



Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: <https://ijred.cbiorc.id>



Research Article

Optimization of sugarcane straw as a solid biofuel for thermochemical processes by water leaching pretreatment

Estela Assureira*  and Marco Assureira 

Department of Engineering, Pontifical Catholic University of Peru, Lima, Peru

Abstract. Sugarcane straw, an abundant agricultural waste, has considerable potential as a renewable fuel due to its energy content, sustained generation, and CO₂ neutrality but its direct utilization is limited by its high levels of ash, alkalis, S, Cl contents that cause severe slagging, fouling, and corrosion in boilers, as well as the harmful emissions released during combustion. To improve the fuel properties of sugarcane straw, a leaching pretreatment with distilled water was developed and applied to the residue under controlled conditions to evaluate the effects of water temperature, residence time and agitation of the leachate on the removal effectiveness of soluble ash-forming components. The leaching process was carried out in batches, maintaining a solid-to-liquid ratio of 1:30, and a feedstock size of 0.5–2 cm. Various combinations of temperature, residence time, and leachate agitation condition were tested to optimize the process. The optimal condition was established at 80 °C and 20 min with continuous agitation, which was applied to the residue, achieving reductions of 38.46% in ash, 78.26 in Cl, 57.14% in S, 9.09% in N, 54.61% in K₂O, and 58.22% in Na₂O, along with an increase in the high heating value, which reached 18.4 MJ/kg. These improvements reduce slagging, fouling and corrosion tendency, as indicated by lower predictive indices and higher ash fusion temperature reflected in the ternary phase diagram, and enhanced energy content. The improvements achieved make the washed sugarcane straw suitable for industrial biofuel applications, reducing issues associated with ash and emissions and providing higher energy content. The water leaching pretreatment also represents a valuable contribution since it can be easily replicated, and the upgraded residue has been valorized by being converted into a clean and sustainable fuel.

Keywords: biomass ash; fouling; slagging; sugarcane straw; water leaching.



© The author(s). Published by CBIORE. This is an open access article under the CC BY-SA license (<http://creativecommons.org/licenses/by-sa/4.0/>).

Received: 2nd July 2025; Revised: 29th Sept 2025; Accepted: 10th Oct 2025; Available online: 12th Oct 2025

1. Introduction

World population expansion, the growth of urban areas, improved living standards, and industrial development are the main factors for the increase of the demand for energy worldwide (Chandrasiri *et al.*, 2022), which is anticipated to reach 5,411.7 Mtoe by 2045 (Shahbeik *et al.*, 2024). The extensive use of fossil fuels to satisfy the energy needs caused their depletion as well as environmental damage, mainly from the high levels of CO₂ emissions generated that cause global warming (Y. Wang & Wu, 2023), and climate change, which are considered the greatest threats and challenges facing humanity in the coming decades (Rimantho *et al.*, 2023). In this scenario, the Paris Agreement, and the additional goals at COP26 are efforts to lower atmospheric emissions of greenhouse gases (Karaeva *et al.*, 2023) to limit the global temperature increase to 2 °C (K. Wang & Tester, 2023), trying to stop global warming (Kayesh & Siddiq, 2023), with urgent changes in the global energy matrix required to ensure energy security, support economic growth, and prevent health and environmental impacts (Kalak, 2023).

Growing concerns over pollution, climate change, and energy security have intensified the search for sustainable alternatives to fossil fuels promoting the use of renewable energy sources, such as biomass, to reduce greenhouse gas

emissions and mitigate global warming (Gopalakrishnan *et al.*, 2025). Currently, owing to its abundance and versatility, biomass is recognized as a strategic and viable alternative to fossil fuels (Javanmard *et al.*, 2025), providing “heat, electricity, fuels” (Alao *et al.*, 2024), and chemicals (Abelha *et al.*, 2019), and contributing to the global transition toward sustainable energy (Javanmard *et al.*, 2025), currently accounting for nearly “10% of global energy supply”, participation that is predicted to increase in the future (Vlček *et al.*, 2023). In this context, torrefaction, combustion, gasification, and pyrolysis represent the principal thermal conversion routes for the effective utilization of its energy potential. However, biomass must overcome certain limitations including its low density and higher moisture content (Dethan *et al.*, 2024), the considerable amount of oxygen it contains, its lower energy density in comparison to fossil fuels, its hydrophilic character, and easy deterioration during storage (Pestaño & Jose, 2016).

Among the various types of biomass resources agricultural waste, generated in crop fields as a result of crop harvesting or in processing plants for harvested products (Santolini *et al.*, 2021), is a potential feedstock to provide energy to industries for a number of reasons including, the large amounts generated sustainably (Ge *et al.*, 2022); the energy content (Santolini *et al.*, 2021); the fact that, as a by-product, it does not compete with land use and food production (Lebendig *et al.*, 2022); to be

* Corresponding author
Email: eassure@pucp.edu.pe (E. Assureira)

considered as a CO₂ neutral alternative for the production of energy (Alao *et al.*, 2024); and due to its contribution to the growth of a circular economy, and the transition towards a sustainable society (Abelha *et al.*, 2019), solving the issues related to its accumulation in the fields and its burning (Deb *et al.*, 2019).

In 2021, the total amount of primary crops produced worldwide was 9.49 Gt, with the most significant crops being sugarcane, corn, rice, and wheat, which together accounted for almost half of this global production. Sugarcane stands out with a contribution close to 20%, generating large amounts of straw as a residue from harvested crops (Food and Agricultural Organization (FAO), 2023), which is projected to increase due to in many countries for health and environmental reasons the traditional burning harvesting system is being replaced by mechanized harvesting (Aguiar *et al.*, 2021). Although having this material in the fields is beneficial for improving soil quality, retaining water, decreasing soil erosion, and supporting the use of less fertilizer, it may also increase pests, harm crops, and the risk of fires that release harmful emissions. Therefore, it is recommended that the amount of sugarcane straw left in the field should not exceed 12% of the total generated and consider it as a feedstock for biofuels, biomaterials and energy generation (Aguiar *et al.*, 2021).

Despite its potential as a fuel, sugarcane straw faces major challenges in energy generation, particularly slagging and fouling, which hinder heat transfer, reduce efficiency, and accelerate the deterioration of conversion systems, thereby negatively affecting boiler operation (Zlateva *et al.*, 2025). Slagging refers to molten ash deposition on reactor walls, while fouling denotes the accumulation of solid particulates on heat exchanger surfaces (Javanmard *et al.*, 2025).

As an herbaceous biomass sugarcane straw contains alkali, alkaline earth metals, and chlorides which promotes ash related issues and corrosion during combustion limiting its use (Peiris & Gunarathne, 2021). In this process, ash undergoes continuous chemical transformations (Ovčáčiková *et al.*, 2022), the original minerals melt and interact to form eutectic mixtures with lower fusion temperature (Lachman *et al.*, 2021). Due to Si has a high melting point, it would not by itself cause slagging and agglomeration but together with K it forms eutectics with a low melting point (500 °C to 700 °C), causing the aforementioned problems (Singhal *et al.*, 2021a), and the presence of S and Cl encourage alkali metals to volatilize, contributing to the issues described. Also, the use of fertilizers to improve the crop contributes to the high contents of N and S in sugarcane straw, which causes high emissions of NO_x and SO_x during its combustion (Fernández *et al.*, 2022), which is another issue to be addressed for its use as fuel.

There is a great interest in biomass pretreatment to improve its characteristics for energy generation, being considered a necessary step for using agro-waste in thermochemical conversion processes (Lebendig *et al.*, 2022). In this context, “biomass leaching, the use of mineral additives, co-combustion with other fuels, decreasing the combustion temperature, among other methods” have been applied to reduce slagging, fouling and corrosion issues when burning herbaceous biomass (Fernández *et al.*, 2022). Previous studies have shown that acid leaching effectively reduces slagging and fouling by removing alkali metals like K and Na. However, it is costly, generates environmentally problematic effluents, may degrade biomass structure and energy density, and involves safety risks in acid handling and storage. To address these drawbacks, non-chemical approaches such as water leaching have been developed as more sustainable alternatives (Javanmard *et al.*,

2025), being considered as a simple and cost-effective method used to reduce the concentrations of harmful ash-forming elements in agricultural waste and to enhance fuel quality since K, Cl, Na, and S are soluble in water (Singhal *et al.*, 2021a). This pretreatment effectively reduces slagging and fouling, preserves biomass quality, and lowers costs and reduce safety risks by avoiding hazardous chemicals and harmful effluents (Javanmard *et al.*, 2025). Also, the discarded water can be reused to irrigate the fields (Peiris & Gunarathne, 2021), and the reduced ash-related issues and emissions lead to lower boiler maintenance and additive requirements, decreasing overall operating costs (Singhal *et al.*, 2021a). The efficiency of water leaching in the reduction of ash and the removal of inconvenient constituents from agricultural wastes that cause the previously mentioned issues are “washing temperature, residence time, solid to liquid ratio, and residue size” which in turn affect the cost of the process being advisable, for industrial applications, to find the optimal conditions (Peiris & Gunarathne, 2021).

