Miscanthus gigantica* were reported. These differences can be partly attributed to species specific productivity and the influence of intensive fertilization practices in those regions.

3.3. Economic and environmental assessment

Fig. 5 shows the annual per-hectare costs associated with *CS* control and the revenues from electricity sales, based on the average electricity price for the last 12 years. The consumer price index was applied to adjust all prices to current values. From an economic perspective, the most cost-effective treatment was T3. As expected, variations in electricity market prices have a significant impact on economic viability. Higher revenues from energy sales were recorded in 2021 and 2022, with values of €943 and 1457 per hectare, respectively. These peaks correspond to elevated energy prices driven by the surge in natural gas prices because of the conflict in Ukraine. Only during these two years, the revenues from electricity sales exceeded the costs of the T3 treatment (Mechanized scraping). Generally, electricity revenues from *CS* waste were lower than the control costs in 10 out of the 12 years analyzed. However, its use would help to reduce these costs, making *CS* waste a potential renewable energy source, and under favorable geopolitical or market scenarios, revenues may exceed costs. If the average electricity prices fluctuate by ±20 %, treatment T3 remains the only option capable of covering its costs with revenues from electricity sales generated by *CS* residues during the period from 2021 to 2023. Only under a maximum selling price would the costs associated with T2, T3, and T4 be amortized during the same period (Fig. 5). Therefore, treatment T3 is the most economically advisable option. Nevertheless, the valorization of the residues will, in any case, help offset the costs associated with controlling this invasive species.

Table 4 gathers the relationship between average electricity sales revenue and the cost of each treatment during the study period. Depending on the control method, electricity sales could cover between 7.11 % and 48.26 % of the incurred costs, highlighting the economic advantage of utilizing *CS* waste for energy generation.

Table 5 summarizes the fossil fuel volume equivalent per cubic meter

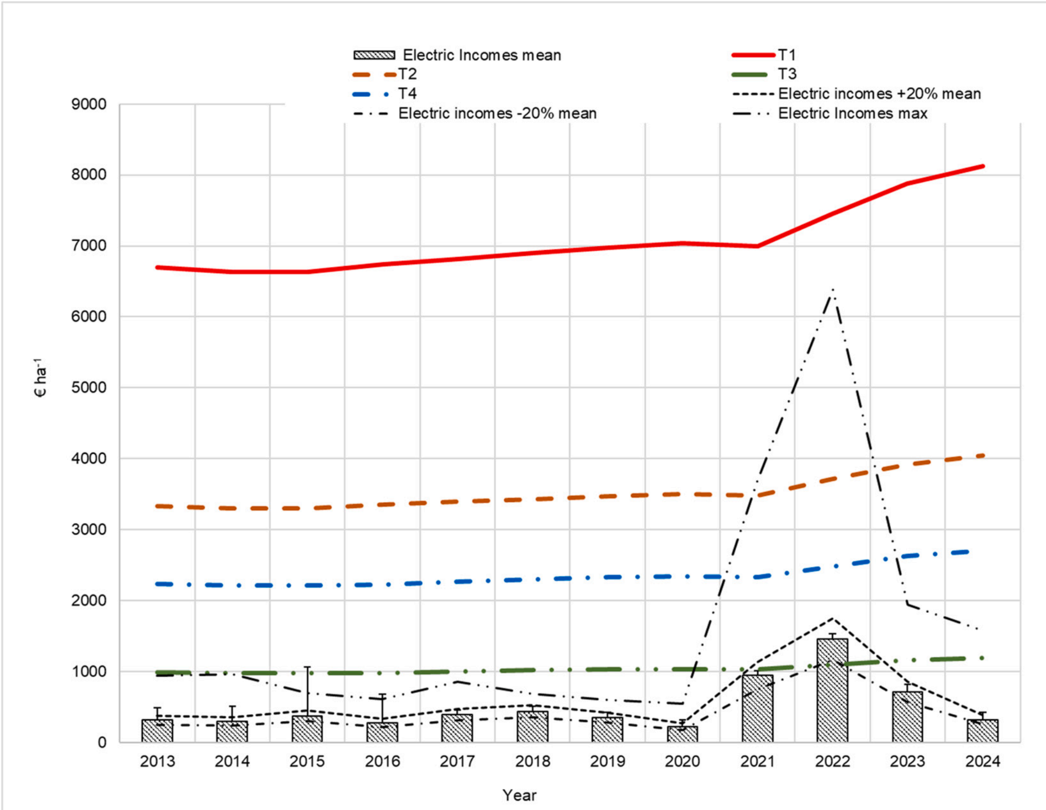

Fig. 5. Costs of each *CS* control treatment versus electricity sales income.

