

Original Article

Effect of Water Temperature, Contact Time and Particle Size on the Leaching Characteristics of Organic and Inorganic Matter from Sugarcane Trash Briquettes

Geoffrey Kubuli Makhanu¹, Obadiah Mwanzi Maube², Patrick Nziu³

¹Department of Physics, Kisii University, Kenya.

²Department of Mechanical and Aerospace Engineering, Technical University of Kenya.

³Department of Mechanical Engineering, Walter Sisulu University, South Africa.

¹Corresponding Author: geoffreymakhanu@yahoo.com

Received: 07 March 2026

Revised: 23 June 2026

Accepted: 04 September 2026

Published: 26 October 2026

Abstract - Global depletion of fossil fuels and the environmental costs of their use motivate renewable alternatives. Sugarcane trash is abundant but rich in potassium, silica, chlorine, and alkali/alkaline earth metals, which drive ash formation, slagging, fouling, corrosion, and hazardous air pollutants during combustion. This study evaluates water leaching as a pretreatment to reduce problematic inorganic/organic constituents and to improve combustion and emission performance of sugarcane trash briquettes. Raw cane trash (CO 421, Migori County) was collected, size-reduced (1, 5, 10 mm), and leached in ultrapure water at 25, 50, and 100 °C for 20, 40, and 60 min using a 3×3×3 full factorial design (27 runs; triplicates). Post-leach solids were densified via hydraulic press (18 MPa; DIN 54385:2016-08). Elemental and ash-forming species (K, Na, Ca, Mg, Si; Cl, S, P) were quantified by standard methods; leachates were analyzed for pH, EC, TOC, and organic acids. Leaching increased C from 46.27 to 49.73 wt% and eliminated detectable Cl; N and S decreased by 39.5% and 66.7%, respectively. Ash-forming K and Mg in solids fell by 63.09% and 44.00%, while Si declined slightly (≈4.3%) and Ca rose (≈15.9%). Leachates were mildly acidic (pH ≈ 5.5) and contained organic acids totaling 2.91% of TOC. Electrical conductivity trends and performance gains were strongest with smaller particle size, higher temperature, and longer contact time. The optimum temperature, time and size were 50 °C, 60-minute and 1 mm, respectively.

Keywords - Water leaching, Sugarcane trash, Biomass briquettes, Ash reduction.

1. Introduction

Global fossil fuel deposits are declining at a high rate, and the use of fossil fuels has resulted in global warming, climate change, and environmental degradation. Alternative renewable energy sources are therefore being explored to provide sustainable solutions. Biomass, including sugarcane trash, is abundant, renewable, and can be processed into biofuels such as briquettes. However, sugarcane trash contains high levels of potassium, silica, chlorine, and alkali/alkaline earth metals, which contribute to ash formation, slagging, fouling, and corrosion during combustion. Like many other biomass fuels, cane trash contains sulfur, nitrogen, chlorine, and heavy metals that contribute to Hazardous Air Pollutants (HAPs) when burned. Such include dioxins, furans, hydrogen chloride, sulfur oxides and nitrogen oxides. High ash content also causes operational problems such as slagging, agglomeration and corrosion of burners. The raw trash from cane is not well-suited for direct thermal conversion because of its low energy density and high mineral content. These problematic inorganic and organic components need to be

removed by leaching and other pretreatment methods. Leaching reduces amount of soluble alkali metals and chlorine. This results in a reduced risk of slagging, fouling and corrosion in combustion systems. Leaching of cane trash can lead to reduced ash fouling and slagging, corrosion and environmental impacts for thermochemical conversion systems. The results of the experiment show that leaching is an effective method to improve the cane trash fuel property, and hence improve the combustion performance and reduce gaseous and particle emissions [1]. In addition, the chlorine and sulfur contained in biomass will accelerate the volatilization of alkali metals. The fouling of the stove is caused by the condensation of inorganic vapor [2]. Biomass feedstock causes uncontrolled ash chemistry, therefore it is beneficial to modify the feedstock to reduce alkali metal, chloride, sulfur and silica content [3].

Another approach to improve biomass feedstock characteristics for high-temperature applications is the leaching of biomass with water as a solvent. Water soluble



salts of alkali metals and chlorine are often removed by leaching [4, 5]. Leaching can reduce corrosion and emissions of acidic pollutants and can reduce the development of harmful species such as dioxins and furans [6]. Leaching is also an important process for the extraction of organic contents to allow coproduct recovery [7]. However, simultaneous removal of organics can lead to an unfavorable loss of dry matter. Thus, the aim was to increase information on the solid-liquid extraction of both inorganic and organic elements from biomass feedstock by using leaching pretreatments [8]

Water leaching is widely recognized as an effective pretreatment to reduce ash-forming elements in agricultural biomass, but the process has not been fully optimized for sugarcane trash under practical operating conditions. The high concentrations of potassium, chlorine, sulfur and other inorganic components continue to limit the widespread utilization of sugarcane trash because of their involvement in slagging, fouling, corrosion and gas emissions during the combustion process. The need to define operating conditions which maximize inorganic removal while maintaining the quality of the fuel from the biomass remains.

Earlier studies [9, 10] have shown that water leaching can decrease the amount of ash-forming compounds in different biomass feedstocks. However, most of the published research has been conducted on a single process parameter, such as the leaching temperature, washing time or biomass-to-water ratio. Only a small number of studies have taken into account the combined effects of particle size, water temperature and contact time in a systematic experimental design. Moreover, there are only a few studies that quantified the removal of inorganic and organic matter from sugarcane trash and identified practical operating conditions for industrial briquette production. Hence, the relationships between these significant operating parameters are not clearly understood.

Burning agricultural biomass has several challenges. These include low energy value, high ash content, pollution, corrosion, and poor combustion performance [9]. Agricultural biomass usually contains more ash because it naturally has alkali metals and other inorganic elements [16]. These problems are mainly caused by elements such as Potassium (K) and Chlorine (Cl) that are found in the raw biomass material [10].

The most common methods used to remove these unwanted elements are post-harvest leaching and natural precipitation. [8] studied the differences in leaching between batch and semi-continuous processes, while Yu [11] studied how the biomass-to-water ratio and leaching time affect the washing process. Moreover, [12] studied the practical use of natural leaching to improve the thermal conversion of rice straw. Both methods can remove large amounts of alkaline compounds and elements such as chlorine, sulfur, and

potassium, and can also reduce the ash content. Most previous studies have focused on removing chemical compounds from ash through leaching at the ash sintering temperature [8, 11, 13-15]. However, there is still a limited understanding of how Alkali and Alkaline Earth Metals (AAEM) can be removed from cane trash under different conditions. These conditions include particle size, leaching water temperature, and leaching time. Previous studies [20] have shown the potential of leaching for the reduction of such elements, but the optimal conditions of temperature, particle size and contact time for this removal had not been fully established and is the basis for this study.