Although numerous studies have reported the use of water leaching to improve the fuel quality of various agricultural wastes, no investigations were found on its application to sugarcane straw. To address this gap, a water leaching pretreatment is proposed to improve the fuel properties of this residue by reducing ash, sulfur, chlorine, and alkali contents, while increasing the high heating value, thereby obtaining a higher-quality solid biofuel. Therefore, the objective of this study is to determine the optimal water leaching condition by analyzing various combinations of temperatures, residence times, agitation, and solid-liquid ratios. For the optimal process, the effect of its application on the combustion behavior of sugarcane straw is evaluated using fuel indices, slagging, fouling, and corrosion prediction indices, and by reinforcing slagging predictions and estimating ash fusion temperatures using ternary phase diagrams. The novelty of this work lies in the application of a controlled water leaching process to sugarcane straw, an agricultural waste for which, to the best of our knowledge, no leaching studies have been reported. This pretreatment improves its fuel properties, thereby enabling the valorization of this agricultural waste as a solid biofuel for thermochemical processes. The simplicity and replicability of the process highlight its potential for scale-up and industrial application.

2. Materials and Methods

2.1 Sample preparation and water leaching experiments

The sugarcane straw was collected after mechanized harvesting in rural areas of Piura, Peru. Figure 1 shows the conditioned feedstock prepared for subsequent analysis and pretreatment. The conditioning process involved chopping the sugarcane straw with a manual guillotine to reduce particle size, followed by sieving with a Gilson SS-15 8-inch vibratory sieve shaker to obtain particles between 0.5 and 2.0 cm in length, while



Fig. 1 Conditioned sugarcane straw (cut and sieved)

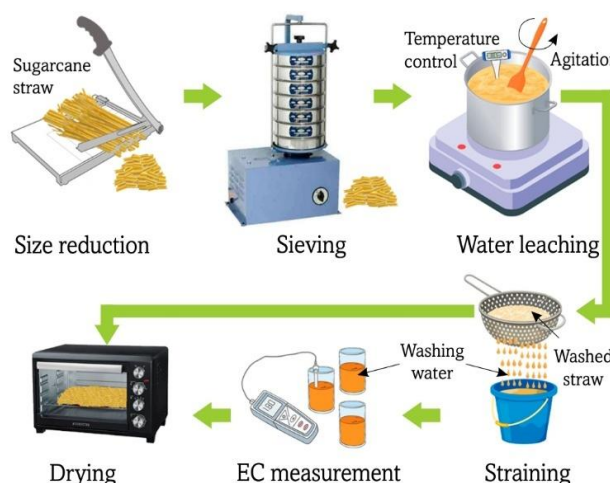


Fig. 2 Sugarcane straw water leaching process

removing fines. The resulting material was homogenized, allowed to air-dry at ambient temperature (22 °C), and stored in hermetic plastic bags for later characterization.

To improve its fuel properties for thermochemical conversion, the conditioned sugarcane straw was subjected to a water leaching pretreatment. This step aimed to reduce the content of ash-forming and problematic elements, thereby enhancing its suitability as a solid biofuel. A leaching batch process was carried out, under controlled conditions, to study the impact of water temperature, residence time, solid-to-liquid ratio (S:L) and agitation of the leachate on the reduction of ash, alkalis (K_2O and Na_2O), S and Cl contents in sugarcane straw. The leaching process was conducted in a cylindrical stainless-steel container; an electric cooker was utilized as a heat source and the temperature of the water was controlled by a HANNA HI-145-20 T digital thermometer fitted with a 300 mm stainless steel probe as shown in Figure 2. For all the experiments 100 g of sugarcane straw was submerged in 3 L of distilled water maintaining a 1:30 S:L ratio. Three temperatures were tested (20 °C, 40 °C and 80 °C), along with two residence times (10 min and 20 min) and three agitation modes (none, periodic, and continuous). In the periodic mode, the water and residue were manually stirred every five minutes for thirty seconds at a speed of about 20 rpm using a plastic paddle, and in the continuous mode the agitation was done throughout all the residence time using the same plastic paddle and keeping constant the stirring rate at about 20 rpm. By combining these factors, 18 distinct leaching conditions were performed and evaluated. For each leaching condition, the experiments were repeated three times as independent replicates yielding a total of 54 experimental runs. The order of execution of the experiments was determined by a random procedure. Each of the 54 treatments was assigned a card. All the cards were placed in a container, mixed carefully, and then randomly removed by hand, thus selecting the experiment to be performed, minimizing potential biases associated with the order of execution. In all cases, the solid-liquid ratio, as well as the other experimental conditions, were kept constant. Upon completion of each run, the washed sugarcane straw was removed from the container, drained through a strainer to eliminate excess liquid, and the resulting filtrate was collected in a separate container for subsequent analysis as shown in Figure 2.

The removal effectiveness of alkalis, Cl and S was determined indirectly by the amount of dissolved solids in the washing water, for which electrical conductivity of the leachate

(EC) was measured immediately after pretreatment using a HANNA HI 99301 conductivity meter (Figure 2). The measurements were carried out three times to obtain independent values, from which the mean and standard deviation were calculated. Since EC is directly correlated with the ionic content of the solution, the criterion for identifying the most effective washing condition was based on the EC value. A higher EC value was interpreted as indicating greater removal effectiveness; therefore, the washing process with the highest mean EC was selected as the most effective. Finally, the sugarcane straw pretreated with the leaching process selected as the most efficient was dried in an electric oven at 103 ± 2 °C, then allowed to absorb moisture for 24 h at ambient temperature, and stored in hermetic plastic bags for preservation and future analysis.

2.2 Characterization of original and washed samples

2.2.1 Proximate analysis

This analysis was used to determine the weight fraction (wt.%) of moisture (M), ash, volatile matter (VM) and fixed carbon (FC) in the samples of sugarcane straw before and after water leaching, performed according to the selected process. To quantify these parameters the procedures indicated by standards ASTM D3173, ASTM D3174, ASTM D3175 and ASTM D3172 were applied (Dethan *et al.*, 2024). The ash content was determined using a Fisher Scientific series 650-58 isothermal muffle furnace; VM was determined using a HOSKINS FA120 oven; and for the moisture content, a GRIEVE LR271 oven was used. FC was calculated by subtracting M, VM and ash contents from 100.

2.2.2 Ultimate analysis

The contents of C, H, S, and N were determined by ASTM D3178, ASTM D3177 and ASTM D3179 standards respectively. Oxygen content, was calculated as the difference between 100 and the sum of these elements including ash, expressed as wt.%. Cl content was determined according to ASTM D2361.

2.2.3 High heating value

The energy content of the samples was determined by finding the value of the high heating value (HHV) according to ASTM D5865 procedures (Ibitoye *et al.*, 2022), using a Parr Instrument 1341 oxygen bomb calorimeter. The results were expressed in MJ/kg.

2.2.4 Fuel ratio index

This index is related to the stability and duration of combustion and flame generation of the samples. It was determined as indicated in equation (1), where FC and VM of the fuel sample are expressed as wt.% on dry basis (Gajera *et al.*, 2023).

$$Fr = FC / VM \quad (1)$$

2.2.5 Active oxidation rate

The presence of S and Cl in a biomass is associated with SO_x , HCl and aerosol emissions, ash deposits and corrosion. The molar ratio $2S/Cl$ is used to predict the risk of corrosion in the boilers at high temperatures (active oxidation) when using biomass as fuel, and is determined by equation (2)

$$A_{ox} = 2S / Cl \quad (2)$$

Table 1
Predictive slagging and fouling indices

Indices	Expression	Range	Risk	Reference	Equation
Alkali	$AI = \frac{(K_2O + Na_2O) \cdot A}{HHV}$	0.17 - 0.34 > 0.34	Probable Certain	(Gudka <i>et al.</i> , 2016), (Smith & Ross, 2019)	(6)
Base-to-acid ratio	$\frac{B}{A} = \frac{F_2O_3 + CaO + MgO + K_2O + Na_2O + P_2O_5}{SiO_2 + TiO_2 + Al_2O_3}$	< 0.5 0.5 - 1 1 - 1.75 > 1.75	Low Medium High Severe	(Garcia-Maraver <i>et al.</i> , 2017), (Lachman <i>et al.</i> , 2021), (Gudka <i>et al.</i> , 2016)	(7)
Fouling	$Fu = (B/A) \cdot (K_2O + Na_2O)$	< 0.6 0.6 - 40 > 40	Low Medium High	(Garcia-Maraver <i>et al.</i> , 2017), (Lachman <i>et al.</i> , 2021), (Gudka <i>et al.</i> , 2016)	(8)
Chlorine	Cl	< 0.2 0.2 - 0.3 0.3 - 0.5 > 0.5	Low Medium High Severe	(Garcia-Maraver <i>et al.</i> , 2017), (Ovčáčíková <i>et al.</i> , 2022)	(9)

If the value of this index is below 2, the risk of corrosion in boiler tubes is high; if it is between 2 and 8, it indicates a moderate to minor corrosion risk; and for values above 8, the Cl content is too low to cause corrosion, which is why it is considered a safe operation (Qian *et al.*, 2021).

