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Qualitative assessment of beach wrack and the influence of pretreatment methods on fuel characterization for energy production

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Abstract. The accumulation of beach wracks poses significant challenges to coastal management, particularly in tourist areas, affecting environmental quality and aesthetics. This study explores the qualitative characteristics of beach wrack as a biofuel source for combustion appliances. Samples collected from beaches in Veneto, Italy, were analyzed according to EN ISO standards for solid biofuels. Proximate and ultimate analysis, heating value, and ash melting behaviour were determined. Raw samples (BW-R) exhibited high moisture content (77%), a substantial ash content (44%), and low heating value (10.7 MJ kg^{-1}), making them unsuitable for direct energy applications. Pretreatments were performed to enhance the properties of the material. One portion was mechanically sieved (BW-S) to remove sand, while another was sieved and washed (BW-SW) to remove the remaining salt and sand. Sieving reduced the ash content to 24% and increased the heating value to 15.3 MJ kg^{-1}. The key improvements came from washing and sieving, which lowered ash content to 13% and increased heating value to 18.1 MJ kg^{-1}. Washing also raised the ash deformation temperature to 1,290 °C, enhancing thermal stability. Pretreatments increased C and H content while reducing S and O, with no significant change in N. Due to high ash content, mixing with sawdust was necessary, resulting in mixtures showing better properties: 4.0% ash for Mix30 (30% beach wrack, 70% sawdust) and 6.9% for Mix50 (50% each) and increased heating values. However, challenges remain in converting beach wrack into viable fuel due to material losses during pretreatment, high costs, and environmental concerns from plastics.

Key words: bioenergy, biofuels, algae, marine biomass, energy recovery.

INTRODUCTION

Beach wrack accumulates along shorelines worldwide and mainly consists of seaweed and seagrass, including roots, rhizomes, stems, and leaves at various stages of decay. It also contains a variety of marine organisms, both dead and alive, such as sponges and crustaceans of multiple sizes (Weinberger et al., 2021; Pal & Hogland, 2022). The composition and quantity of beach wrack are highly variable and depend on geographical location, seasonal changes, and the characteristics of the nearshore environment (Martins et al., 2024). For example, Weinberger et al. (2021) conducted sampling along the Schleswig-Holstein coast in the Baltic Sea, observing significant variation in the composition of beach wrack based on geographic location. In their study, seagrass and bladder wrack dominated beaches on the northwestern coastal sections, while opportunistic algae were prevalent in the southeastern parts. Moral et al. (2023) studied beach wrack along the Andalusian coast in the Mediterranean region, noting the presence of various marine species, including *Dictyota dichotoma*, *Posidonia oceanica* leaves and rhizomes, and *Zostera noltii*.

The accumulation of beach wrack worldwide is influenced by numerous temporal and environmental factors, such as wind and currents, as well as beach-specific features like slope and morpho dynamics (Robbe et al., 2021; Martins et al., 2024). According to Hyndes et al. (2022), significant amounts of macroalgal biomass (exceeding 100 kg m^{-1}) have been reported on beaches in Argentina, Western Canada, the Mediterranean Sea, and Southwestern Australia. Beach wracks are ecologically important because they provide an essential source of organic matter, serving as food and habitat for invertebrates, reptiles, small mammals, and shorebirds. However, excessive accumulations are associated with several challenges (Villares et al., 2016; Martins et al., 2024). Decomposing beach wrack releases greenhouse gases, including CH_4, CO_2, and hydrogen sulfide, contributing to environmental pollution (Pal & Hogland, 2022; Björk et al., 2023; Martins et al., 2024). Additionally, excessive accumulation negatively impacts tourism by detracting from the landscape, producing unpleasant odors, and imposing costs on local municipalities for its removal (Chubarenko et al., 2021; Pal & Hogland, 2022; Martins et al., 2024). Beach wrack is often mechanically collected and dumped in landfills, representing a significant economic burden (Weinberger et al., 2021; Pal & Hogland, 2022; Martins et al., 2024).