Table 4
Percentage relationship between average electricity sales revenue and control costs.

Year	T1	T2	T3	T4
2013	4.74	9.53	32.19	14.22
2014	4.49	9.02	30.49	13.47
2015	5.63	11.31	38.23	16.89
2016	4.09	8.21	28.06	12.40
2017	5.75	11.54	39.00	17.24
2018	6.35	12.76	43.13	19.06
2019	5.01	10.06	33.98	15.02
2020	3.16	6.36	21.48	9.49
2021	13.47	27.07	91.46	40.42
2022	19.55	39.26	132.66	58.63
2023	9.06	18.20	61.48	27.17
2024	3.97	7.98	26.96	11.92
Average ± Std dev	7.11 ± 4.61	14.27 ± 9.26	48.26 ± 31.27	21.33 ± 13.32

Std: standard deviation.

of *CS* waste and the estimated CO_2 sequestration per cubic meter of *CS* waste. These values are slightly higher than those reported for other biomasses such as rice husk, sugarcane bagasse, maize waste, and bamboo waste (Protásio et al., 2013), but lower than those for coffee waste and jackfruit seeds (Alves et al., 2020). A similar trend was observed for CO_2 sequestration, as they are derived from the fossil fuel volume equivalent. It can be concluded that mixing *CS* waste with other biomasses would not significantly alter the CO_2 emissions, supporting its feasibility as a complementary feedstock. Substituting fossil fuels (especially diesel and fuel oil in boilers) with *CS* waste would help reduce CO_2 emissions, thereby improving environmental outcomes.

While many studies do not account for combustion-related emissions when evaluating biomass fuel quality due to the assumption of carbon neutrality, this assumption has been increasingly challenged. However, some authors argue that the concept of zero emissions does not align with reality (Maj, 2018). In this context, it is believed that an analysis of the emissions generated during the combustion of *CS* waste would provide a more accurate basis to determine the suitability of their valorization through combustion. Table 6 presents estimated emissions produced during the combustion of *CS* waste, based on its elemental composition.

Overall, the emission levels from the combustion of *CS* waste were

Table 5
Fossil fuel volume equivalence and potential CO_2 sequestration of CS waste and others biomass waste.

	Equivalent volume (Liter fossil/m^3 waste)				Potential CO_2 capture (kg CO_2)				Reference
Feedstocks	Petroleum	Diesel oil	Fuel oil	Gasoline	Petroleum	Diesel oil	Fuel oil	Gasoline	
CS waste	94.05	96.02	87.22	106.76	322.59	338.95	256.42	420.65	This work
Coffee waste	119.10	121.57	113.43	135.20	408.51	429.15	324.67	532.67	(Protásio et al., 2013)
Sugarcane bagasse	48.60	49.52	45.07	56.18	166.72	175.15	132.51	217.40	(Protásio et al., 2013)
Maize waste	76.95	78.55	71.35	87.35	263.98	277.27	209.76	344.15	(Protásio et al., 2013)
Bamboo waste	74.94	76.30	69.49	85.07	257.05	270.04	204.29	385.18	(Protásio et al., 2013)
Jackfruit seed	234.18	239.05	217.14	265.82	803.84	843.84	638.39	1047.35	(Alves et al., 2020)

Table 6
Emission factors of *CS* waste versus other feedstocks.