2.2.6 Environmental index

This index indicates the proportion of burnable C with respect to the N content in a biomass which does not provide energy and is transformed into NO_x. It was determined by equation (3) where the values of both variables are expressed as wt.% on dry basis. For thermochemical processes it is desirable that this index be greater than 30 (Toscano *et al.*, 2023).

$E_{nv} = C / N$ (3)

2.2.7 Hydrogen/Carbon and Oxygen/Carbon atomic ratios

These ratios were used to characterize sugarcane straw as fuel in a Van Krevelen diagram, and were calculated by equation (4) and equation (5).

$(H/C)_{atr} = H_a / C_a$ (4)

$(O/C)_{atr} = O_a / C_a$ (5)

where H_a, O_a and C_a are the number of moles of atoms in each 100 g of biomass obtained by dividing the contents of C, H and O, expressed as wt.% on dry basis, by their respective atomic weights (Toscano *et al.*, 2023).

2.2.8 Slagging and fouling prediction

To predict slagging and fouling issues, the first step was to determine the ash composition of the samples, which was performed by X-ray fluorescence using a BRUKER S4 PIONEER spectrometer following ASTM D4326 procedures. Then, some indices developed for coal, which have also been applied to biomass in previous studies (García *et al.*, 2015), were adopted in this work. The indices adopted in this study are shown in Table 1 and calculated according equation (6) to equation (9) in which the oxides are referred to their concentration by weight in the ashes. In the case of the AI index, the HHV is expressed in GJ/kg while A represents the mass fraction of ash in the fuel measured on a dry basis, and K₂O and Na₂O are the mass fractions of alkali oxides in the ash. Also, the value of Cl is expressed as a mass fraction of this element on a dry basis.

Additionally, ternary diagrams based on the composition of the ashes of several biomass samples, were used to identify the type of ash and estimate the ash fusion temperatures (AFTs) of sugarcane straw, in order to predict the risk of ash deposition during combustion in thermal equipment (Vassilev *et al.*, 2014).

3. Results and Discussion

3.1 Selection of washing process conditions

The literature review shows that the decrease in particle size and the increase in the S:L ratio, temperature, and washing time contribute to achieving a greater reduction in the ash, alkalis, S and Cl contents of the biomass, however, this affects the design and cost of the washing pretreatment (Peiris & Gunarathne, 2021). In the present study sugarcane straw samples were cut to a length of 0.5–2.0 cm, smaller sizes were not preferred to facilitate the cutting operation, reduce the time and energy required, and because washing smaller particle sizes of the residue could present difficulties for their separation from water, increasing the possibility of mass loss. For all the experiments 100 g of sugarcane straw was submerged in 3 L of distilled water maintaining a 1:30 S:L ratio which was selected considering that in preliminary tests carried out with smaller volumes of water, difficulties occurred in ensuring complete soaking of the cut pieces, as well as in agitating the soaked material in the washing water. Also, larger S:L ratios require more water which implies more cost, being a limitation for industrial applications. For the selected S:L ratio, as shown in Table 2, three washing temperatures, two residence times, and three agitation conditions of the soaked material were tested, and based on EC

Table 2
Electrical conductivity of the leachate [mS/cm]

Water stirring		A0 (none)		A1 (periodic)		A2 (continuous)	
T [°C]	t [min]	Mean	SD	Mean	SD	Mean	SD
20	10	1.40	0.017	1.48	0.017	1.51	0.015
	20	1.49	0.020	1.52	0.000	1.54	0.000
40	10	1.59	0.012	1.60	0.010	1.66	0.006
	20	1.61	0.006	1.64	0.006	1.67	0.010
80	10	1.74	0.006	1.76	0.006	1.84	0.006
	20	1.74	0.010	1.81	0.015	1.92	0.010

values recorded the removal efficacy of ash, alkalis, S, and Cl was estimated.

The EC of distilled water (0.05 mS/cm) measured before the experiments was subtracted from EC measurements made. The tests were replicated 3 times for each of the 18 washing conditions carried out, considering for each case the EC average value of the leachate as final result. It was observed that the EC increases when the severity of the leaching process is greater due to the more favorable conditions to increase the conduction of inorganic water-soluble components from sugarcane straw to distilled water during the pretreatment. As shown in Table 2 the measured value of the EC is greater as the temperature of the leachate increases. This result is consistent with previous research on the leaching of other herbaceous biomasses under different conditions. For example, prolonged washing (3 h) of wheat straw, rice husk, and cotton stalk in deionized water at 30 °C, 60 °C, and 90 °C, with a S:L ratio of 1:80, showed increased ash and K removal efficiency with increasing temperature (Deng *et al.*, 2013). Other studies also found that the EC value increased as the process time and temperature increased. This was found after washing wheat straw for 5 min and 10 min at a 1:15 S:L ratio and varying the temperature from 20 °C to 80 °C. The highest EC value reported was 1.89 mS/cm for washing for 10 min at 80 °C (Singhal *et al.*, 2021b).

It was observed that washing sugarcane straw without agitation, the time parameter had not a significant influence on water-soluble elements release from the residue as washing temperature increases. As it can be seen in Table 2, the gap between EC values recorded at 10 min and 20 min decreased as temperature increased, having no variation at 80 °C, reaching a value equal to 1.74 mS/cm in both cases. This situation changed when the soaked material was agitated continuously. For 80 °C, the EC values were 1.84 mS/cm at 10 min and 1.92 mS/cm at 20 min, representing the highest values obtained, which in turn was an indicator of the removal efficiency achieved with respect to the mentioned harmful elements that are present in sugarcane straw. Taking everything into account, it was determined that the optimal conditions for washing sugarcane straw were a 0.5–2.0 cm-sized feedstock, washed for 20 min at 80 °C with a S:L ratio of 1:30, and continuous agitation of the leachate, being the washing option selected.

The use of washing water as fertilizer, given its potassium and mineral content, would prevent it from becoming a waste effluent. However, it requires pretreatment, and improper management could harm soil fertility. Large-scale implementation involves additional costs. Further research is needed to assess feasibility, scalability, and cost-benefit.

3.2 Proximate analysis and fuel ratio index

The results of proximate analysis of sugarcane straw samples before and after water leaching, denoted as O-SCS and W-SCS respectively, are presented in Table 3. It is observed that the values of ash, VM and FC content of O-SCS sample are similar to the values reported in the literature for other herbaceous biomasses such as rice straw, wheat straw and corn stalk (Deng

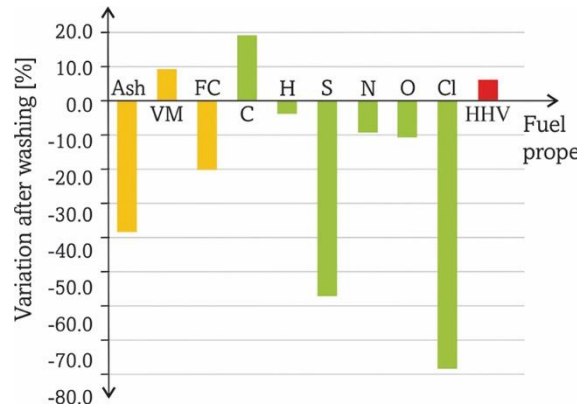


Fig. 3 Changes in fuel properties due to washing process

et al., 2013), and results of additional studies on wheat straw conducted under different conditions (Singhal *et al.*, 2021b). However, after the washing process applied to sugarcane straw the ash content decreased 38.46% from 9.1 to 5.6 wt.% of dry matter. The reduction achieved is comparable or even higher than other results reported in previous studies conducted for different biomasses. While some researchers found that washing wheat straw for 10 min at 80 °C with a S:L ratio of 1:15 reduced the amount of ash by 33.26% (Singhal *et al.*, 2021b) , other researchers found that washing for 6 h at room temperature (22 °C) with a similar solid-to-liquid ratio (1:20) removed less than 15% of the ash from the same residue (Yu *et al.*, 2014), whereas other studies indicates that washing rice straw at 90 °C for 3 h using S:L ratios of 1:80, reduced the amount of ash by 28.73% (Deng *et al.*, 2013). In the present study, the decrease of ash content achieved after washing process was essentially caused by the reduction of the amounts of water-soluble inorganic components in sugarcane straw such as Na, S, Cl, and K, which was evidenced by the high EC value of 1.92 mS/cm achieved. It is considered that the high operating temperature of 80 °C, and the continuous stirring of water contributed to the ash removal as well as dust, and foreign particles extraction from the residue.

Due to, biomass combustion generates ash deposition and corrosion issues in plants where thermochemical processes take place, it is an important factor to be considered for the design of the combustion chamber, gas cleaning and ash extraction systems (Kongto *et al.*, 2022). The low ash content obtained after washing sugarcane straw suggest that W-SCS sample may fire well in boilers with fewer problems of ash deposition and corrosion. Therefore, it is expected a better combustion process with lower cleaning and maintenance costs. Also, the VM of sugarcane straw increased from 75.1 wt.% to 81.8 wt.%, measured on dry basis, which represents an increment of 8.82%, while the FC decreased 20.25% as shown in Table 3 and Figure 3.