The frequency and volume of beach wrack accumulation are expected to increase due to extreme climatic events, global warming, and anthropogenic activities, leading to yet unquantified ecological and economic consequences (Sparrevik et al., 2015; Katakula et al., 2020; Chubarenko et al., 2021). Despite its increasing prevalence, there are limited economically viable options for valorization. In the context of a circular economy, alternative uses for beach wrack are crucial to reducing costs and mitigating its negative impacts. Numerous applications have been explored, ranging from coastal protection and bioenergy production to agricultural uses (Pal & Hogland, 2022; Moral et al., 2023; Martins et al., 2024). These efforts highlight the importance of innovative solutions for transforming beach wrack from waste into valuable resources. The energy applications for beach wrack have mainly focused on gasification and biogas production (Rudovica et al., 2021; Vincevica-Gaile et al., 2022). Burlakovs et al. (2022) investigated the biogas potential of beach wrack containing macroalgal biomass from the Gulf of Riga (Latvia) and Kalmar (Sweden) through anaerobic digestion. Results showed that pretreatment and conditioning are crucial to enable methane production. Additional tests on brown algae biomass using soaking, washing, and drying revealed that washing with fresh water mitigated salt inhibition and improved biomethane yield. Vincevica-Gaile et al. (2022) assessed the use of Baltic Sea beach wrack for gasification, obtaining syngas with promising methane content despite the material's low heating value. However, high moisture and sand content posed significant challenges. These technologies often require complex infrastructure, intensive pretreatments, and controlled conditions, which can limit large-scale implementation, particularly in decentralized or resource-constrained settings (Martins et al., 2024). In contrast, direct combustion is technically more straightforward and compatible with existing biomass boilers. Yet, its application to beach wrack remains unexplored, highlighting a critical research gap.

This study evaluates the qualitative characteristics of beach wrack collected on Italian beaches. Key parameters will be analyzed, including proximate composition, the heating value, ash melting behaviour, and ultimate analysis. Due to the high moisture content and the presence of contaminants such as sand and salt in beach wrack (Vincevica-Gaile et al., 2022), the feasibility of applying pretreatment processes will also be investigated. The study will assess the potential benefits of pretreatments such as sieving, washing, and their combinations to enhance the fuel properties of beach wrack for bioenergy applications. Moreover, the possibility of mixing beach wrack with sawdust to further improve the fuel characteristics will be assessed.

MATERIALS AND METHODS

Samples collection and preparation

Beach wrack samples were collected from various locations along the shoreline and beach of Sottomarina in Chioggia (45°12′53″N, 12°17′41″E) (Fig. 1, a). The collection was carried out on a single day, during low tide, to ensure consistency in sample conditions. Only the most recent deposits, characterized by high moisture content and lack of visible decomposition, were selected to minimize variability. At each point, material was hand-collected from the surface layer (0–10 cm depth), avoiding mixing with sand or older, more decomposed biomass. The collected material was pooled to create a single, representative batch for analysis. This approach aimed to minimize spatial heterogeneity while reflecting the general composition of beach wrack found along that coast.

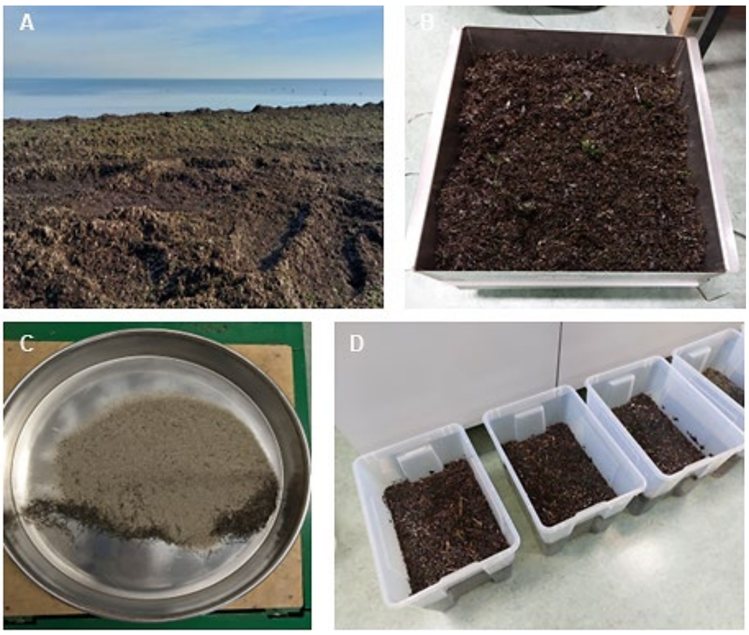

Figure 1. (A) Beach wrack accumulated along the shoreline; (B) Samples arranged in trays for air drying in an oven; (C) Sand removal during the sieving process; (D) Washing of sieved samples to eliminate residual salt and sand.