This study aims to address this knowledge gap by systematically investigating the combined effects of particle size, water temperature and leaching time on the removal of inorganic and organic constituents from sugarcane trash. Unlike previous studies, a three-level full factorial experimental design was used to investigate the interaction of these operating variables and to identify practical conditions to simultaneously improve the biomass quality and reduce the ash-forming elements. The results offer operational advice on the pretreatment of sugarcane trash for production of briquettes and other thermochemical conversion technologies.

Thus, the objective of this study was to evaluate the influence of particle size, water temperature and contact time on the leaching characteristics of inorganic and organic constituents from sugarcane trash, using a three-level full factorial experimental design. The study also aimed to find out the operating conditions that improve the fuel quality by lowering the ash forming elements and increasing the suitability of sugarcane trash for briquette production and thermochemical energy conversion. Therefore, the present study aims to evaluate the effect of the main leaching parameters (particle size, water temperature, and leaching time) on the removal of Alkali and Alkaline Earth Metal (AAEM) species from sugarcane trash, through a Response Surface Methodology (RSM) approach. It has been reported that water leaching is an effective pretreatment for enhancing the fuel properties of biomass through the removal of water-soluble inorganic constituents that cause slagging, fouling, corrosion and pollutant emissions during thermochemical conversion [1, 4, 8, 11]. The leaching studies on agricultural residues like rice straw, rice husk, wheat straw, oil palm biomass, switchgrass, mallee biomass and pongamia pod have shown the reduction of alkali metals and chlorine and improvement in combustion characteristics [3, 13, 15-19]. The studies, however, were mainly limited to a single biomass feedstock or specific operating parameters and generally focused on removal of ash-forming inorganic species without simultaneous assessment of the effect of particle size, water temperature and contact time on extraction of inorganic and organic matter. The present study adds to the existing knowledge by a systematic study of the combined effects of three important operating parameters (particle size, leaching

temperature and contact time) using a three-level full factorial experimental design. In this study, we examine the interaction of these variables and quantify the effects on elemental composition, ash-forming species, organic matter, electrical conductivity and leachate chemistry simultaneously, which is different from previous work that usually looked at one or two process variables in isolation [8, 16]. Additionally, this work determined practical operating conditions for the pretreatment

of sugarcane trash for the purpose of briquette production, finding that 50 °C, 60 minutes and 1 mm particle size were an effective compromise between leaching efficiency and practical application. The findings shown in Table 1 are new knowledge that can be used in the optimization of sugarcane trash pretreatment and contribute to a more general understanding of upgrading biomass for cleaner and more efficient thermochemical energy conversion.

Table 1. Review of sugarcane trash pretreatment process

Parameter	Present study	Previous findings	Discussion
Carbon content	Increased from 46.27% to 49.73%	[1] also reported increased carbon after leaching, although the increase was smaller.	The increase is attributed to removal of soluble impurities and surface contaminants, resulting in a higher proportion of carbon in the remaining biomass.
Chlorine removal	100% removal	[1, 11] also reported nearly complete chlorine removal.	This confirms that chlorine is predominantly present as water-soluble salts and can be effectively removed by hot-water leaching.
Sulfur removal	66.67%	[1] reported almost complete sulfur removal.	The lower sulfur removal observed in this study may be associated with differences in sugarcane variety, soil characteristics, and cultivation conditions in Kenya.
Potassium removal	63.09%	[11] Chin and [13, 16] also reported substantial potassium removal after water washing.	The present study achieved comparable removal while simultaneously optimizing particle size, temperature, and contact time using a factorial experimental design.
Calcium behaviour	Increased by 15.9%	[16, 19] reported little change or slight increases after washing.	Calcium is largely associated with water-insoluble mineral phases; therefore, its apparent increase reflects the removal of other soluble constituents rather than additional calcium formation.
Optimum operating conditions	50 °C, 60 min, 1 mm	Previous studies investigated similar variables individually, but generally did not establish a practical combined operating condition for sugarcane trash.	The present study provides an optimized operating window that balances leaching efficiency with practical implementation for briquette production.

Water leaching has been extensively studied as a facile and environmentally friendly pretreatment to enhance the fuel quality of lignocellulosic biomass for thermochemical conversion. Many studies have proved that water washing can effectively remove water-soluble alkali metals, chlorine, sulfur and other inorganic elements that cause ash deposition, slagging, fouling, corrosion and harmful gaseous emissions during combustion [1, 4, 6]. Leaching decreases the concentration of these undesirable components and thus contributes to an improved combustion efficiency, higher ash fusion temperatures and higher operational reliability of biomass-fired energy systems. Early studies by [1] demonstrated that water leaching greatly improved the fuel properties of processed sugarcane biomass by removing chlorine and alkali metals, thus reducing the risk of ash-related operational problems. Similarly, water washing was effective in removing inorganic constituents from pine bark and switchgrass [3], which improved the suitability of these

materials for thermal conversion. As reported by [4], water washing also showed positive effects on biomass fuel properties, pyrolysis behavior, combustion characteristics and ash fusibility, confirming the significance of pretreatment before energy utilization. The influence of operating conditions on leaching performance has been investigated by several researchers. The results obtained by [8] in comparing batch and semi-continuous leaching systems revealed that the operating mode has a significant effect on the efficiency of the removal of inorganic and organic components. [11] examined the effect of leaching pretreatment on biomass fuel properties and found that water washing could substantially reduce the content of potassium and chlorine and improve the combustion quality. Recently, Bandara [18] studied the impacts of rice husk pretreatment on water temperature, particle size and washing time, and observed that higher temperature and lower particle size enhanced ash removal. Similarly, the fuel properties of pongamia pods were

improved by hot-water leaching, but the removal of calcium and silica was limited due to their relatively low solubility in water [19]. Previous studies have shown that leaching can enhance the fuel quality and reduce the environmental impacts associated with biomass utilization. [13] demonstrated the efficiency of water leaching in alleviating operational problems associated with ash in oil palm biomass and fast growing timber species.

Moreover, [17] further reported that water washing not only removed inorganic nutrients but also facilitated the recovery of valuable soluble compounds from biomass. Furthermore, [5, 7, 21] stated that cleaner biomass fuels prepared by pretreatment had better combustion behavior and reduced emission of pollutants, thus making biomass briquettes a more sustainable renewable energy source.