These results express the same behavior with respect to an increase in VM and a reduction in FC content and are consistent with findings reported in the literature about washing other herbaceous biomasses. Studies on washing wheat and rice straw at 90 °C for 3 h showed that VM increased by 11.57% and 7.32%, while the FC content decreased by 22.33% and 7.92%, respectively (Deng *et al.*, 2013). Also, after washing wheat straw for even longer periods of time at 22 °C, other researchers found that VM increased by 8.5% and FC decreased by 24.29% (Yu *et al.*, 2014), whereas other studies for the same residue carried out under short residence time (10 min) at high temperature (80

Table 3

Proximate analysis (wt.%, dry basis), high heating value [MJ/kg] and fuel ratio index

Sample	Proximate analysis			Fuel index	Heating value
	Ash	VM	FC	Fr	HHV
O-SCS	9.1	75.1	15.8	0.21	17.4
W-SCS	5.6	81.8	12.6	0.15	18.4

°C) resulted in a 5.2% rise in VM and a nearly 2.7% reduction in FC content (Singhal *et al.*, 2021b). However, some differences were observed among the results reported in the literature, but also in comparison with those obtained in the present study, which may be due to the differences in composition and properties of the treated biomass materials, as well as the particular characteristics of the washing processes applied. Based on earlier findings, the increase achieved in VM after the washing process is beneficial as it allows for faster combustion of the waste with more energy (Wu *et al.*, 2019). Also, the high VM content in biomass is an indicator of high flammability of the fuel, low ignition temperature, simple and fast ignition, high reactivity during combustion, and less amounts of unburned C in the ash. This fact is of great importance in co-combustion processes as it provides to the mixture coal-biomass greater flame stability (Vassilev *et al.*, 2015). In the case of sugarcane straw, W-SCS has a higher content of VM than O-SCS, and it is expected that W-SCS will show a more pronounced behavior in these aspects during combustion than the unwashed residue. In this context, the Fuel Ratio Index (Fr), defined as the ratio FC/VM, was used to evaluate the reactivity of sugarcane straw, since it is associated with flame production, char formation, and fuel consumption rate during combustion. Higher values of this ratio are generally associated with improved fuel properties, as observed for coals and biochar. Nevertheless, several studies have indicated that solid fuels with $Fr > 1.5$ tend to exhibit weak combustion flames and ignition difficulties, which often requires the use of auxiliary fuels for ignition (Kongto *et al.*, 2022). In contrast, biomass typically presents much lower values, usually below 0.25 (Vassilev *et al.*, 2015), due to its high volatile matter and relatively low fixed carbon content (Gajera *et al.*, 2023), resulting in easy ignition, high flame intensity, and rapid burning rates (Vassilev *et al.*, 2015). According to our results, the Fr index of sugarcane straw decreased after washing, from 0.21 in the O-SCS sample to 0.15 in the W-SCS sample, as shown in Table 3. Both values confirm that sugarcane straw is highly ignitable; however, the washed sample is expected to exhibit an even faster ignition response than the untreated one, consistent with its higher VM content after the pretreatment. When compared with other herbaceous biomasses reported in the literature, the values obtained in this study fall within the expected range. For untreated materials (Yu *et al.*, 2014), the reported values were rice straw (0.23), wheat straw (0.24), corn stover (0.235), and miscanthus (0.174), which display similar or slightly higher ratios than sugarcane straw. After water leaching, the Fr values for these biomasses also decrease (Yu *et al.*, 2014): rice straw (0.20), wheat straw (0.167), corn stover (0.179), and miscanthus (0.15). Another study for wheat straw reported that this index decreased from 0.228 to 0.21 (Singhal *et al.*, 2021b). These findings indicate that the water leaching pretreatment modifies the combustion behavior of sugarcane straw in a manner consistent with other herbaceous biomasses, suggesting an improvement in ignition properties. Other analyses, as well as the evaluation of additional fuel indices, are required to assess the suitability of the washed residue as a solid fuel for thermochemical conversion processes.

3.3 Effect of the washing process on the HHV

As shown in Table 3, the HHV of O-SCS is 17.4 MJ/kg which lies within the range of 16.0 to 17.6 MJ/kg reported in the literature for this residue (Aguiar *et al.*, 2021). For comparison with other herbaceous biomasses such as wheat straw, rice straw, and corn stalk, previous studies reported HHV values of 18.85 MJ/kg, 16.56 MJ/kg, and 17.45 MJ/kg respectively (Deng *et al.*, 2013), and an additional report indicated 17.92

MJ/kg for wheat straw (Singhal *et al.*, 2021a). It can be observed that the result obtained is consistent with those reported in other studies. After leaching sugarcane straw, the HHV increased by 5.75% (18.4 MJ/kg) as shown in Figure 3 which represents a moderate increase with respect to the original value. In contrast, studies performed at 90 °C for 3 h of leaching time reported a decreasing trend, with reductions in HHV of 30.3% for wheat straw, and about 10% for rice straw and corn stalk (Deng *et al.*, 2013). Conversely, another study on wheat straw reported an increase of 0.45% for leaching process carried out at a particle size of 3 cm and a residence time of 10 min, and an increase about 1.0% at the same conditions with a residence time of 30 min (Singhal *et al.*, 2021a). These discrepancies between our results in which it was observed a moderate increase in the HHV after leaching process compared with a reported decrease in one study and a very slight increase in another, could be explained by the variations in the treated agricultural waste composition as well as differences in the specific characteristics of the leaching processes applied.

3.4 Ultimate analysis and fuel indices

3.4.1 Atomic Ratios (H/C and O/C)

The ultimate analysis presented in Table 4 shows that C increased from 43.9 wt.% to 52.2 wt.% of dry matter, corresponding to a 18.91% increment after washing, while H and O contents had a reduction of 4.17% and 9.78% respectively (Figure 3). These results are reflected in the reduction of H/C and O/C atomic ratios (previously defined as $(H/C)_{atr}$ and $(O/C)_{atr}$ in the methodology) in the W-SCS sample compared to the O-SCS sample as can be observed in the Van Krevelen diagram presented in Figure 4 in which is possible to see the differences in composition and oxidation levels between the

Table 4
Ultimate analysis (wt.%, dry basis) and fuel indices

Sample	Elemental composition						Fuel indices	
	C	H	S	N	O	Cl	A _{ox}	C/N
O-SCS	43.9	5.52	0.28	0.33	40.9	0.69	0.90	133
W-SCS	52.2	5.29	0.12	0.30	36.5	0.15	1.77	174

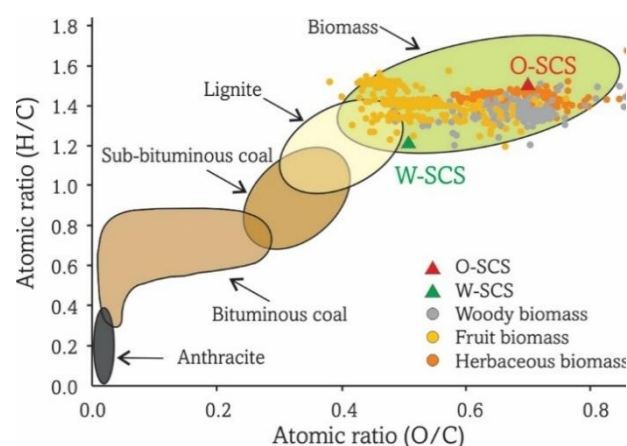


Fig. 4 Van Krevelen diagram for sugarcane straw
Adapted from Toscano *et al.* (2023)

samples analyzed in the present study, and with respect to other solid fuels.

For sugarcane straw the values of H/C and O/C atomic ratios before washing (O-SCS) were 1.50 and 0.70, and after washing (W-SCS) were 1.21 and 0.52 respectively. Based on these results, both samples are located in the biomass zone in the Van Krevelen diagram as expected. O-SCS sample was located in the region that corresponds to herbaceous biomasses showing higher (O/C) values with respect to other types solid fuels, and compared coal has higher contents of H and O in relation to C, which causes it to have a lower energy content. According to the literature review, this is because the energy in C-H and C-O bonds is lower than that of the C-C bonds (Vassilev *et al.*, 2015). With respect to the W-SCS sample, it was located in a region closer to the lignite, indicating that it has a higher HHV, which can be corroborated with the results reported in Table 3, supporting the concept that a solid fuel has a higher energy content when the (H/C) and (O/C) have a lower value (Toscano *et al.*, 2023). Also, high contents of C and H are desired in agricultural byproducts for combustion, while O is undesirable since it does not contribute to the calorific value.