Due to their high moisture content and the presence of sand and salt, preliminary treatments were conducted to enhance their combustion performance and facilitate further analysis (Fig. 2).

The representative sample was divided into portions for a comparative assessment, each subjected to specific preparation treatments. All samples were air-dried at 60 °C for 24 hours to reduce their initial moisture content (Fig. 1, b).

The first portion of the dried beach wrack (BW-R) was used as it is, without additional processing. A second portion was sieved to remove fine particles and sand (BW-S) to improve qualitative characteristics. The sieving was carried out using a series of sieves with pore sizes of 1.00 mm, 2.00 mm, 3.15 mm, 16 mm, 31.5 mm, and 100 mm, operated for 15 minutes. Particles smaller than 2 mm, classified primarily as sand, were removed during this process (Fig. 1, c).

Recognizing that sieving alone could not effectively remove the sand adhering to the debris, a third portion of the sieved sample was subjected to an additional washing step. The material was submerged in tap water-filled tanks for 1 hour to remove residual sand and dissolve salts, resulting in the washed and sieved sample (BW-SW) (Fig. 1, d). This systematic approach enabled a comprehensive comparison of the impact of various pre-processing treatments on the characteristics of beach wrack.

Lastly, to further improve the combustion characteristics of beach wrack for combustion uses, BW-SW was mixed with spruce sawdust at two different proportions: 30% (Mix30, containing 30% beach wrack and 70% sawdust) and 50% (Mix50, containing equal parts of beach wrack and sawdust) (see Fig. 2).

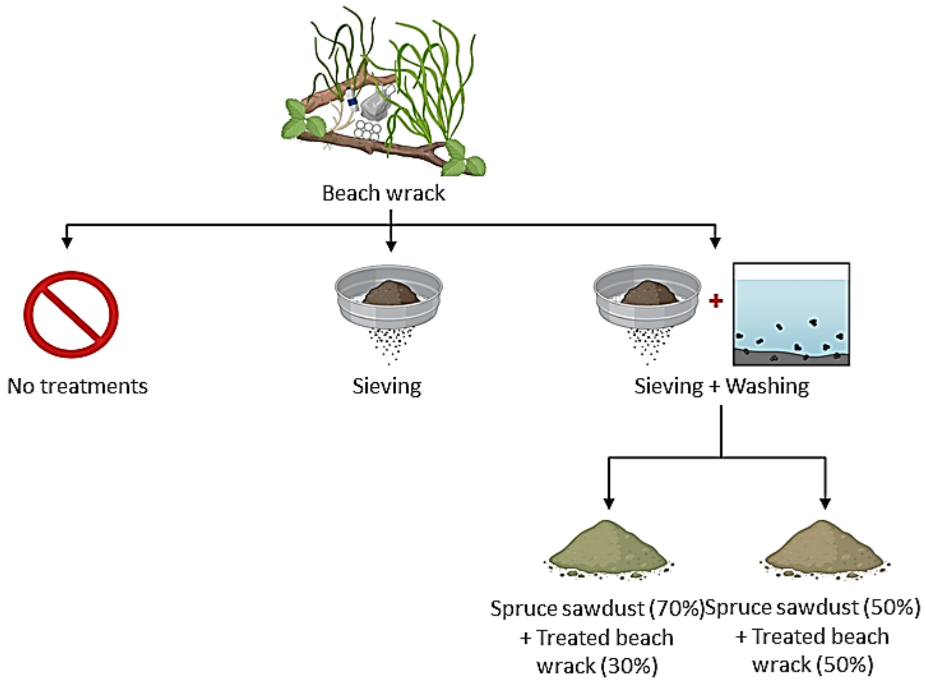

Figure 2. Experimental setup for processing beach wrack. Three treatment options were applied: no treatment (only drying), sieving, and sieving combined with washing. The latter was then mixed with spruce sawdust in two different ratios (70% sawdust + 30% treated wrack, and 50% sawdust + 50% treated wrack) to produce the final composted material.

Proximate and ultimate analysis, heating value, and ash melting behaviour

Table 1 summarizes the characterization tests conducted. The analyses included proximate analysis, heating value determination, and ash melting behaviour assessment. According to the EN ISO 14780:2017 standard, grinding was performed using a Retsch® SM100 knife mill and an IKA® MF 10 cutting mill to obtain homogeneous samples of suitable size.