However, despite these major advances, the literature has been focused on individual biomass feedstocks or isolated operating variables. In contrast, only a few studies have systematically studied the combined effects of particle size, water temperature and contact time on the removal of inorganic and organic matter from sugarcane trash using a factorial experimental design. Therefore, further studies are needed to determine practical operating conditions for maximum pretreatment efficiency and to improve the overall fuel quality of sugarcane trash for briquette production.

2. Methodology

2.1. Materials and Equipment

The study was carried out at the Sony Sugar Laboratories in Migori County, Kenya. This location was selected because the equipment and raw materials needed for the experiment were available there. Raw cane trash was used as the feedstock material because agricultural biomass contains inorganic

elements such as Potassium (K) and Chlorine (Cl), which can affect its combustion performance [10, 16]. The sugar cane variety (*Saccharum* spp.) used in this study was CO 421, obtained from Sony Sugar in Migori County. This variety was selected because it is commonly grown in the region. The raw cane trash was reduced into smaller pieces before the leaching process. Particle size is an important factor because it can affect the removal of inorganic elements from biomass during leaching [8, 11]. After size reduction, the material was stored in plastic bags until the leaching experiments were carried out. The leaching process was used to reduce unwanted alkaline and inorganic compounds in the biomass, as reported in previous biomass leaching studies [8, 11, 12]. The equipment used in the study included a Jeffco cutter grinder, heating bath, water pump, leaching tank, hydraulic press, bomb calorimeter, muffle furnace, and digital scale. These tools were used for preparing the cane trash, carrying out the leaching treatments, and measuring the properties of the treated biomass.

2.2. Experimental Design

A 3-Level Full Factorial Design was used in the Design of Experiments (DoE). The design included 27 experimental runs, as shown in Table 2. This method was selected because the study considered three factors, with each factor tested at three different levels. Indeed, the factors were particle size [1 mm, 5 mm, and 10 mm], leaching temperature [25 °C, 50 °C, and 100 °C], and leaching time [20 minutes, 40 minutes, and 60 minutes]. Also, these factors are important because changes in leaching conditions can affect the removal of inorganic elements from biomass [8, 11]. In addition, the 3-level design was used because it can show possible changes or curves in the response when the experimental factors are changed. Again, the use of three levels for each factor also helps to determine whether there is a quadratic relationship between the response and each factor [8, 11].

Table 2. The 3 factorial experimental design

Particle Size in mm	Temperature (°C)	Time in minutes								
		20			40			60		
		Particle Size (mm)	Temperature (°C)	Time in minutes	Particle Size in (mm)	Temperature (°C)	Time in minutes	Particle Size in (mm)	Temperature (°C)	Time in minutes
1	25	1	25	20	1	25	40	1	25	60
1	50	1	50	20	1	50	40	1	50	60
1	100	1	100	20	1	100	40	1	100	60
5	25	5	25	20	5	25	40	5	25	60
5	50	5	50	20	5	50	40	5	50	60
5	100	5	100	20	5	100	40	5	100	60
10	25	10	25	20	10	25	40	10	25	60
10	50	10	50	20	10	50	40	10	50	60
10	100	10	100	20	10	100	40	10	100	60

Jeffco cutter grinder cut diameters of 1 mm, 5 mm and 10 mm. Two hundred and fifty grams of each size of cane trash was dried at 105°C for 24 hours in an Isotemp Programmable Muffle Furnace (Fisher Scientific). Then, 15 grams of each oven-dried feedstock sample were added to 30 millitres of ultra-pure water (resistivity > 18.2 M-cm) in a hot water bath. The water was subjected to three experimental temperatures 25°C, 50°C and 100 °C. The desired temperature was maintained using a Julabo Refrigerated and Heating Circulator. The samples were stirred manually for five minutes, and then the top of the leaching tank was pushed through with a circular steel mesh so that the sample is completely immersed in water, after residence times of 20, 40 and 60 min. in the three experiments. During the leaching process, a fixed 100 mL sample was taken from the leaching

bath after every 10 minutes. After each sample was removed, the same amount of fresh ultrapure water was added to the leaching mixture. Indeed, this was done to keep the amount of liquid in the leaching bath constant. Similar washing and leaching methods have been used to study the removal of inorganic elements from biomass [8, 11]. The process was repeated until the leaching reached equilibrium. Equilibrium was reached when there was no further increase in the amount of organic matter and Alkali and Alkaline Earth Metals (AAEM) removed from the biomass. Also, this was checked by measuring the electrical conductivity of the leachate. Electrical conductivity helps to show the amount of dissolved substances released from the biomass during the leaching process [8, 11]. The leaching process is schematically shown in Figure 1.