Feedstocks	Emission factors (kg ton^{-1})				Reference
	E_{CO}	E_{CO2}	E_{NOX}	E_{SO2}	
CS waste	58.16	1345.67	5.64	3.89	This work
Larch needles	56.34	1379.53	3.20	0.18	(Maj, 2018)
Anthracite coal	82.01	1969.00	4.09	5.20	(Maj, 2018)
Wheat straw	50.57	1238.24	1.83	0.14	(Maj, 2018)
Rapeseed pods	48.33	1183.53	2.16	0.21	(Maj, 2018)
Jackfruit seed	51.46	1232.43	8.71	0.11	(Alves et al., 2020)
Oat grain	50.38	1262.98	5.39	0.16	(Maj, 2018)
Buriti husks	50.93	1236.58	3.32	–	(da Silva et al., 2023)
Buriti pits	50.61	1244.43	3.95	–	(da Silva et al., 2023)

slightly higher than those from other agroforest biomass (Table 6), particularly regarding SO_2 and NO_x. The level of NO_x emissions (5.64 kg ton^{-1}) was high and comparable to that of oat grain and buriti wastes, but lower than that of jackfruit seed (8.71 kg ton^{-1}). This may be attributed to the higher nitrogen content in *CS* wastes compared to other types of biomass. *CS* leaves contain 2.6 times more nitrogen than stems; therefore, the higher the proportion of stems, the lower the nitrogen content of the residue and, consequently, the lower the NO_x emissions. Nitrogen content can vary depending on soil fertility where the plants grow, so when residues from multiple sources are mixed, the overall nitrogen concentration of the residue may be altered. To mitigate NO_x emissions, biomass-related strategies could be employed 1) Harvesting *CS* plants in spring–summer, when stems are not yet fully developed, would have a negative impact, whereas harvesting in winter would be beneficial because the proportion of stems is higher. In addition, nitrogen concentration in leaves varies seasonally according to the vegetative stage of the plant. Harvesting in autumn–winter would therefore result in lower nitrogen content in the total residue, further reducing NO_x emissions, 2) Blending with other types of biomass with lower nitrogen content, as shown in Table 5, would help reduce NO_x emissions, 3) Leave the harvested residues in the field for a period to enable natural, cost-free leaching of nitrogen-containing compounds, reducing NO_x emissions.

Other tools, such as flue gas treatment, urea or NH_3 injection in high-temperature zones (~1000 °C), or the use of catalysts, are expensive and not applicable to these residues due to scalability issues, since in most cases they represent only a portion of a biomass mixture used to feed the plant.

As a positive aspect, the high nitrogen concentration in CS waste could be advantageous for its potential use as a soil fertilizer. In comparison to anthracite coal, *CS* waste combustion produced lower CO, CO_2, and SO_2 emissions, due to the higher carbon and sulfur content in coal. This implies that co-combustion of anthracite coal and *CS* waste may reduce CO, CO_2, and SO_2 emissions but increase NO_x emissions, which could contribute to acid rain formation. Interestingly, this finding contrasts with the widely held view that biomass co-firing reduces NO_x and SO_2 emissions, based on the lower nitrogen and sulfur content of biomass compared to coal, which shows a consistent trend across different experimental furnaces (Liu et al., 2021). A potential solution would be to blend *CS* waste with low-nitrogen coals (high quality coals) to minimize NO_x emissions during bioenergy production.

It is also essential to assess emissions within a life cycle framework, accounting for all stages from waste generation to its delivery at the power plant. For this reason, it should be noted that the emissions associated with harvesting *CS* waste should not be attributed to bioenergy production, as these activities are related to invasive species control and would occur regardless of energy valorization.

The industrial-scale application of alternative thermochemical processes, such as pyrolysis, for the valorization of CS residues could provide significant advantages in terms of emission reduction—particularly NO_x—due to the oxygen-free operating conditions. However, the substantial capital investment and the energy requirements involved in post-processing the resulting bioproducts may undermine the overall CO_2 neutrality of the process. In contrast, blending these residues with others of lower nitrogen content prior to direct combustion could help mitigate this drawback, offering a more practical short-term approach. Moreover, biomass combustion plants for forest residues are currently widespread, making the integration of residues with similar characteristics highly feasible. Given the homogeneity of CS residues, another potential valorization route would be pelletization. However, this process would require reducing the moisture content below 10 % to ensure storage without microbial degradation (Gao et al., 2021). Such drying would entail significant energy consumption, resulting in increased costs associated with processing prior to their final use as fuel.

The findings of this study could help reduce fossil fuel consumption and improve quality of life by lowering CO_2 emissions, since the carbon released was previously captured by the plants. Additionally, this approach contributes to lowering the management costs of an invasive species that threatens native ecosystems.