3.4.2 Chlorine Content (Cl)

Another aspect considered in the present study was that the O-SCS sample exhibited a high Cl concentration (0.69 wt.% dry matter), exceeding the critical limit of 0.5 wt.% indicated in Table 1, which suggests a high probability of slagging and fouling during combustion. This initial Cl level was relatively high compared with several reported values for other agricultural residues, such as wheat straw (0.40 wt.%) and rice straw (0.53 wt.%) (Qian *et al.*, 2021), or wheat straw (0.23 wt.%) and rice straw (0.19 wt.%) (Deng *et al.*, 2013). However, it was closer to the upper range of values reported by (Yu *et al.*, 2014), who found 0.85 wt.% for wheat straw, 0.40 wt.% for rice straw, and 0.78 wt.% for corn stover. After washing, the Cl content in sugarcane straw decreased by more than 78%, reaching 0.15 wt.% in the W-SCS sample (Table 4, Figure 3), which highlights the effectiveness of the pretreatment in reducing Cl and lowering the risk of operational problems. The reduction of Cl through washing represents a general trend observed across agricultural residues; for instance, one study reported decreases of about 76% for wheat straw and 93% for rice straw under washing conditions at 90 °C (Deng *et al.*, 2013). The reduction achieved in the present study is consistent with this broader trend.

According to the literature review, Cl contributes to the mobility of alkaline elements such as K and their reactions with silicon, which generates a decrease in the AFTs, and as a consequence the occurrence of slagging and fouling at typical temperatures (800 °C to 900 °C) at which boilers operate (Garcia-Maraver *et al.*, 2017). Also, as established by prior studies biomasses with ash contents in the range of 6 to 15 wt.% and Cl contents ≥ 1 wt.% have a high risk of generating corrosion during the combustion because the Cl and the alkali metals present in the ashes, such as K and Na, upon entering into a vapor state react to form alkaline chlorides (KCl, NaCl) which then, with SO₂ and O₂, give rise to the formation of sulphates (K₂SO₄, Na₂SO₄) which form deposits, while the Cl₂ in the gaseous state remains free, and attacks the internal metal parts of the boilers and thermal equipment generating corrosion (Qian *et al.*, 2021).

In conclusion, during biomass combustion the formation of deposits due to condensation of alkaline chloride, and the reaction of chlorine with the metallic parts of the superheater cause corrosion (Hansen *et al.*, 2022). The significant decrease

of Cl achieved in the present study after washing is beneficial for the use of W-SCS as fuel due to the lower emissions of gases and vapors, as well as the lower tendency to corrosion and ash deposition.

3.4.3 Sulfur Content (S)

The S content in sugarcane straw decreased from 0.28 to 0.12 wt.% after leaching, representing a 57.1% removal (Table 4, Figure 3). During combustion, S is mainly released as SO₂ and, to a lesser extent, as SO₃, as well as alkali and alkaline earth sulfates, which contribute both to SO_x emissions and to the formation of aerosols and ash deposits (Sommersacher *et al.*, 2012). Our results are in good agreement with previous studies, which also reported significant reductions in S after washing agricultural straws, although the effect was generally less pronounced than for Cl, which was also observed in our case. One study reported S removal values of 82.3% for wheat straw and 89.4% for rice straw, based on elemental analysis (Deng *et al.*, 2013), confirming that leaching can substantially reduce the sulfur content in these residues. Plants primarily absorb sulfur as sulfate anions through their roots and as SO₂ through their aerial parts, so that part of the sulfur is retained in the biomass as organic compounds or inorganic anions. The relatively high removal obtained here can be attributed to the presence of "mobile and water-soluble S compounds" and the weak binding of these species in the organic matrix, which favors their extraction during leaching (Singhal *et al.*, 2021a). Overall, the reduction in S achieved in this study is expected to be beneficial, as it may contribute to lower SO_x emissions and mitigate related problems such as acid rain, fine particulate matter formation, slagging, fouling, and high-temperature corrosion during combustion of the washed sugarcane straw.

3.4.4 2S/Cl Ratio

The molar ratio 2S/Cl (defined as A_{ox} in the methodology) is widely used as an integrated indicator to predict corrosion risks in biomass-fired boilers and combustion units (Hansen *et al.*, 2022). Previous studies indicated that ratios below 2 indicate a Cl surplus in aerosols and are associated with severe corrosion risks, whereas values above 4 are associated to minor corrosion risk, and ratios exceeding 8 are generally considered safe (Sommersacher *et al.*, 2012). According to this criterion, the index calculated for sugarcane straw increased from 0.90 in the O-SCS sample to 1.77 in the W-SCS sample (Table 4), reflecting a considerable improvement but still remaining below the critical threshold (<2). These findings are consistent with literature data: untreated agricultural residues such as wheat straw, rice straw, and corn stover show values of 0.85, 0.87, and 0.79, respectively (Qian *et al.*, 2021), all of them below 2 and therefore associated with high corrosion risks. On the other hand, one study reported that washing residues such as wheat and rice straw raised the 2S/Cl ratio from values close to 1 to levels above 2 (Deng *et al.*, 2013), confirming the effectiveness of this pretreatment in mitigating combustion-related problems. Overall, while water leaching proves to be an effective strategy to reduce Cl and improve the 2S/Cl ratio of sugarcane straw, additional measures such as co-firing with low-Cl biomass, the use of sulfate-forming additives, or subsequent torrefaction are recommended to further minimize corrosion and deposition risks under practical operating conditions.

3.4.5 Nitrogen Content (N) and C/N Ratio

In biomass combustion, the N content is the main source of NO_x emissions, serving as a key indicator of emission risk. According

to this parameter, fuels are classified as low-N (<0.4 wt.% db.), medium-N (0.4–1 wt.% db.), or high-N (1–10 wt.% db.). Values above 0.4 wt.% N are generally associated with elevated NO_x emissions, for which emission control measures are required (Ozgen *et al.*, 2021). In this study, the O-SCS presented an N content of 0.33 wt.% (db.), as shown in Table 4, which places the untreated sugarcane straw in the low-N category. After leaching, the N content decreased slightly to 0.30 wt.% (db.), corresponding to a 9% reduction. Both values remain below the 0.4 wt.% (db.) threshold, confirming a low risk of NO_x emissions, while the slight reduction in N after leaching suggests an even lower emission potential.

To complement this analysis, the C/N ratio was used as an additional indicator of the risk of NO_x formation. This index expresses the amount of combustible C relative to N, which mainly contributes to NO_x emissions rather than to energy release. High C/N values (>30) are generally associated with reduced NO_x formation and better suitability for thermochemical processes (Toscano *et al.*, 2023). For the O-SCS sample, the C/N ratio was 133, while after washing it increased to 174, representing a 30% improvement (Table 4). These values are higher than those typically reported for herbaceous biomasses, which generally exhibit C/N ratios below 100, as documented for wheat straw, corn stalks, and rapeseed stalks (Toscano *et al.*, 2023). In fact, the O-SCS value already exceeds the range of most untreated herbaceous residues reported in other studies, and is comparable to the value of 110.74 reported in one study for wheat straw (Wu *et al.*, 2019). When comparing with other studies, the effect of water leaching pretreatment on the C/N ratio shows both similarities and differences. For instance, one study reported an increase from 110.74 to 183.96 for wheat straw (Wu *et al.*, 2019), while another found a more moderate increase from 91.71 to 114.53 (Singhal *et al.*, 2021b). In addition, increases were reported for corn stover, from 70.16 to 138.79, and for wheat straw, from 92.55 to 140.00 (Yu *et al.*, 2014). In this context, the C/N value obtained for sugarcane straw after leaching, 174, is higher than most reported cases, except for the study on wheat straw, which reached a comparable level of 183.96 (Wu *et al.*, 2019). These differences can be attributed to several factors. First, the intrinsic variability of biomass composition, depending on crop type, growth conditions, and fertilization practices, directly affects the N content and, consequently, the C/N ratio. Second, the leaching pretreatment conditions also influence the magnitude of the increase, which explains why similar residues (e.g., wheat straw) can yield distinct C/N responses after washing. Overall, the results obtained confirm that water leaching pretreatment enhances the C/N ratio of sugarcane straw, aligning it with or even exceeding the values observed for other herbaceous biomasses. This outcome reflects an improved balance between C availability and N limitation, which supports the suitability of W-SCS as a solid biofuel for thermochemical processes.

3.5 Effect of the washing process on the ash composition

The results of ash oxide constituent analysis of original (O-SCS) and washed sugarcane straw (W-SCS) are presented in Table 5. It can be seen that SiO₂, K₂O and CaO are the main components of the ashes (nearly 72 wt.%) before washing. As has been previously reported in the literature, during biomass combustion, silica concentrations alone do not cause sintering of ash (Singhal *et al.*, 2021a), but together with alkali metals such as Na and K they form eutectics, lowering the melting point of ash and creating conditions for its sintering, and slag formation at normal boiler operating temperatures (Liu *et al.*, 2021). In addition, Cl and S contents in biomass facilitate the volatilization

Table 5

Ash composition before and after washing

Oxides	O-SCS (wt.%)	W-SCS (wt.%)
SiO ₂	49.9	63.5
Al ₂ O ₃	6.65	4.7
Fe ₂ O ₃	3.02	2.64
CaO	10.1	11.1
MgO	4.08	2.93
SO ₃	8.68	3.98
Na ₂ O	2.25	0.94
K ₂ O	12.16	5.52
TiO ₂	0.41	0.25
P ₂ O ₅	1.47	1.21
MnO	0.09	0.08
SrO	0.05	0.05

of alkali metals, and thus the generation of acid gases and aerosols, which contributes with the aforementioned problems, and the occurrence of fouling issues caused by the condensation and deposition of particles on the heat transfer surfaces and corrosion of the metal surfaces of boilers (Yu *et al.*, 2014) considered one of the main challenges to ensuring the continuous and prolonged operation of combustion plants (Liu *et al.*, 2021). According to the literature review, the presence of K, Na and Cl in agricultural waste generates serious problems of sintering, slagging, fouling, and corrosion when is used as fuel in boilers, making it necessary to incur high maintenance costs.