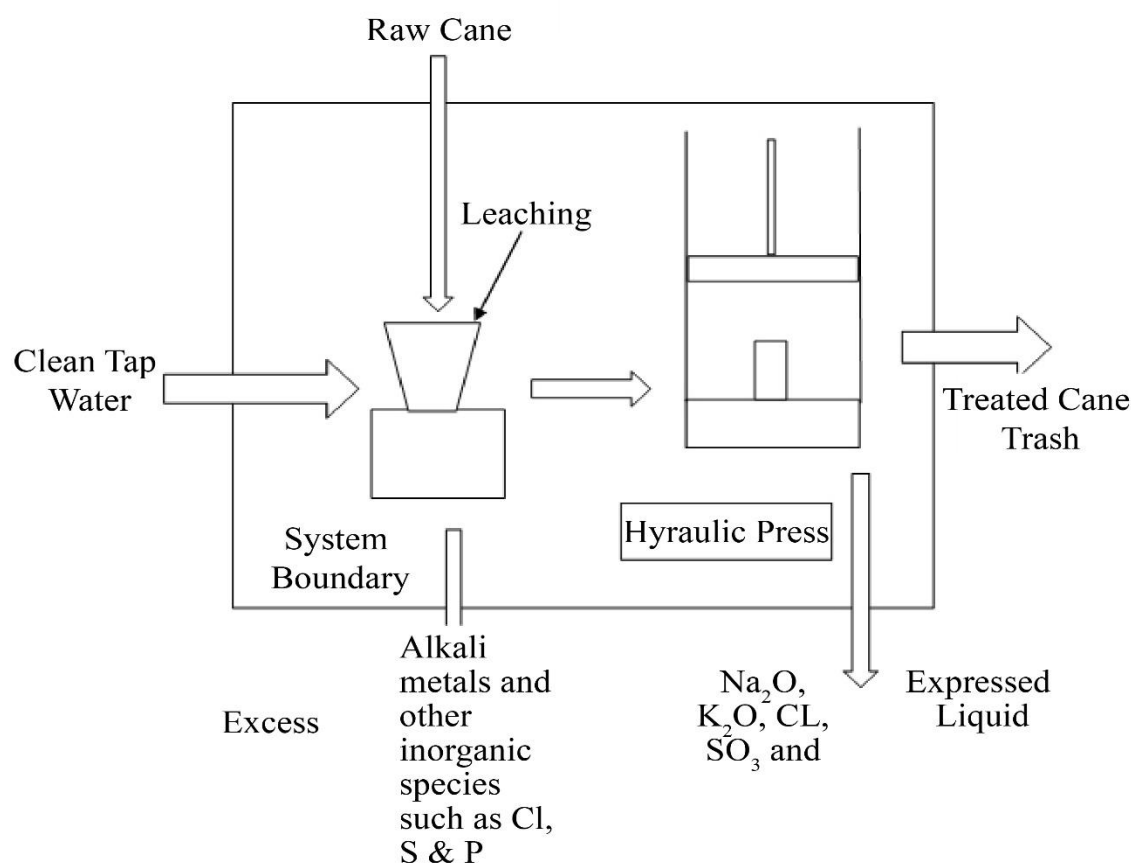


Fig. 1 Schematic presentation of the leaching process

The leachate samples were analyzed to measure pH, Total Organic Carbon (TOC), and the concentration of Alkali and Alkaline Earth Metals (AAEM). The AAEM species measured were Sodium (Na^+), Potassium (K^+), Magnesium (Mg^{2+}), and Calcium (Ca^{2+}). Other elements measured included Chlorine (Cl^-), Sulfur (SO_4^{2-}), and Phosphorus (PO_4^{3-}) [10, 16]. These elements are important because inorganic compounds such as potassium and chlorine can affect the combustion properties of agricultural biomass [10,

16]. Moreover, the electrical conductivity of the leachate was measured according to the ASTM D1125-14 standard using a Pro 30 conductivity meter [10, 16]. The conductivity measurements were used to determine when the leaching process reached equilibrium. Similar studies have used leaching to examine the removal of inorganic elements from biomass under different washing conditions [8, 11, 12]. To improve the reliability of the results, each leaching test was repeated three times for every sample.

2.3. Statistical Analysis

All experiments were performed in triplicate to enhance the reliability and reproducibility of the experimental results. The results were expressed as the mean $\pm$ standard deviation. A three-level factorial experimental design (3.3) was used to evaluate the individual and interactive effects of particle size, water temperature and leaching time on the removal of inorganic and organic constituents from sugarcane trash. The factorial design allowed us to evaluate the three operating variables simultaneously with a minimum experimental bias and the interaction effects among the factors. Descriptive statistical analysis was used to summarize the experimental data, and the observed trends were interpreted by comparing treatment combinations and their corresponding responses. The best operating conditions were found taking into account the combined effects of ash reduction, the efficiency of elemental removal and the maintenance of the fuel quality. This statistical approach enhanced the robustness of the experimental results and gave a systematic foundation for practical pretreatment conditions for sugar cane trash briquettes.

2.4. Particle Size Distribution

The particle size distribution of the samples was measured using a Camsizer Model AS200 Digit CA [8, 11]. The software provided by the equipment manufacturer was used to record and analyze the particle size distribution based on the volume of the sample. Also, particle size is an important factor in biomass leaching because it can affect the removal of inorganic elements from the biomass [8, 11]. The particle size distribution test was carried out according to the ASTM E3340 standard.

2.5. Elemental Analysis of Feedstock

After oven drying, both the leached and unleached feedstock samples were ground using a mini-Wiley mill with a 40-mesh screen. The ground samples were then analyzed for ash, nitrogen, sulfur, and alkali metals, including Potassium (K), Sodium (Na), Calcium (Ca), and Magnesium (Mg). These elements were analyzed because inorganic elements in agricultural biomass can affect ash formation and combustion performance [9, 10, 16].

The ash content of each feedstock sample was determined according to ASTM E1755-01 (Standard Test Method for Ash in Biomass). Ash content was measured as the percentage of residue remaining after the oven-dried sample was burned at 575 °C. Measuring ash is important because agricultural biomass can have high ash content due to the presence of alkali metals and other inorganic elements [16].

The concentrations of potassium, calcium, sodium, and magnesium were measured using Atomic Absorption Spectroscopy with a Varian SpectrAA 200FS. One gram of each feedstock sample was placed in a porcelain dish and heated in an electric furnace for about 20 minutes. The

samples were then heated in a muffle furnace at 550 °C for 6 hours. After heating, the ash samples were cooled in a desiccator for one hour. Then, 10 mL of 5% HCl was added to each dish. After 10 minutes, the samples were filtered through a Whatman No. 1 filter into a 50 mL volumetric flask. The concentration of alkali metals in the extracted samples was then determined in mg/g. The analysis of these metals was important because leaching can reduce alkali and alkaline earth metals present in biomass [8, 11].

The total chlorine content of each feedstock sample was measured according to ASTM E776-16 (Standard Test Method for Forms of Chlorine in Refuse Derived Fuel by the Oxygen Bomb Combustion/Ion Selective Electrode Method). The total chlorine concentration was reported in parts per million (ppm). Chlorine was measured because it is one of the inorganic elements that can cause problems during biomass combustion [10]. Total nitrogen and sulfur were measured using a LECO-3000 CNS analyzer. For each test, 0.2 g of the feedstock sample was placed in a tin foil, wrapped, and loaded into the auto-sampler. Before testing the samples, three blanks and three standards were loaded into the instrument. An additional standard and blank were included after every tenth sample to maintain the accuracy of the analysis. Each sample was analyzed three times to improve the reliability of the results.

2.5.1. Silicon (Si) Analysis

Silicon was determined in the ash obtained from the unleached and the leached cane trash samples. Also, the feedstock samples were oven-dried, ground through a 40-mesh screen and subjected to ash preparation as described above. Indeed, the silicon concentration was determined from the prepared ash samples and the given results were expressed as mg Si/g dry cane trash. Each sample was analyzed in triplicate, and the results were reported as the mean $\pm$ standard deviation.

2.6. Quantification of Organic Matter in the Leachate Sample

After collection, the water leachate samples were immediately analyzed for organic matter using a Total Organic Carbon analyzer (TOC; Shimadzu TOC-VCPH). The amount of Total Organic Carbon (TOC) removed during leaching was standardized against the Total Carbon present in the original cane trash sample. This made it easier to directly compare the amount of organic matter removed from different samples. Leaching conditions can influence the amount of material removed from biomass during the washing process [8, 11]. The concentrations of Alkali and Alkaline Earth Metals (AAEM) in the leachate samples were also determined using Ion Chromatography (IC). Measuring these elements was important because AAEM species can influence the ash and combustion properties of agricultural biomass [9, 10, 16]. Chloride (Cl^-), Sulfate (SO_4^{2-}), and Phosphate (PO_4^{3-}) were analyzed using a DIONEX ICS-1100 Ion Chromatography

system fitted with a suppressed conductivity detector. An IonPac AS22-Fast 4 × 150 mm column and an IonPac AG22-Fast 4 × 30 mm guard column were used to separate the anions. A solution containing 22.5 mM sodium carbonate and 7 mM sodium bicarbonate was used as the eluent. The analysis of these inorganic species is important because leaching can remove compounds such as chlorine, sulfur, and other inorganic elements from biomass [8, 11, 12].