4. Conclusions

This study investigated the valorization of waste generated during the control of the invasive species *Cortaderia selloana* (pampas grass) as a potential feedstock for bioenergy production via combustion in power plants. The waste generated from the control of *CS* has physicochemical characteristics compatible with direct combustion applications. Variables such as biomass calorific value, bulk density, ash content, adiabatic flame temperature (AFT), and fuel value index (FVI) were comparable to those of conventional energy crops commonly used in bioenergy production. Moisture content (MC) was identified as a critical factor, as it negatively affects energy efficiency and increases unburned pollutants. The biomass yield and its calorific value generated an average energy yield of 166 GJ ha^{-1} yr^{-1}, comparable to energy crops currently used for bioenergy production. Economic assessment indicated that electricity revenues from *CS* waste combustion could partially offset and under certain market conditions, even exceed the cost associated with invasive species control. From an environmental perspective, *CS* waste combustion generated lower emissions of CO (decrease: 29.08 %), CO_2 (decrease: 31.69 %), and SO_2 (decrease: 25.19 %) compared to anthracite coal, although NO_x emissions were higher (increase: 27.48 %). These results suggest that, despite its NO_x output, *CS* waste represents a cleaner alternative to fossil fuels. The combustion of *CS* waste for bioenergy production, in addition to reducing emissions, would eliminate the need for chemical treatments to control *CS*, resulting in a dual positive environmental impact.

This study introduces a sustainable approach to valorize invasive *CS* by converting its waste into bioenergy. It provides novel experimental data on biomass yield, energy output, and emissions, while assessing economic feasibility and environmental impact. The work integrates energy production with invasive species management, offering a practical and eco-friendly solution aligned with circular economy principles.

The limitations of this study are related to the variability in the production of these waste, which depends on the soil quality where the plants grow. This could be improved by developing a database of productivities from different stands, which would allow for a more accurate quantification of the amount of waste generated. Future research should focus on valorizing these residues through alternative thermochemical processes that transform them into high value-added products and on characterizing these products, in accordance with market demands.

CRediT authorship contribution statement

S. Pérez: Methodology, Investigation, Funding acquisition, Conceptualization. **J. Fernandez-Ferreras:** Supervision, Resources, Funding acquisition, Formal analysis, Data curation. **I. Fernandez:** Writing – original draft, Validation, Methodology, Formal analysis.

Funding

This research was funded by Solvay, under projects 3399 and 3824, EUROPEAN COMMISSION, Marie Sklodowska-Curie Actions—RISE, grant number 101007733 (CELISE project) and Government of Cantabria “Bridge Projects 2023” (PID2022-138142OB-I00).

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

No data was used for the research described in the article.

References

Al Omari, S.A.B., Hamdan, M.O., Selim, M.Y., Elnajjar, E., 2019. Combustion of jojoba-oil/diesel blends in a small-scale furnace. Renew. Energy 131, 678–688. https://doi.org/10.1016/j.renene.2018.07.009.

Alves, J.L.F., da Silva, J.C.G., Mumbach, G.D., Domenico, M. Di, da Silva Filho, V.F., de Sena, R.F., Machado, R.A.F., Marangoni, C., 2020. Insights into the bioenergy potential of jackfruit wastes considering their physicochemical properties, bioenergy indicators, combustion behaviors, and emission characteristics. Renew. Energy 155, 1328–1338. https://doi.org/10.1016/j.renene.2020.04.025.

Anyaoha, K.E., 2022. Synergistic perspective on biomass co-utilization in thermo-chemical processes. Bioresour. Technol. Rep. https://doi.org/10.1016/j.biteb.2022.101043.

Bentini, M., Mantelli, R., 2013. Prototype for the harvesting of cultivated herbaceous energy crops an economic and technical evaluation. Biomass Bioenergy 57, 229–237. https://doi.org/10.1016/j.biombioe.2013.07.008.

Braga, R.M., Melo, D.M.A., Sobrinho, E.V., Barros, J.M.F., Melo, M.A.F., Carvalho, A.F. M., do Socorro B Fontes, M., Freitas, J.C.O., 2017. Catalytic upgrading of Elephant grass (*Pennisetum purpureum Schum*) pyrolysis vapor using WO3 supported on RHA and RHA-MCM-41. Catal. Today 279, 224–232. https://doi.org/10.1016/j.cattod.2016.06.003.