During combustion the combination of K and Cl forms KCl vapor, causing corrosive fly ash that seriously affect the metal surfaces of the boiler superheater, and SiO₂ in contact with the alkaline vapors generated, forms alkaline silicates that contribute to sintering and fouling issues (Peiris & Gunarathne, 2021), therefore, it is considered that due to its ash composition untreated sugarcane straw has a higher slagging, and fouling tendency which limits its use as a fuel. After washing the alkali metal oxides in the sugarcane straw ash decreased significantly. Table 5 shows that K₂O decreased from 12.16 wt.% to 5.52 wt.% while Na₂O decreased from 2.25 wt.% to 0.94 wt.% which represents a reduction of 54.61% and 58.22% respectively (Figure 5), and due to the reduction of these oxides the SiO₂ increased 27.25%. Several studies suggested that water washing

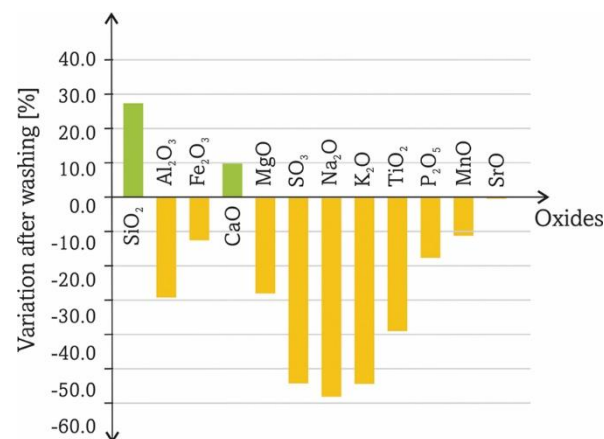


Fig. 5 Changes in ash composition due to washing

pretreatment is an efficient method to decrease the ash content, and the soluble alkali metals found in a biomass, which reduces the issues associated with ash. Some studies, reported that K_2O and Na_2O decreased by 63.53% and 13.25% respectively after washing wheat straw at 90 °C, and after washing rice straw under the same conditions, the reduction achieved for these components were 82.74% and 58.33% respectively (Deng *et al.*, 2013). Other experiences of washing wheat straw at 80 °C for 10 min, showed that the K_2O content in the ash decreased from 16.32 wt.% to 11.62 wt.% representing a decrease of nearly 29% (Singhal *et al.*, 2021b). According to what was mentioned, the results obtained in the present study are consistent with what has been found in previous studies. The reduction in K_2O and Na_2O content after washing sugarcane straw are similar and even higher than those reported by other researchers after washing other herbaceous biomasses. Differences in the washing processes, as well as in the composition of the treated agricultural waste, could explain some of the discrepancies in the reduction levels achieved from the collected results. In closing, it can be said that the washing method applied in the present study greatly improves the fuel properties of sugarcane straw. Consequently, an increase of the AFTs of this agricultural waste is expected, as well as a reduction of corrosion, slagging and fouling tendency during combustion, ensuring a safer operation and less deterioration of boilers and facilities.

3.6 Slagging and fouling prediction

3.6.1 Slagging and fouling indices

Theoretical indices AI, B/A, Fu and CI, which are presented in Table 1, were applied to our data (Table 5) to estimate the tendency of slagging and fouling issues during combustion of sugarcane straw. The results obtained for O-SCS sample were AI= 0.75, B/A = 0.58, Fu = 8.37, and CI = 0.69% exceeding in all cases the specified safety limits (Table 1) as shown in Figure 6, suggesting a moderate to severe risk of ash deposition and corrosion in boilers during combustion. After water leaching, W-SCS exhibited improved index values which decreased considerably (AI= 0.20, B/A = 0.36, Fu = 2.30, and CI = 0.15%) demonstrating the effectiveness of the pretreatment in reducing ash-related risks. This improvement is consistent with the expected removal of alkali and chlorine species during leaching. When compared with other untreated herbaceous biomasses reported in the literature, it was found a study on rice straw reporting a B/A index of 1.29, which indicates a high slagging tendency, as well as a Fu index of 0.76, reflecting a moderate fouling tendency (Tsai *et al.*, 2023). Another study reported a B/A index of 0.9 for wheat straw suggesting a moderate

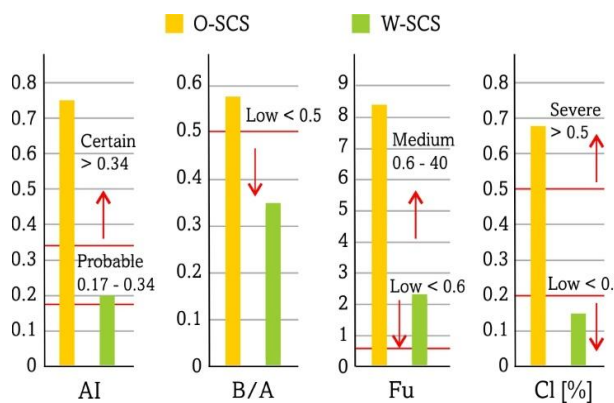


Fig. 6 Variation of slagging and fouling indices

slagging tendency (Singhal *et al.*, 2021b). In addition, further research indicated Cl contents of 0.59% and 0.61% for rice straw and wheat straw respectively (Garcia-Maraver *et al.*, 2017), evidencing a high probability of corrosion during combustion. Therefore, our results are consistent with those reported for other agricultural residues in terms of ash deposition and corrosion tendency.

Improvements associated with water leaching process have also been documented in the literature, mainly reflected in the reduction of predictive indices. For instance, in the case of wheat straw, subjected to a treatment at 80 °C for 10 min, with a S:L ratio of 1:15, exhibited an improvement in the index B/A with a 50% decrease, reducing from an initial value of 0.90 to 0.45 (Singhal *et al.*, 2021b). With regards to the washed sugarcane straw (W-SCS), the index B/A decreased by 38.0%, although this reduction is lower than that reported for other herbaceous biomasses such as wheat straw, the result obtained is consistent with the trend reported for other washed herbaceous biomasses such as wheat straw, confirming the effectiveness of water leaching in mitigating slagging and fouling risks associated with the use of sugarcane straw as fuel.

3.6.2 Ternary diagrams

The ternary phase diagram was used to predict the slag formation tendency and estimate the AFTs from O-SCS and W-SCS samples when used as fuel. In addition to our samples, the diagram in Figure 7 also includes reference points from the literature for other herbaceous biomasses, provided for comparison purposes (Latif *et al.*, 2025).

The ash oxides presented in Table 5 were separated into three groups, according to their negative and positive effect on melting behavior, and then transferred to the ternary diagram developed by Vassilev (Vassilev *et al.*, 2015). The O-SCS sample falls in the S zone of medium acidity, with an ash deformation temperature (DT) below 1100 °C, indicating a high probability of ash deposition and slag formation as reported in the literature for other biomass residues (Putra *et al.*, 2023). This behavior is expected due to the high K_2O content in its ash, and similar to

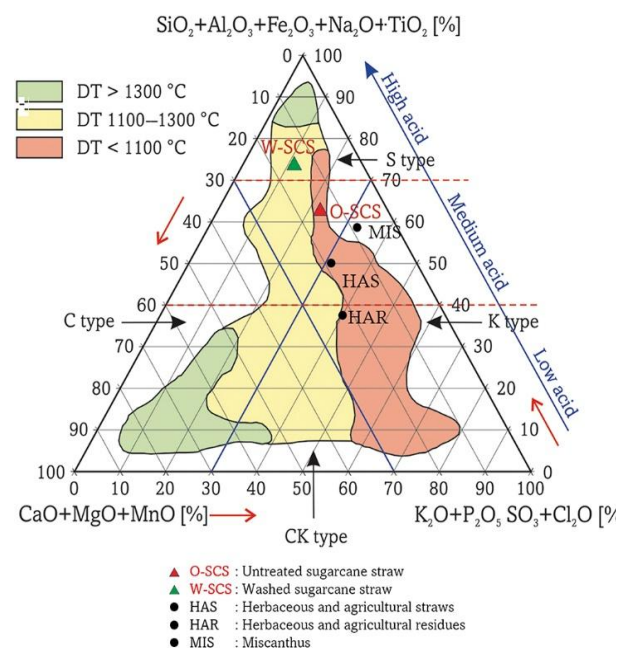


Fig. 7 Ash fusion temperature and slagging tendency before and after washing. Adapted from (Vassilev *et al.*, 2015)

that reported for miscanthus and other herbaceous biomasses, which also exhibit DT values below 1100 °C (Latif *et al.*, 2025). After washing, sample W-SCS remains in the S zone but shifts closer to the coal region (green area), with DT values increasing to 1100–1300 °C, which reflects a medium risk of slagging, as expected from the reduction of problematic elements in the ash. This behavior is consistent with previous studies; for instance, wheat straw exhibited a DT temperature of 1109 °C and rises to 1404 °C after washing pretreatment (Deng *et al.*, 2013). The results obtained in the present study indicates that the effectiveness of our process is in line with results reported for other biomasses subjected to similar treatments. Also, these results demonstrated that the water washing pretreatment, by removing problematic elements such as potassium from sugarcane straw, generates an increase in the ash fusion temperature, reducing the slagging and fouling problems at the usual operating temperatures of boilers. This fact, added to the results of the calculated slagging and fouling predictive indices, would indicate a low risk of ash deposition and corrosion problems during the combustion of washed sugarcane straw, allowing the use of this biomass as fuel in thermochemical processes in a safer way and with fewer inconveniences in the operation and maintenance of the boilers due to ash deposition issues.