2.7. Identification of Organic Acids in Leachate Samples

The organic acids present in the leachate samples were measured using Ion Chromatography (IC) with a DIONEX ICS-3000 system fitted with a suppressed conductivity detector. The organic acid anions measured were formate, acetate, and oxalate. Measuring these organic compounds helps to understand the materials released from biomass during the leaching process [8, 11].

Indeed, an IonPac AS20 column, measuring 2 mm × 250 mm, and an IonPac AG20 guard column, measuring 2 mm × 50 mm, were used to separate the organic acid anions. A 5 mM potassium hydroxide solution was used as the eluent during the analysis.

3. Results and Discussion

3.1. Elemental Concentration after Leaching and Unleached Cane Trash Samples

The composition of the dry biomass, expressed as a percentage by weight, is presented in Table 3. For comparison, the leaching results for sugar cane trash fibers reported in [1] were also used. In the original unleached cane trash, carbon had the highest concentration at 46.27%, followed by oxygen at 41.53%. The concentrations of hydrogen, nitrogen, sulfur, and chlorine were 6.20%, 0.43%, 0.06%, and 0.02%, respectively. Similarly, [1] reported H at 5.71%, N at 0.48%, and S at 0.22%.

In addition, the unleached biomass reported in the previous study had a higher chlorine concentration of 0.65% [1]. In comparison, the unleached cane trash in the present study had a much lower Cl concentration of 0.04%. This shows that the amount of Cl in cane trash can vary between different samples.

Also, leaching increased the carbon content of the cane trash. This may be because the washing process removed some of the unwanted materials attached to the surface of the cane trash, including contaminants collected during harvesting. Also, as these materials were removed, the percentage of carbon in the remaining biomass increased. The C content increased from 46.27% in the unleached cane trash to 49.73% after leaching. A similar result was reported by [11], where the C content increased from 43.50% to 44.90% after leaching [21]. Water leaching also caused a large reduction in chlorine, sulfur, and nitrogen. Chlorine was completely removed, and

no detectable amount of Cl remained in the cane trash after leaching. Similarly, [11] did not detect any Cl in the biomass after leaching. Sulfur, just like chlorine, can also cause problems during biomass combustion. After water leaching, the S content of the cane trash decreased by 66.67%, from 0.06% to 0.02%. In comparison, the previous study reported that almost 100% of the sulfur was removed. These results show that water leaching can greatly reduce unwanted elements such as Cl and S from cane trash.

3.2. Statistical Analysis of Experimental Results

The experimental results showed that the leaching characteristics of sugarcane trash were collectively affected by the particle size, water temperature and contact time. The most important factor controlling the removal of water-soluble inorganic constituents was particle size, since smaller particles have greater surface area for mass transfer between the biomass and leaching medium. The increase in water temperature resulted in the increased dissolution of alkali metals and other soluble compounds, while the extent of extraction increased with the extension of contact time until equilibrium conditions were obtained. These observations are consistent with the previous findings of [8], Bandara [18] and [19], who showed that higher temperature and smaller particle size significantly improve the efficiency of biomass leaching. The results also show that the simultaneous optimization of these operating parameters is more effective in improving the biomass quality than the variation of one parameter at a time. Thus, the optimal conditions found of 50 °C, 60 min and a particle size of 1 mm are a practical compromise between pretreatment efficiency and the operational feasibility for industrial biomass processing.

All the experiments were performed in triplicate, and the results are shown as mean ± standard deviation. The effects of particle size, water temperature and contact time on leaching behaviour of sugarcane trash were systematically evaluated using a three-level full factorial experimental design (3.3). The factorial design permitted to evaluate the individual effect of each operating parameter and also to compare between treatment combinations. The optimum operating conditions were determined by considering inorganic removal efficiency, ash reduction and maintaining the quality of biomass fuel in conjunction. Further studies using statistical inferential techniques such as Analysis of Variance (ANOVA), regression modelling and response surface methodology to quantify the statistical significance of the interactions of the process factors can help to strengthen the process optimization.

The authors suggest that future studies should apply multivariate statistical methods, such as Principal Component Analysis (PCA), cluster analysis, and Response Surface Methodology (RSM), to determine the interaction between operating variables and the most important factors influencing biomass leaching performance.

Table 3. Elemental composition of unleached and leached cane trash samples

Element	Original Unleached Mean	SD	Leached Mean	SD	Corrected Percentage Change	Un-Leached Biomass [1]	Leached Biomass [1]
C	46.27	0.39	49.73	0.31	+7.48%	45.13	47.42
H	6.20	0.09	5.99	0.11	-3.39%	5.71	6.06
O	41.53	0.48	42.84	0.28	+3.15%	41.69	41.54
N	0.43	0.03	0.26	0.02	-39.53%	0.48	0.35
S	0.06	-	0.02	-	-66.67%	0.22	0.04
Cl	0.02	-	ND	-	ND / not directly calculable*	0.65	0.02

Table 4. Comparative elemental composition of unleached and leached sugarcane trash with previous study results

Wt.% dry Cane trash	Original Unleached Cane Trash		Leached Cane Trash		Percentage change	Un-Leached biomass reported by [1]	Leached Biomass reported by [1]
	Mean	Standard Deviation	Mean	Standard Deviation			
C	46.27	0.39	49.73	0.31	+7.5%	45.13	47.42
H	6.20	0.09	5.99	0.11	-3.30%	5.71	6.06
O	41.53	0.48	42.84	0.28	+0.74%	41.69	41.54
N	0.43	0.03	0.26	0.02	-39.50%	0.48	0.35
S	0.06		0.02		-66.67%	0.22	0.04
Cl	0.02		ND		-100%	0.65	0.02

3.3. Experimental Replication and Uncertainty of Measurement

The experiments were performed in triplicate for each experimental condition to increase the reliability and reproducibility of the measurements. Average values and standard deviations are presented to quantify the experimental variability. The instruments were calibrated according to the corresponding ASTM analytical procedures before the analyses. Sources of uncertainty include minor variations in biomass composition, sample preparation, particle size distribution, temperature control during leaching and analytical measurements. To minimize these uncertainties, care was taken to keep the operating conditions the same and to use standardized analytical procedures throughout the investigation.