Table 1. Characterization tests performed, units of measure, and reference standards

Parameter	Unit of measure	Reference standard
Proximate analysis		
Moisture content (M)	wt %, as received	EN ISO 18134-2:2024
Ash content (A)	wt %, dry basis	EN ISO 18122:2022
Volatile matter (VM)	wt %, dry basis	EN ISO 18123:2023
Fixed carbon (FC)	wt %, dry basis	/
Heating value		
Lower Heating Value, dry basis (LHVdry)	MJ kg^{-1}	EN ISO 18125:2017
Higher Heating Value, dry basis (HHVdry)	MJ kg^{-1}	EN ISO 18125:2017
Ash melting behaviour		
Deformation temperature (DT)	°C	EN ISO 21404:2020

To determine the moisture content (MC), the samples were air-dried in an oven (Binder® FD 115) at 105 °C ± 2 °C for 24 hours. The ash content (A) was determined by burning the samples at 550 °C in a muffle furnace (Nabertherm® LVT 15/11/P330). Volatile matter was determined by burning the samples at 900 °C in a muffle furnace (Nabertherm® LVT 15/11/P330) covered with a lid for 7 minutes. Fixed carbon (FC) was calculated indirectly by subtracting the volatile matter (VM) and ash content (A) from 100%, as described in Eq. (1). The higher heating value (HHV) and lower heating value (LHV) were determined using an Ika® C200 calorimeter. Using a Ckic® 5E-AF4105 the ash melting behaviour was determined.

$$FC = 100 - (VM + A) \quad (1)$$

The ultimate analysis was conducted using a CHNS analyzer (Elementar®, UNICUBE Elemental Analyzer). The oxygen concentration (%, dry basis) was calculated as the difference using Eq. (2).

$$O = 100 - (C + H + N + S) \quad (2)$$

where C is the carbon content (%, dry basis), H is the hydrogen content (%, dry basis), N is the nitrogen content (%, dry basis), and S is the sulfur content (%, dry basis).

Statistical analysis

The statistical analysis of the data was performed using a one-way ANOVA with a 95% confidence interval. Before ANOVA, the normality of the data distribution was checked using the Shapiro-Wilk test, and homoscedasticity was assessed using the Levene test. The Tukey HSD test (honestly significant difference) was used to identify significant differences among the sample means of the parameters. The statistical analyses were performed using RStudio® (v4.3.1; R Core Team 2024) and Microsoft® Excel® 2019.

RESULTS AND DISCUSSION

Pretreatments

Beach wrack requires pretreatment before it can be used effectively as a fuel source due to its high moisture content, as well as significant levels of ash from salt and sand contamination (Vassilev & Vassileva, 2016); Petrounias et al., 2023. The beach wrack collected along the shoreline exhibited an initial mean moisture content of 77.2%, which is unsuitable for combustion as substantial energy would be required to evaporate the water. Similarly high values were reported by Vincevica-Gaile et al. (2022), who observed a moisture content of 63.4% in beach wrack collected from the Baltic Sea.

Another major limitation is the high content of sand and salt in the material. Fig. 3, a illustrates the size distribution of the material after sieving. Fine materials, mainly sand, accounted for 82.5% of the total sample weight. In comparison, the remaining 17.5% consisted of larger materials (> 3.15 mm), with 14.0% exceeding this size threshold (Fig. 3, b). This indicates that most of the beach wrack weight is composed of undesirable fines and sand, which must be removed to reduce the ash content and ensure optimal combustion performance. The values obtained are significantly higher than the percentages reported in previous studies (Vincevica-Gaile et al., 2022). This considerable discrepancy may be attributed to differences in sampling methods, as well as climatic factors such as rain and storms, which can increase or decrease the sand content in the algal biomass (Vincevica-Gaile et al., 2022).