4. Conclusion

Sugarcane straw is an agricultural waste that because of its considerable ash content and the high amounts of K, Na, S, and Cl cause severe slagging, fouling, and corrosion in boilers during combustion, being necessary the development and application of a pretreatment to improve its fuel properties.

The present study demonstrated that leaching pretreatment with distilled water is a simple method to improve sugarcane straw fuel properties, by significantly lowering the quantity of soluble ash-forming components that increase the probability of slagging, fouling, and corrosion. A feedstock size of 0.5–2 cm, 20 min soaking at 80 °C, a S:L ratio of 1:30, and continuous agitation of the material were the optimum leaching conditions, obtaining a considerable reduction of 38.46% in ash, 78.26 in Cl, 57.14% in S, 54.61% in K₂O, and 58.22% in Na₂O.

Washing sugarcane straw caused a slight increase in the HHV that reached a value of 18.4 MJ/kg. The incremented of 5.75% achieved after the pretreatment is mainly attributed to the reduction in ash content, which cause an increase in the amount of organic matter in this agricultural waste. This enhancement of the HHV is coherent with the decrease of the H/C an O/C atomic ratios that showed the washed sample. The reduction in N, S, and Cl content in sugarcane straw, due to the washing process, allows for a more environmentally friendly fuel with lower NO_x, SO_x, and HCl emissions. Washing causes the ash fusion temperature of sugarcane straw to rise noticeably due to the elimination of undesirable components such as potassium. The ternary phase diagram shows that after the washing process, the DT temperature rose between 100 °C to 200 °C, lowering the tendency of ash melting and adhesion in boilers during combustion, which is in line with predictions made by fouling and slagging indices. It is advised to apply the suggested graphical method, and theoretical predictive indicators as a preliminary assessment of AFTs, slagging, and fouling tendencies of the residue.

Author Contributions: E. Assureira.: Conceptualization, methodology, formal analysis, writing—original draft, M. Assureira.: supervision,

resources, project administration, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Abelha, P., Mourão Vilela, C., Nanou, P., Carbo, M., Janssen, A., & Leiser, S. (2019). Combustion improvements of upgraded biomass by washing and torrefaction. *Fuel*, 253(September 2018), 1018–1033. <https://doi.org/10.1016/j.fuel.2019.05.050>
- Aguiar, A., Milessi, T. S., Mulinari, D. R., Lopes, M. S., da Costa, S. M., & Candido, R. G. (2021). Sugarcane straw as a potential second generation feedstock for biorefinery and white biotechnology applications. *Biomass and Bioenergy*, 144(105896). <https://doi.org/10.1016/j.biombioe.2020.105896>
- Alao, K. T., Gilani, S. I. U. H., Sopian, K., Alao, T. O., Oyebamiji, D. S., & Oladosu, T. L. (2024). Biomass and organic waste conversion for sustainable bioenergy: A comprehensive bibliometric analysis of current research trends and future directions. *International Journal of Renewable Energy Development*, 13(4), 750–782. <https://doi.org/10.61435/ijred.2024.60149>
- Chandrasiri, Y. S., Weerasinghe, W. M. L. I., Madusanka, D. A. T., & Manage, P. M. (2022). Waste-Based Second-Generation Bioethanol: A Solution for Future Energy Crisis. *International Journal of Renewable Energy Development*, 11(1), 275–285. <https://doi.org/10.14710/ijred.2022.41774>
- Deb, U., Bhuyan, N., Bhattacharya, S. S., & Katagi, R. (2019). Characterization of agro-waste and weed biomass to assess their potential for bioenergy production. *International Journal of Renewable Energy Development*, 8(3), 243–251. <https://doi.org/10.14710/ijred.8.3.243-251>
- Deng, L., Zhang, T., & Che, D. (2013). Effect of water washing on fuel properties, pyrolysis and combustion characteristics, and ash fusibility of biomass. *Fuel Processing Technology*, 106(2013), 712–720. <https://doi.org/10.1016/j.fuproc.2012.10.006>
- Dethan, J. J. S., Bale-Therik, J. F., Lalel, H. J. D., & Telupere, F. M. S. (2024). Optimisation of Particle Size of Torrefied Kesambi Leaf and Binder Ratio on the Quality of Biobriquettes. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 12(1), 1–21. <https://doi.org/10.13044/J.SDEWES.D12.0490>
- Fernández, M. J., Chaloupková, V., & Barro, R. (2022). Water leaching of herbaceous biomass bales to reduce sintering and corrosion. *Fuel*, 312(122744). <https://doi.org/10.1016/j.fuel.2021.122744>
- Food and Agricultural Organization (FAO). (2023). World Food and Agriculture – Statistical Yearbook 2023. In *World Food and Agriculture – Statistical Yearbook 2023*. <https://doi.org/10.4060/cc8165en>
- Gajera, B., Datta, A., Gakkhar, N., & Sarma, A. K. (2023). Torrefied Mustard Straw as a Potential Solid Biofuel: a Study with Physicochemical Characterization and Thermogravimetric and Emission Analysis. *Bioenergy Research*, 16(4), 2371–2385. <https://doi.org/10.1007/s12155-023-10600-y>
- Garcia-Maraver, A., Mata-Sanchez, J., Carpio, M., & Perez-Jimenez, J. A. (2017). Critical review of predictive coefficients for biomass ash deposition tendency. *Journal of the Energy Institute*, 90(2), 214–228. <https://doi.org/10.1016/j.joei.2016.02.002>
- García, R., Pizarro, C., Álvarez, A., Lavín, A. G., & Bueno, J. L. (2015). Study of biomass combustion wastes. *Fuel*, 148, 152–159. <https://doi.org/10.1016/j.fuel.2015.01.079>
- Ge, Z., Cao, X., Zha, Z., Ma, Y., Zeng, M., Wu, Y., Li, F., & Zhang, H. (2022). The sintering analysis of biomass waste ash based on the in-situ exploration and thermal chemical calculation in the gasification process. *Combustion and Flame*, 245, 112381. <https://doi.org/10.1016/j.combustflame.2022.112381>
- Gopalakrishnan, N. K., Balasubramanian, B., Meyyazhagan, A., Chaudhary, A., Palani, V., Kamyab, H., & Pappuswamy, M. (2025). Exploring the efficiency and scalability of using algae as a biomass feedstock for biofuel production. *Algal Research*, 90(August), 1–8.