3.4. Elemental Analysis of Ash after Leaching

According to Table 4, the main ash-related elements found in the biomass samples were calcium, potassium, magnesium, and sodium. In general, the leaching process was effective in removing many of the elements associated with ash. Similar results were reported by [16] where after leaching, the potassium and magnesium contents of the cane trash decreased significantly. The K content decreased to 7.08 mg/g, giving a removal rate of 63.09%, while the Mg content decreased to 0.30 mg/g, with a removal rate of 44%. These results show that water leaching can effectively remove some ash-related elements from cane trash [16]. The silicon content also decreased slightly after leaching. It decreased from 16.64 mg/g in the original unleached cane trash to 15.93 mg/g in the leached cane trash. Also, this represents a reduction of about 4.3%. Silicon is an important element in clay because clay

minerals mainly contain silicates (Bostron et al., 2012). Therefore, the small reduction in Si may have occurred because washing removed dirt and clay particles attached to the surface of the cane trash. However, the calcium content increased by 15.9%, from 16.08 mg/g in the unleached cane trash to 18.64 mg/g after leaching. Also, this increase may have occurred because other inorganic elements were removed during leaching, making the proportion of Ca in the remaining biomass higher. This agrees with the findings of [19], who reported that hot-water treatment had little effect on Si and Ca because these elements generally have low solubility in water. Similarly, [16] reported higher CaO, MgO, and Na₂O contents in washed biomass samples.

Similarly, washing can greatly reduce some ash-related elements in biomass. Again, changes in water temperature and particle size had only a small effect on the removal of these elements. However, the removal generally increased when the temperature was increased, and the particle size was reduced. This shows that smaller particles and higher temperatures may improve the leaching process. In addition, it is important to note that Ca showed a greater reduction after leaching in the study by Yu [11]. Also, the Ca content in the original unleached cane trash used in the present study was about 14.5 times higher than that of the biomass used by Yu [11]. This difference may be caused by differences in biomass type or growing conditions, such as soil quality and water hardness.

3.5. Leaching Effects on Organic Matter

Leaching removed a noticeable amount of organic material from the cane trash, especially when hot water and smaller particle sizes were used. About 2.91% of the carbon

in the cane trash sample was removed during the leaching process. Similar results were reported by [17] in a study using different samples of mallee biomass. Table 5 presents the pH, organic acid content, and cation-to-anion ratio of the leachate produced after equilibrium water leaching of the cane trash samples. Under the different leaching conditions, the average pH of the leachate was 5.5, with a standard deviation of 0.04, as shown in Table 5. This pH value shows that the leachate was acidic. Similarly, the acidic nature of the leachate

suggests that some of the organic matter removed from the cane trash contained organic acids. Ion chromatography analysis confirmed the presence of organic acids such as acetate, formate, and oxalate in the leachate samples, as shown in Table 5. These organic acids accounted for about 2.91% of the total organic carbon removed from the cane trash. These findings show that water leaching removes not only inorganic elements but also a small amount of organic material from cane trash [17].

Table 5. Mass of ash related elements in sample, mg/g dry cane trash

Wt.% dry Cane trash	Original Unleached Cane Trash ash		Leached Cane Trash ash		Percentage change	Un-Leached biomass reported by Yu [11]	Leached Biomass reported by Yu [11]
Ca	16.08	1.09	18.64	0.93	15.90	1.16	0.94
K	19.18	0.95	7.08	0.40	75.24	7.27	3.04
Mg	0.54	0.06	0.30	0.06	44.00	1.28	0.60.
Na	ND	NA	ND	NA	NA	1.92	0.80
Si	16.64	3.21	15.93	1.89	4.20	17.90	23.18

Table 6. Properties of the leachates obtained from water washing of cane trash samples at equilibrium leaching conditions

Property		Quantity In Leachate	
		Mean	Standard deviation
Concentrations of organic acid anions (% of TOC in leachate)	Ethanol	0.80	0.35
	Glycerol	0.17	0.11
	Acetate	0.03	0.02
	Propionic Acid	0.52	0.09
	Lactic Acid	0.15	0.46
	Glucose	0.51	0.15
	Formate	0.02	0.29
	Oxalate	0.71	0.06
	Total	2.91	
Cation/anion ratio	(Na+K+2Mg+2Ca)/(Cl+2S+3P)	3.3	0.89
pH		5.5	0.04

Table 6 shows that the average pH of the leachate obtained from cane trash under different leaching conditions was 5.5, with a standard deviation of 0.04. This value clearly shows that the leachate was acidic. The acidic condition suggests that some of the organic matter removed from the cane trash contained organic acids. Ion chromatography analysis confirmed the presence of organic acids such as acetate, formate, and oxalate in the leachate, as shown in Table 5. These organic acids represented about 2.91% of the total organic carbon removed from the cane trash. Similar removal of organic material during biomass leaching has been reported by [17].

Table 6 also shows the cation-to-anion ratio of the leachate, calculated as $(\text{Na} + \text{K} + 2\text{Mg} + 2\text{Ca})/(\text{Cl} + 2\text{S} + 3\text{P})$. The cation-to-anion ratio was 3.3. This high ratio suggests that some of the Alkali and Alkaline Earth Metal (AAEM) species removed from the cane trash were not originally present as water-soluble salts. In addition, the results also show that

organic acids released from the biomass remained in the leachate during water leaching. These acids may have helped to remove some acid-soluble but water-insoluble AAEM species from the cane trash. For example, some organically bound AAEM species may have been removed through ion exchange. This means that water leaching may remove more inorganic elements than those that are naturally soluble in water [8, 11].

Therefore, water leaching may overestimate the actual amount of water-soluble inorganic species present in biomass. Also, a better method may be needed to clearly and accurately measure these water-soluble inorganic species without the additional effects caused by interactions between the biomass and the leachate. Also, the acids and sugars removed from the cane trash during leaching could also be recovered and used in other downstream processes. Sugars and organic acids were major parts of the organic matter removed and could therefore be useful coproducts of the leaching process. However, further

analysis is needed to identify all the organic compounds in the leachate and to better explain the differences observed in the anion balance.

3.6. Electrical Conductivity

Electrical Conductivity (EC) is used to show the amount of dissolved ions present in a liquid sample. During leaching, alkali metals and other inorganic elements are removed from the cane trash and released into the water. As more ions enter the leaching water, its electrical conductivity increases. Therefore, a higher EC value can indicate greater removal of

inorganic elements from the biomass during leaching [8, 11]. As shown in Table 7, ions were then removed more easily from the pulverized cane trash than from the chopped cane trash when excess leaching water was used.