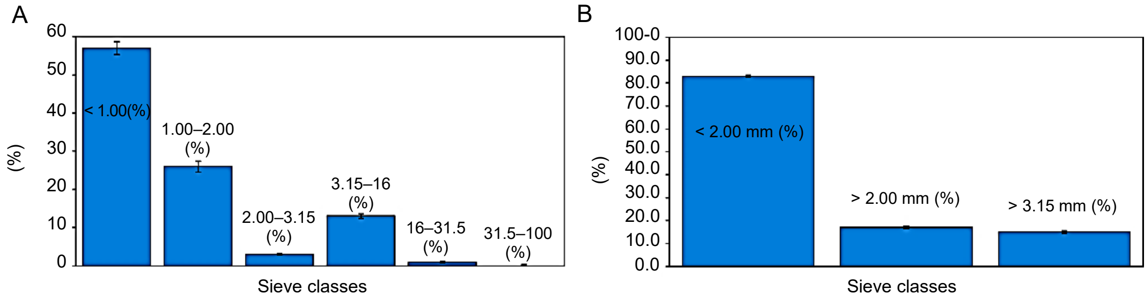

Figure 3. (A) Size distribution of beach wrack; (B) Percentage of sand removed and non-fine material after sieving.

Sieving alone is effective in mechanically separating a substantial portion of the sand and reducing salt levels. However, washing is necessary for complete salt removal. The washing eliminates residual salt and reduces the material weight, removing an additional 21.9% of the mass.

Proximate analysis

Fig. 4 (a, b, c, d) illustrates the proximate analysis results for raw beach wrack (BW-R) and pretreated samples. The moisture content was determined after air-drying the samples and allowing them to equilibrate at room temperature. BW-R exhibited higher moisture content than the pretreated materials. This confirms that pretreatments, particularly drying and washing, effectively reduce water retention, enhancing the material's suitability for combustion.

The high ash content in the beach wrack poses a critical challenge, worsening the combustion performance. Ash content significantly impacts factors such as ash deposit formation, storage, and disposal (Obernberger et al., 2006). Furthermore, elevated ash levels in biomass can contribute to slagging and fouling in biomass boilers, reducing their operational reliability and performance (Racero-Galaraga et al., 2024).