Burner, D.M., Hale, A.L., Carver, P., Pote, D.H., Fritschi, F.B., 2015. Biomass yield comparisons of giant miscanthus, giant reed, and mischane grown under irrigated and rainfed conditions. Ind. Crop. Prod. 76, 1025–1032. https://doi.org/10.1016/j.indcrop.2015.07.071.

Cardoso, M.B., Ladio, A.H., Dutrus, S.M., Lozada, M., 2015. Preference and calorific value of fuelwood species in rural populations in northwestern Patagonia. Biomass Bioenergy 81, 514–520. https://doi.org/10.1016/j.biombioe.2015.08.003.

Coskun, C., Oktay, Z., Ilten, N., 2009. A new approach for simplifying the calculation of flue gas specific heat and specific exergy value depending on fuel composition. Energy 34, 1898–1902. https://doi.org/10.1016/j.energy.2009.07.040.

Daverey, A., Pandey, D., Verma, P., Verma, S., Shah, V., Dutta, K., Arunachalam, K., 2019. Recent advances in energy efficient biological treatment of municipal wastewater. Bioresour. Technol. Rep. 7. https://doi.org/10.1016/j.biteb.2019.100252.

Dierking, R.M., Allen, D.J., Brouder, S.M., Volenec, J.J., 2016. Yield, biomass composition, and N use efficiency during establishment of four *Miscanthus* × *giganteus* genotypes as influenced by N management. Biomass Bioenergy 91, 98–107. https://doi.org/10.1016/j.biombioe.2016.05.005.

Ditl, P., Šulc, R., 2024. Calculations of CO_2 emission and combustion efficiency for various fuels. Energy 290. https://doi.org/10.1016/j.energy.2023.130044.

Domènech, R., Vilà, M., 2007. *Cortaderia selloana* invasion across a Mediterranean coastal strip. Acta Oecol. 32, 255–261. https://doi.org/10.1016/j.actao.2007.05.006.

Eufrade-Junior, H., Leonello, E., Guerra, S., 2020. Stump and coarse root biomass from eucalypt forest plantations in a commercial-scale operation for bioenergy. Biomass Bioenergy 142, 105784. https://doi.org/10.1016/j.biombioe.2020.105784.

Ezzati, S., Mohammadi, J., 2024. A decision support model for planning of spatial large extent biomass to bioenergy procurement network. Bioresour. Technol. Rep. 27. https://doi.org/10.1016/j.biteb.2024.101886.

Fernández, J., Hidalgo, M., del Monte, J.P., 2005. *Cynara cardunculus l.* as a perennial crop for non-irrigated lands: yields and applications. Acta Hortic. 681, 109–116. https://doi.org/10.17660/ActaHortic.2005.681.10.

Gao, C., Sulong, Z., Nan A., Hongming, N., Huan Y., Chengbo, G., 2021. Comprehensive comparison of multiple renewable power generation methods: a combination analysis of life cycle assessment and ecological footprint. Renew. Sust. Energ. Rev. 147, 111255. https://doi.org/10.1016/j.rser.2021.111255.

Glaude, P.A., Fournet, R., Bounaceur, R., Molière, M., 2010. Adiabatic flame temperature from biofuels and fossil fuels and derived effect on NOx emissions. Fuel Process. Technol. 91, 229–235. https://doi.org/10.1016/j.fuproc.2009.10.002.

Gominho, J., Curt, M.D., Lourenço, A., Fernández, J., Pereira, H., 2018. *Cynara cardunculus L.* as a biomass and multi-purpose crop: a review of 30 years of research. Biomass Bioenergy. https://doi.org/10.1016/j.biombioe.2018.01.001.

Ierna, A., Mauro, R.P., Mauromicale, G., 2012. Biomass, grain and energy yield in *Cynara cardunculus L.* as affected by fertilization, genotype and harvest time. Biomass Bioenergy 36, 404–410. https://doi.org/10.1016/j.biombioe.2011.11.013.

International Organization for Standardization, 2017a. ISO 18134-2 Solid Biofuels — Determination of Moisture Content — Oven Dry Method.

International Organization for Standardization, 2017b. ISO 18125 Solid Biofuels — Determination of Calorific Value.

International Organization for Standardization, 2022. ISO 18122 Solid Biofuels — Determination of Ash Content.