Again, this may be because pulverizing reduces the particle size and increases the surface area of the biomass that comes into contact with water. Smaller particle sizes can therefore improve the removal of soluble inorganic elements during the leaching process [8, 11].

Table 7. Electrical conductivity of excess leachate and expressed liquids from the laboratory cane trash investigation

Electrical Conductivity	Leachate Type	Maximum			Minimum		
		Value	Run No.	Acronym	Value	Run No.	Acronym
	Excess Leachate	3.7	23	H-L-P	0.64	11	C-S-C
	Expressed Liquid	5.48	11	C-S-C	3.09	23	H-L-P

However, the opposite result was even observed for the expressed liquid collected during the milling process. At first, the results may appear different when the effects of leaching time, temperature, and particle size are compared between the excess leachate and the expressed liquid. However, this difference can be explained by also considering the amount of ions remaining in the cane trash after leaching.

During leaching, stronger treatment conditions, such as smaller particle size, higher water temperature, and longer leaching time, remove more water-soluble ions from the cane trash and transfer them into the leaching water [8, 11]. Therefore, after the strong leaching treatment, fewer water-soluble ions remain in the cane trash. When the treated cane trash is later milled, fewer ions are released into the expressed liquid compared with the samples treated under less severe conditions, such as larger particle size, lower water temperature, and shorter leaching time.

The electrical conductivity results also clearly show the importance of particle size. Among the factors studied, particle size had the greatest effect on the removal of ions from the cane trash. Smaller particles allowed more contact between the biomass and water, which also improved the removal of water-soluble ions during leaching [8, 11].

3.8. Mechanistic Interpretation of the Leaching Process

The observed leaching behavior is explained mainly by diffusion-controlled mass transfer between the biomass particles and the surrounding water. In the leaching process, water penetrates into the biomass structure and dissolves water soluble inorganic salts together with selected organic compounds. Smaller particle size means bigger surface area and shorter paths of diffusion, which accelerates the transfer of soluble constituents to the surrounding solution. The increase in water temperature enhances the molecular diffusion, reduces the solution viscosity and improves the

dissolution kinetics, resulting in higher extraction efficiencies. The relatively low removal of calcium and silica observed in this study is in agreement with their lower water solubility and stronger association with structural mineral phases within the biomass matrix. These mechanisms account for the higher removal efficiencies achieved for smaller particle size, higher temperature and longer contact time.

3.9. Sensitivity and Uncertainty Analysis

The experimental results show that particle size was the most important operating parameter influencing the leaching efficiency, followed by water temperature and contact time. Replicate measurements generally showed little variability, suggesting that the experiment had acceptable repeatability. However, uncertainties may arise from natural variability in biomass composition, differences in moisture content, minor variations in leaching temperature and analytical measurement errors. These uncertainties do not affect the overall trends observed in this investigation, but should be considered when applying the results to large-scale industrial systems. Future studies should include formal sensitivity analyses and uncertainty propagation methods to quantify the impact of individual process parameters on biomass pretreatment efficiency.

3.10. Techno-Economic and Environmental Assessment

The practical application of water leaching for pretreatment of sugarcane trash needs to be evaluated not only from the point of view of removal of contaminants but also from an economic and environmental point of view. From a techno-economic point of view, the main operating costs are attributed to the water consumption, the heating needs, the particle size reduction and the drying of the treated biomass. While the dissolution of alkali metals and chlorine is enhanced by raising the temperature of the water, the energy consumption also increases at excessively high temperatures. The present study revealed an effective operating temperature

at 50 °C with the significant removal of ash-forming constituents without the energy intensive boiling water. Similarly, size reduction to 1 mm enhanced the leaching efficiency due to increased surface area available for mass transfer. In addition, contact time of 60 minutes was enough to obtain adequate extraction before equilibrium was reached. These conditions are a practical compromise between pretreatment efficiency and operating cost.

From the environmental point of view, water leaching leads to a cleaner biomass utilization by lowering the potassium, chlorine, sulfur and other inorganic constituents that cause slagging, fouling, corrosion and hazardous gaseous emissions during combustion. It is expected that lower concentrations of these elements will reduce the formation of hydrogen chloride, sulfur oxides, particulate matter and ash deposits, which improves combustion efficiency and extends the lifespan of the equipment [4, 6]. Pretreatment can also reduce maintenance requirements, improve energy recovery, and reduce the environmental burden of ash disposal and equipment replacement from a life-cycle point of view. The Life Cycle Assessment (LCA) has been established as an accepted framework for the evaluation of the environmental performance of biomass systems, as it considers impacts that occur from raw material preparation through conversion to final utilization. Although a full LCA and techno-economic analysis are beyond the scope of the present study, the improved fuel properties observed after leaching suggest that the proposed pretreatment would be beneficial for the overall sustainability of sugarcane trash briquette production.

3.11. Valorization of Leachate Byproducts

In addition to improving the quality of the biomass, the leaching process produces a liquid stream containing dissolved organic compounds that can provide additional economic value. Organic compounds detected in the leachate in the present study included ethanol, glycerol, acetate, propionic acid, lactic acid, glucose, formate and oxalate. Instead of being treated as waste, these compounds can be recovered and used as substrates for fermentation, biochemical production, biofertilizer production or other biorefinery applications.

The recovery of these soluble compounds can improve the overall economics of biomass pretreatment by generating valuable coproducts and supporting the principles of a circular bioeconomy. The leachate was acidic (pH ca. 5.5), which further suggests the presence of dissolved organic acids capable of supporting downstream chemical processing. Water leaching has been reported to remove inorganic nutrients and valuable soluble organic compounds from biomass, as in previous studies [8, 17]. Although the current study was more focused on improving fuel quality, future studies should investigate efficient separation, purification and utilization of these dissolved organics to maximize resource recovery and minimize waste generation.

3.12. Comparative Analysis with Alternative Pretreatments

Water leaching is one of the several pretreatment techniques available to improve the biomass fuel quality. Chemical leaching using dilute acids or alkalis usually gives higher removal efficiencies for inorganic constituents, but it requires chemical reagents, increases the operation cost, and produces secondary wastewater requiring treatment. Biological pretreatment is environmentally attractive due to mild operating conditions, but it requires long residence times and may cause partial degradation of structural biomass components. Thermal pretreatments like torrefaction and steam explosion enhance grindability and energy density, but require much higher energy input and special equipment. Water leaching has several practical advantages over these alternatives, such as lower chemical consumption, relatively simple equipment requirements, reduced environmental risks and compatibility with existing briquetting production systems. The present study shows that significant reductions of potassium, chlorine, sulfur and other undesirable constituents can be achieved by the use of heated water only at moderate operating conditions. Hence, water leaching is a feasible and economic pretreatment method, particularly in areas rich in sugarcane residues and where low-cost processing technologies are required.