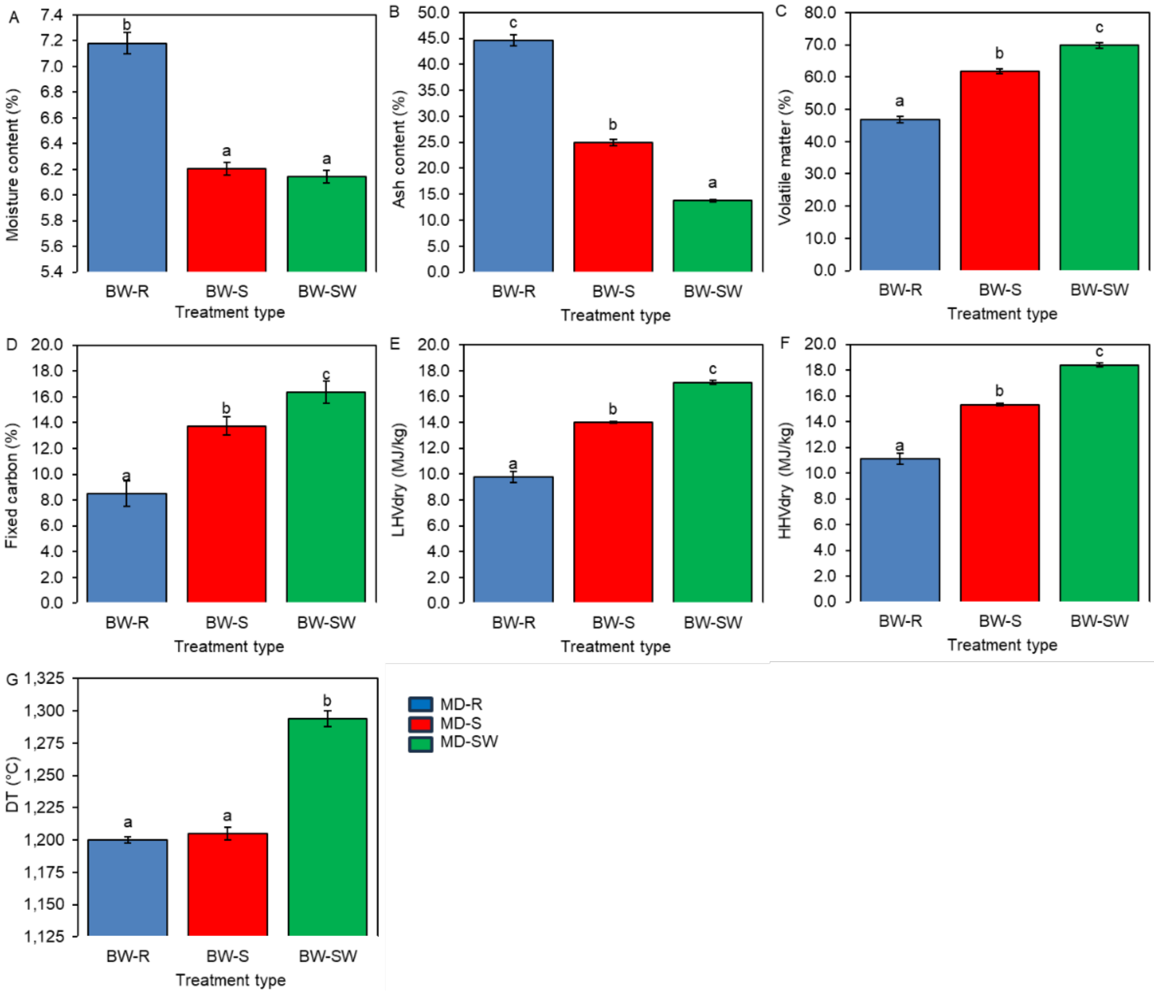

Figure 4. Mean values of moisture content (A), ash content (B), volatile matter (C), fixed carbon (D), lower heating value (E), higher heating value (F), and ash melting behaviour (G) of beach wrack samples. Mean values marked with different letters indicate significant differences according to Tukey's HSD post hoc test ($P < 0.05$). Error bars represent the standard deviation.

The untreated material exhibited an ash content of 44.6%, primarily attributed to the significant presence of sand and salt deposits accumulated in the marine environment. Sieving markedly reduced the ash content by effectively removing a substantial portion of the entrained sand, while enhancing the proportions of volatile matter (VM) and fixed carbon (FC) by eliminating inert material. BW-S showed a reduced ash content of 25.0%, representing a reduction of 43.95% compared to BW-R. Despite this improvement, the ash content remains relatively high and may hinder combustion performance. The washing of the sieved material (BW-SW) further improved its quality by promoting the removal of residual salts and finer sand particles adhered to the algal matrix. BW-SW decreased ash content to 13.8%, representing a reduction of 44.8% compared to BW-S. However, even in the washed material, the ash content remains elevated. This persistent inorganic fraction is largely due to the intrinsic chemical composition of marine macroalgae and the strong adhesion of mineral particles to the biomass surface, as also reported by Petrounias et al. (2023). Therefore, even the best-performing sample (BW-SW) retains non-negligible ash levels, which may limit its direct application in conventional combustion systems without further pre-treatment or co-processing strategies. The ash content detected in beach wrack is significantly higher than that of woody biofuels commonly used for bioenergy production, such as wood chips and sawdust, which typically exhibit ash contents ranging from 0.3% to 6.0% (ISO, 2021). The elevated ash content in beach wrack not only reduces combustion performance and shortens equipment lifespan but also increases challenges related to ash disposal and maintenance costs in power plants (Fitria et al., 2025).

The pretreatments also significantly influenced the volatile matter and fixed carbon content. In both cases, these parameters increased with treatment. Volatile matter content is critical for determining a fuel's ignition characteristics, as materials with higher VM ignite more easily at lower temperatures and require less energy for combustion (Vincevica-Gaile et al., 2022). However, a higher VM content may also result in a lower heat output because a substantial portion of the material is lost as volatiles during combustion. On the contrary, the fixed carbon content, which correlates with the calorific value, is more favourable for energy production (Racero-Galaraga et al., 2024). The VM content increased from 49.9% in BW-R to 61.9% in BW-S and 69.9% in BW-SW. These increases indicate a significant enhancement in fuel reactivity and ignition properties due to the pretreatments applied.

Fixed carbon represents the fuel fraction that remains after the moisture removal and volatile components. This parameter is closely associated with the calorific value and serves as a critical indicator of the energy potential of biomass. It is important to clarify that fixed carbon refers not to pure carbon but to the carbon content within organic compounds that are formed in conjunction with other elements (Yap et al., 2023; Racero-Galaraga et al., 2024;). Among the beach wrack samples, fixed carbon increased from 8.5% in BW-R to 13.7% in BW-S and 16.3% in BW-SW.