- <https://doi.org/10.1016/j.algal.2025.104251>
- Gudka, B., Jones, J. M., Lea-Langton, A. R., Williams, A., & Saddawi, A. (2016). A review of the mitigation of deposition and emission problems during biomass combustion through washing pre-treatment. *Journal of the Energy Institute*, 89(2), 159–171. <https://doi.org/10.1016/j.joei.2015.02.007>
- Hansen, L. J., Fendt, S., & Spliethoff, H. (2022). Impact of hydrothermal carbonization on combustion properties of residual biomass. *Biomass Conversion and Biorefinery*, 12(7), 2541–2552. <https://doi.org/10.1007/s13399-020-00777-z>
- Ibitoye, S. E., Mahamood, R. M., Jen, T. C., & Akinlabi, E. T. (2022). Combustion, Physical, and Mechanical Characterization of Composites Fuel Briquettes from Carbonized Banana Stalk and Corn cob. *International Journal of Renewable Energy Development*, 11(2), 435–447. <https://doi.org/10.14710/ijred.2022.41290>
- Javanmard, A., Daud, W. M. A. W., Patah, M. F. A., & Ying, C. Y. (2025). Impact of water-washing pretreatment on key properties of torrefied palm kernel shells: A statistical optimization study. *Industrial Crops and Products*, 228(June), 1–6. <https://doi.org/10.1016/j.indcrop.2025.120729>
- Kalak, T. (2023). Potential Use of Industrial Biomass Waste as a Sustainable Energy Source in the Future. *Energies*, 16(4). <https://doi.org/10.3390/en16041783>
- Karaeva, A., Magaril, E., & Al-Kayiem, H. H. (2023). Review and Comparative Analysis of Renewable Energy Policies in the European Union, Russia and the United States. *International Journal of Energy Production and Management*, 8(1), 11–19. <https://doi.org/10.18280/ijepm.080102>
- Kayesh, M. S., & Siddiq, A. (2023). The Impact of Renewable Energy Consumption on Economic Growth in Bangladesh: Evidence from ARDL and VECM Analyses. *International Journal of Energy Production and Management*, 8(3), 149–160. <https://doi.org/10.18280/ijepm.080303>
- Kongto, P., Palamanit, A., Ninduangdee, P., Singh, Y., Chanakaewsoomboon, I., Hayat, A., & Wae-hayee, M. (2022). Intensive exploration of the fuel characteristics of biomass and biochar from oil palm trunk and oil palm fronds for supporting increasing demand of solid biofuels in Thailand. *Energy Reports*, 8(November), 5640–5652. <https://doi.org/10.1016/j.egy.2022.04.033>
- Lachman, J., Baláš, M., Lisý, M., Lisá, H., Milčák, P., & Elbl, P. (2021). An overview of slagging and fouling indicators and their applicability to biomass fuels. *Fuel Processing Technology*, 217(106804). <https://doi.org/10.1016/j.fuproc.2021.106804>
- Latif, M., Brammer, J. G., & Morris, J. (2025). Evaluation of Different Classes of Additives on Ash Melting Characteristics of Garden Grass Waste. *Waste and Biomass Valorization*, 0123456789. <https://doi.org/10.1007/s12649-025-02991-0>
- Lebendig, F., Funcia, I., Pérez-Vega, R., & Müller, M. (2022). Investigations on the Effect of Pre-Treatment of Wheat Straw on Ash-Related Issues in Chemical Looping Gasification (CLG) in Comparison with Woody Biomass. *Energies*, 15(9). <https://doi.org/10.3390/en15093422>
- Liu, Y. J., Yan, T. G., An, Y., Zhang, W., & Dong, Y. (2021). Influence of water leaching on alkali-induced slagging properties of biomass straw. *Ranliao Huaxue Xuebao/Journal of Fuel Chemistry and Technology*, 49(12), 1839–1850. [https://doi.org/10.1016/S1872-5813\(21\)60147-0](https://doi.org/10.1016/S1872-5813(21)60147-0)
- Ovčáčíková, H., Velička, M., Vlček, J., Topinková, M., Klárová, M., & Burda, J. (2022). Corrosive Effect of Wood Ash Produced by Biomass Combustion on Refractory Materials in a Binary Al–Si System. *Materials*, 15(16). <https://doi.org/10.3390/ma15165796>
- Ozgen, S., Cernuschi, S., & Caserini, S. (2021). An overview of nitrogen oxides emissions from biomass combustion for domestic heat production. *Renewable and Sustainable Energy Reviews*, 135(December 2019), 110113. <https://doi.org/10.1016/j.rser.2020.110113>
- Peiris, M. A., & Gunarathne, D. S. (2021). Parametric and kinetic study of washing pretreatment for K and Cl removal from rice husk. *Heliyon*, 7(11), e08398. <https://doi.org/10.1016/j.heliyon.2021.e08398>
- Pestaño, L. D. B., & Jose, W. I. (2016). Production of solid fuel by torrefaction using coconut leaves as renewable biomass. *International Journal of Renewable Energy Development*, 5(3), 187–197. <https://doi.org/10.14710/ijred.2022.41290>
- Putra, H. P., Kuswa, F. M., Ghazidin, H., Darmawan, A., Prabowo, & Hariana. (2023). Slagging-fouling evaluation of empty fruit bunch and palm oil frond mixture with bituminous ash coal as co-firing fuel. *Bioresource Technology Reports*, 22(April), 101489. <https://doi.org/10.1016/j.biteb.2023.101489>
- Qian, X., Xue, J., Yang, Y., & Lee, S. W. (2021). Thermal properties and combustion-related problems prediction of agricultural crop residues. *Energies*, 14(15). <https://doi.org/10.3390/en14154619>
- Rimantho, D., Hidayah, N. Y., & Pratomio, V. A. (2023). Performance Evaluation of Wood Pellets Derived from Biomass Waste as a Sustainable Energy Source. *International Journal of Energy Production and Management*, 8(4), 251–258. <https://doi.org/10.18280/ijepm.080407>
- Santolini, E., Bovo, M., Barbarelli, A., Torreggiani, D., & Tassinari, P. (2021). Turning agricultural wastes into biomaterials: Assessing the sustainability of scenarios of circular valorization of corn cob in a life-cycle perspective. *Applied Sciences (Switzerland)*, 11(14). <https://doi.org/10.3390/app11146281>
- Shahbeik, H., Kazemi Shariat Panahi, H., Dehghani, M., Guillemin, G. J., Fallahi, A., Hosseinzadeh-Bandbafha, H., Amiri, H., Rehan, M., Raikwar, D., Latine, H., Pandalone, B., Khoshnevisan, B., Sonne, C., Vaccaro, L., Nizami, A. S., Gupta, V. K., Lam, S. S., Pan, J., Luque, R., ... Aghbashlo, M. (2024). Biomass to biofuels using hydrothermal liquefaction: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 189(PB), 113976. <https://doi.org/10.1016/j.rser.2023.113976>
- Singhal, A., Kontinen, J., & Joronen, T. (2021a). Effect of different washing parameters on the fuel properties and elemental composition of wheat straw in water-washing pre-treatment. Part 1: Effect of washing duration and biomass size. *Fuel*, 292(120206). <https://doi.org/10.1016/j.fuel.2021.120206>
- Singhal, A., Kontinen, J., & Joronen, T. (2021b). Effect of different washing parameters on the fuel properties and elemental composition of wheat straw in water-washing pre-treatment. Part 2: Effect of washing temperature and solid-to-liquid ratio. *Fuel*, 292(January). <https://doi.org/10.1016/j.fuel.2021.120209>
- Smith, A. M., & Ross, A. B. (2019). The influence of residence time during hydrothermal carbonisation of miscanthus on bio-coal combustion chemistry. *Energies*, 12(3), 13–22. <https://doi.org/10.3390/en12030523>
- Sommersacher, P., Brunner, T., & Obernberger, I. (2012). Fuel Indexes : A Novel Method for the Evaluation of Relevant Combustion Properties of New Biomass Fuels. *Energy Fuels*, 26(1), 380–390. <https://doi.org/https://doi.org/10.1021/ef201282y>
- Toscano, G., De Francesco, C., Gasperini, T., Fabrizi, S., Duca, D., & Ilari, A. (2023). Quality Assessment and Classification of Feedstock for Bioenergy Applications Considering ISO 17225 Standard on Solid Biofuels. *Resources*, 12(6). <https://doi.org/10.3390/resources12060069>
- Tsai, C. H., Shen, Y. H., & Tsai, W. T. (2023). Thermochemical Characterization of Rice-Derived Residues for Fuel Use and Its Potential for Slagging Tendency. *Fire*, 6(6), 1–10. <https://doi.org/10.3390/fire6060230>
- Vassilev, S. V., Baxter, D., & Vassileva, C. G. (2014). An overview of the behaviour of biomass during combustion: Part II. Ash fusion and ash formation mechanisms of biomass types. *Fuel*, 117(PART A), 152–183. <https://doi.org/10.1016/j.fuel.2013.09.024>
- Vassilev, S. V., Vassileva, C. G., & Vassilev, V. S. (2015). Advantages and disadvantages of composition and properties of biomass in comparison with coal: An overview. *Fuel*, 158, 330–350. <https://doi.org/10.1016/j.fuel.2015.05.050>
- Vlček, J., Ovčáčíková, H., Velička, M., Topinková, M., Burda, J., & Matějková, P. (2023). The Corrosion Effect of Fly Ash from Biomass Combustion on Andalusite Refractory Materials. *Minerals*, 13(3), 357. <https://doi.org/10.3390/min13030357>
- Wang, K., & Tester, J. W. (2023). Sustainable management of unavoidable biomass wastes. *Green Energy and Resources*, 1(1), 100005. <https://doi.org/10.1016/j.gerr.2023.100005>
- Wang, Y., & Wu, J. J. (2023). Thermochemical conversion of biomass: Potential future prospects. *Renewable and Sustainable Energy Reviews*, 187(January), 113754. <https://doi.org/10.1016/j.rser.2023.113754>
- Wu, S., Chen, J., Peng, D., Wu, Z., Li, Q., & Huang, T. (2019). Effects of

- water leaching on the ash sintering problems of wheat straw. *Energies*, 12(3). <https://doi.org/10.3390/en12030387>
- Yu, C., Thy, P., Wang, L., Anderson, S. N., Vanderghenst, J. S., Upadhyaya, S. K., & Jenkins, B. M. (2014). Influence of leaching pretreatment on fuel properties of biomass. *Fuel Processing Technology*, 128, 43–53. <https://doi.org/10.1016/j.fuproc.2014.06.030>
- Zlateva, P., Yordanov, K., Murzova, M., & Terziev, A. (2025). Consumer preferences for solid biomass fuels for energy purposes. *International Journal of Renewable Energy Development*, 14(1), 52–61. <https://doi.org/10.61435/ijred.2025.60473>



© 2025. The Author(s). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution-ShareAlike 4.0 (CC BY-SA) International License (<http://creativecommons.org/licenses/by-sa/4.0/>)