3.13. Study Limitations

The present investigation mainly focused on major inorganic species, selected elemental constituents, electrical conductivity, pH, total organic carbon and the principal organic compounds present in the leachate. Other potentially important components like heavy metals, phenolic compounds, dissolved lignin derivatives, hemicellulose degradation products and additional soluble carbohydrates were not investigated. Future studies should therefore expand the spectrum of compounds investigated in order to obtain a more comprehensive understanding of the chemistry of biomass leaching and to assess more opportunities for resource recovery from the leachate.

4. Conclusion and Recommendation

Leaching was very efficient in removing inorganic compounds that form ash from sugarcane trash. Leaching decreased ash, chlorine, sulfur and nitrogen contents and increased carbon and volatile matter contents. Of the operating variables, particle size was the most significant, with smaller particles having a faster leaching rate, and temperature increased the total leaching capacity significantly. In practice, particle size reduction can reduce the required leaching bath. Heating of the leach water improves the quality of the treated fuel. Within the experimental conditions investigated, a water temperature of 50 °C, a contact time of 60 minutes, and a particle size of 1 mm provided an even effective operating condition for reducing ash-forming inorganic constituents from sugarcane trash. While smaller particles sometimes performed better at higher temperatures, such combinations are unlikely to be cost-effective at scale, so the medium

temperature with small particles provided a good balance of efficacy and feasibility. Thus, washing with hot water is suggested as a pre-treatment at the front-end for cane trash. For plants where the goal is to reduce slagging and corrosion and improve downstream fuel properties, a default initial configuration is the 50 °C, 60-minute, 1 mm configuration, which can then be optimized against site specific constraints. Further work based on these results should focus on recovery and valorization of the extracted organic acids and sugars as co-products. Improvement of analytical methods is needed to more accurately quantify water-soluble AAEM species during batch leaching to avoid overestimation resulting from organic acidity in the leachate.

References

- [1] Scott Q Turn et al., "Fuel Characteristics of Processed, High-Fiber Sugarcane," *Fuel Processing Technology*, vol. 81, no. 1, pp. 35-55, 2003. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] Yu Wang, Kai Wu, and Yu Sun, "Effects of Raw Material Particle Size on the Briquetting Process of Rice Straw," *Journal of the Energy Institute*, vol. 91, no. 1, pp. 153-162, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] Xinliang Liu, and Xiaotao T. Bi, "Removal of Inorganic Constituents from Pine Barks and Switchgrass," *Fuel Processing Technology*, vol. 92, no. 7, pp. 1273-1279, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Lei Deng, Tao Zhang, and Defu Che, "Effect of Water washing on Fuel Properties, Pyrolysis and Combustion Characteristics, and ash Fusibility of Biomass," *Fuel Processing Technology*, vol. 106, pp. 712-720, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] Musti KS Sastry et al., "Biomass briquettes: A sustainable and environment Friendly Energy Option for the Caribbean," *Fifth International Symposium on Energy*, Puerto Rico Energy Center, 2013. [[Google Scholar](#)]
- [6] Peter Thy et al., "Inorganic Composition and Environmental Impact of Biomass Feedstock," *Energy & Fuels*, vol. 27, no. 7, pp. 3969-3987, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Murari Mohon Roy, and Kenny W. Corscadden, "An Experimental Study of Combustion and Emission of Biomass Briquette in a Domestic Wood Stove," *Applied Energy*, vol. 99, pp. 206-212, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Sui Boon Liaw, and Hongwei Wu, "Leaching Characteristics of Organic and Inorganic Matter from Biomass by Water: Differences between Batch and Semi-Continuous Operations," *Industrial & Engineering Chemistry Research*, vol. 52, no. 11, pp. 4280-4289, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] J.H. Zhou, C.S. Cheung, and C.W. Leung, "Combustion, Performance, Regulated and Unregulated Emissions of a Diesel Engine with Hydrogen Addition," *Applied Energy*, vol. 126, pp. 1-12, 2014. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] Christian L'Orange, John Volckens, and Morgan DeFoort, "Influence of Stove Type and Cooking Pot Temperature on Particulate Matter Emissions from Biomass Cook Stoves," *Energy for Sustainable Development*, vol. 16, no. 4, pp. 448-455, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] C. Yu et al., "Influence of Leaching Pretreatment on Fuel Properties of Biomass," *Fuel Processing Technology*, vol. 128, pp. 43-53, 2014. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [12] Paulien Harmsen et al., "Literature Review of Physical and Chemical Pretreatment Processes for Lignocellulosic Biomass," Biomass, Report, 1-49, 2010. [[Google Scholar](#)]
- [13] K.L. Chin et al., "Reducing ash Related Operation Problems of Fast Growing Timber Species and Oil Palm Biomass for Combustion Applications using Leaching Techniques," *Energy*, vol. 90, pp. 622-630, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Prabahar Ravichandran, Duncan Gibb, and Kenneth Corscadden, "Controlled Batch Leaching Conditions for Optimal Upgrading of Agricultural Biomass," *Journal of Sustainable Bioenergy Systems*, vol. 3, no. 3, pp. 186-193, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Shibo Wu et al., "Effects of Water Leaching on the ash Sintering Problems of Wheat Straw," *Energies*, vol. 12, no. 3, pp. 1-14, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] C.A. Ogden et al., "In-Field Direct Combustion Fuel Property Changes of Switchgrass Harvested from Summer to Fall," *Fuel Processing Technology*, vol. 91, no. 3, pp. 266-271, 2010. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Hongwei Wu et al., "Removal and Recycling of Inherent Inorganic Nutrient Species in Mallee Biomass and Derived Biochars by Water Leaching," *Industrial & Engineering Chemistry Research*, vol. 50, no. 21, pp. 12143-12151, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgements

This research is jointly supported by Walter Sisulu University, Kisii University and Technical University of Kenya.

- [18] Yasas Wishvajith Bandara, Pringa Gamage, and Duleeka Sandamali Gunarathne, “Hot Water Washing of Rice Husk for Ash Removal: The Effect of Washing Temperature, Washing Time and Particle Size,” *Renewable Energy*, vol. 153, pp. 646-652, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Jinxia Fu et al., “Water Leaching for Improving fuel Properties of Pongamia Pod: Informing Process Design,” *Fuel*, vol. 305, pp. 1-13, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] “EPA Course 345: Emission Capture and Gas Handling System Inspection,” U.S. Environmental Protection Agency, 1993. [[Publisher Link](#)]
- [21] N. Said et al., “Effect of Water Washing on the Thermal Behavior of Rice Straw,” *Waste Management*, vol. 33, no. 11, pp. 2250-2256, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]