International Organization for Standardization, 2025. ISO 17828 Solid Biofuels — Determination of Bulk Density.

International Organization for Standarization, 2021. ISO 17225-4 Solid Biofuels — Fuel Specifications and Classes —Graded Wood Chips.

Jifara Daba, B., Mekuria Hailegiorgis, S., 2023. Torrefaction of corncob and khat stem biomass to enhance the energy content of the solid biomass and parametric optimization. Bioresour. Technol. Rep. 21. https://doi.org/10.1016/j.biteb.2023.101381.

Lai, Y., Liu, X., Davies, M., Fisk, C., Holliday, M., King, D., Zhang, Y., Willmott, J., 2024. Characterisation of wood combustion and emission under varying moisture contents using multiple imaging techniques. Fuel 373, 132397. https://doi.org/10.1016/j.fuel.2024.132397.

Lanning, F.C., Eleuterius, L.N., 1989. Silica deposition in some C3 and C4 species of grasses, sedges and composites in the USA. Ann. Bot. 64, 395–410.

Liu, Q., Zhong, W., Tang, R., Yu, H., Gu, J., Zhou, G., Yu, A., 2021. Experimental tests on co-firing coal and biomass waste fuels in a fluidised bed under oxy-fuel combustion. Fuel 286. https://doi.org/10.1016/j.fuel.2020.119312.

Maj, G., 2018. Emission factors and energy properties of agro and forest biomass in aspect of sustainability of energy sector. Energies (Basel) 11. https://doi.org/10.3390/en11061516.

Ministry for Ecological Transition and the Demographic Challenge, 2025. Strategy for the management, control and possible eradication of Pampas Grass (*Cortaderia selloana*) and other *Cortaderia* species. https://www.miteco.gob.es/es/biodiversidad/publicaciones/pbl_fauna_flora_estrategia_cortaderia.html.

Monti, A., Di Virgilio, N., Venturi, G., 2008. Mineral composition and ash content of six major energy crops. Biomass Bioenergy 32, 216–223. https://doi.org/10.1016/j.biombioe.2007.09.012.

Monti, A., Zanetti, F., Scordia, D., Testa, G., Cosentino, S.L., 2015. What to harvest when? Autumn, winter, annual and biennial harvesting of giant reed, miscanthus and switchgrass in northern and southern Mediterranean area. Ind. Crop. Prod. 75, 129–134. https://doi.org/10.1016/j.indcrop.2015.06.025.

Mythili, R., Venkatachalam, P., Subramanian, P., Uma, D., 2013. Characterization of bioresidues for biooil production through pyrolysis. Bioresour. Technol. 138, 71–78. https://doi.org/10.1016/j.biortech.2013.03.161.

Nhuchhen, D.R., Afzal, M.T., Dreise, T., Salema, A.A., 2018. Characteristics of biochar and bio-oil produced from wood pellets pyrolysis using a bench scale fixed bed, microwave reactor. Biomass Bioenergy 119, 293–303. https://doi.org/10.1016/j.biombioe.2018.09.035.

Nussbaumer, T., 2003. Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. Energy Fuel 17, 1510–1521. https://doi.org/10.1021/ef030031q.

Pashakolaie, V.G., Gonella, S., Muhit, I.B., 2025. Integrating modern bioeconomy into macroeconomics: a comprehensive review of impacts and interactions. Bioresour. Technol. Rep. https://doi.org/10.1016/j.biteb.2025.102125.

Pegoretti Leite de Souza, H.J., Muñoz, F., Mendonça, R.T., Sáez, K., Olave, R., Segura, C., de Souza, D.P.L., de Paula Protásio, T., Rodríguez-Soalleiro, R., 2021. Influence of lignin distribution, physicochemical characteristics and microstructure on the quality of biofuel pellets made from four different types of biomass. Renew. Energy 163, 1802–1816. https://doi.org/10.1016/j.renene.2020.10.065.

Pelegrín, M., Sáez-Tovar, J.A., Andreu-Rodríguez, J., Pérez-Murcia, M.D., Martínez-Sabater, E., Marhuenda-Egea, F.C., Pérez-Espinosa, A., Bustamante, M.A., Aguló, E., Vico, A., Paredes, C., Moral, R., 2018. Composting of the invasive species Arundo donax with sewage and agri-food sludge: agronomic, economic and environmental aspects. Waste Manag. 78, 730–740. https://doi.org/10.1016/j.wasman.2018.06.029.

Pérez, A., Ruiz, B., Fuente, E., Calvo, L.F., Paniagua, S., 2021. Pyrolysis technology for *Cortaderia selloana* invasive species. Prospects in the biomass energy sector. Renew. Energy 169, 178–190. https://doi.org/10.1016/j.renene.2021.01.015.

Pershing, D.W., Wendt, J.O.L., 1971. Pulverized coal combustion: the influence of flame temperature and coal composition on thermal and fuel NO_x. In: 16th Symposium on Combustion. The Combustion Institute, Pittsburgh, PA, pp. 491–501.

Protásio, T., Bufalino, L., Tonoli, G.H., Guimarães Junior, M., Trugilho, P., Mendes, L., 2013. Brazilian lignocellulosic wastes for bioenergy production: characterization and comparison with fossil fuels. Bioresources 8, 1166–1185. https://doi.org/10.15376/biores.8.1.1166-1185.

Reyes, M., Pérez, J.F., Sastre, R., 2024. Combustion performance and flame front morphology of producer gas from a biomass gasification-based cookstove. Fuel 362. https://doi.org/10.1016/j.fuel.2023.130763.

Rodríguez, F., Lombardero-Vega, M., San Juan, L., de las Vecillas, L., Alonso, S., Morchón, E., Liendo, D., Uranga, M., Gandarillas, A., 2021. Allergenicity to worldwide invasive grass *Cortaderia selloana* as environmental risk to public health. Sci. Rep. 11. https://doi.org/10.1038/s41598-021-03581-5.

Rosso, L., Facciotto, G., Bergante, S., Vietto, L., Nervo, G., 2013. Selection and testing of *Populus* alba and Salix spp. as bioenergy feedstock: preliminary results. Appl. Energy 102, 87–92. https://doi.org/10.1016/j.apenergy.2012.07.042.

Sanongraj, S., Rattanaweerapan, T., Dechapanya, W., 2023. Production and characteristics of refuse derived fuel from open-dump solid waste. Bioresour. Technol. Rep. 22. https://doi.org/10.1016/j.biteb.2023.101448.

Schwerz, F., Neto, D.D., Caron, B.O., Nardini, C., Sgarbossa, J., Eloy, E., Behling, A., Elli, E.F., Reichardt, K., 2020. Biomass and potential energy yield of perennial woody energy crops under reduced planting spacing. Renew. Energy 153, 1238–1250. https://doi.org/10.1016/j.renene.2020.02.074.

da Silva, J.B.S., Cabral, A.A., Bezerra, G.V.P., da Cruz, N.C., Conconi, C.C., Cruz, G., 2023. Buriti (*Mauritia flexuosa L.*) wastes as potential lignocellulosic feedstock for bioenergy production: physicochemical properties, thermal behavior, and emission factors. Ind. Crop. Prod. 206. https://doi.org/10.1016/j.indcrop.2023.117689.

Spanish National Institute of Statistics, 2023. Total Greenhouse Gases in Spain. https://www.ine.es/.

Stolarski, M.J., Śnieg, M., Krzyżaniak, M., Tworkowski, J., Szczukowski, S., 2018. Short rotation coppices, grasses and other herbaceous crops: productivity and yield energy value versus 26 genotypes. Biomass Bioenergy 119, 109–120. https://doi.org/10.1016/j.biombioe.2018.09.014.

United Nations Development Programme, 2025. The SDGS in Action. https://www.undp.org/sustainable-development-goals.

Vasileiadou, A., 2025. Advancements in waste-to-energy (WtE) combustion technologies: a review of current trends and future developments. Discov. Appl. Sci. https://doi.org/10.1007/s42452-025-06907-4.

Werther, J., Saenger, M., Hartge, E.U., Ogada, T., Siagi, Z., 2000. Combustion of agricultural residues. Prog. Energy Combust. Sci. 26, 1–27.

Zhu, J., Fei, X., Yin, K., 2025. Assessment of waste-to-energy conversion technologies for biomass waste under different shared socioeconomic pathways. Energ. Environ. Sustain. 1, 100021. https://doi.org/10.1016/j.eesus.2025.100021.