The proximate analysis results observed in this study align closely with the findings reported in previous literature. Vincevica-Gaile et al. (2022) documented an ash content of 22.1%, volatile matter of 58.2%, and fixed carbon of 15.4%, comparable to those observed in the sieved sample (BW-S). However, washing further enhanced the quality, as evidenced by the improved values in the washed sample (BW-SW). A study by Felix et al. (2022) reported proximate data with a moisture content of 10.46%, ash content of 29.29%, volatile matter of 48.85%, and fixed carbon content of 11.60%. Vincevica-Gaile et al. (2022) claimed that beach wrack composition varies significantly due to the diversity of algal species and seasonal factors. This variability poses challenges for standardization, which is crucial for using beach wrack as a biomass feedstock for bioenergy applications.

Heating values

Determining heating values is a crucial step in selecting biomass conversion pathways, as HHV is a key indicator of the biomass's potential for energy conversion (Vincevica-Gaile et al., 2022). Pretreatments such as sieving and washing enhance fuel quality by increasing fixed carbon and reducing ash content. Fixed carbon positively correlates with heating values, making it a critical parameter to assess fuel efficiency (Racero-Galaraga et al., 2024).

In this study, the lower heating value (LHV) increased from 9.8 MJ kg^{-1} in the raw sample (BW-R) to 14.0 MJ kg^{-1} in the sieved sample (BW-S) and further to 16.3 MJ kg^{-1} in the sieved and washed sample (BW-SW). Similarly, HHV exhibited a parallel trend, increasing from 11.1 MJ kg^{-1} in BW-R to 15.3 MJ kg^{-1} in BW-S and reaching 18.4 MJ kg^{-1} in BW-SW.

For comparison, Vincevica-Gaile et al. (2022) reported a LHV of 13.7 MJ kg^{-1} and an HHV of 14.7 MJ kg^{-1} for beach wrack collected in the Baltic region. These values are comparable to those of the BW-S sample but notably lower than those of the BW-SW, underscoring the significant impact of pretreatments on improving the fuel properties of beach wrack. Nevertheless, when compared to forest biomass, such as wood chips and sawdust, which typically exhibit HHV values ranging from 18.5 to 20.5 MJ kg^{-1} (ISO, 2021), beach wrack still presents significantly lower energy content.

Ash melting behaviour

The ash melting behaviour is significantly influenced by the elemental composition of the fuel (Racero-Galaraga et al., 2024; Obernberger et al., 2006). Low ash melting temperatures can lead to fouling and corrosion in furnaces and boilers. All samples demonstrated high deformation temperatures (DT), exceeding 1,200 °C (Fig. 4, g). Sieving showed minimal impact on DT, with a slight but statistically insignificant increase. In contrast, washing significantly improved the melting temperature of the ash, increasing it to almost 1,300 °C. This improvement indicates that washing effectively reduces problematic elements, particularly alkaline elements such as Na and Cl found in salt, which contribute to low ash melting temperatures (Racero-Galaraga et al., 2024). This, in turn, further enhances the suitability of the material for combustion applications.

Ultimate analysis

Fig. 5 presents the results of the proximate analysis of beach wrack. The C content significantly increased after the pretreatments, rising from 37.6% in BW-R to 39.4% in BW-S and 45.7% in BW-SW. The H content slightly increased from 4.2% in BW-R to 4.6% in BW-S; however, this change was not statistically significant. Conversely, washing significantly increased H content, resulting in a concentration of 5.4%. The C and H contents positively influence the HHV values, while the O content negatively affects them (Obernberger et al., 2006). Accompanied by a reduction in ash content, this explains why BW-SW exhibits superior energy content compared to the other samples.

The treatments did not significantly affect the nitrogen (N) content; no significant differences were observed among the samples. Nitrogen content is critical in air pollution, as it contributes to nitrogen oxides release (NOx, NO, and NO_2). An increase in N concentration in the fuel correlates with higher NOx emissions (Ozgen et al., 2021).

S and O contents significantly decreased from untreated samples (BW-R) to the sieved and washed samples (BW-SW). Low sulfur content in the fuel is essential to minimize the risk of sulfur dioxide (SO_2) emissions. Moreover, high sulfur content primarily increases the risk of corrosion in combustion appliances (Obernberger et al., 2006).

The obtained values are significantly higher than those reported by Vincevica-Gaile et al. (2022), who analyzed beach wrack from the Baltic Sea. Their samples contained 37.33% C and 30.52% O, with average contents of H, N, and S at 4.66%, 3.33%, and 1.23%, respectively. This discrepancy can be attributed to differences in the origin and composition of the beach wrack.

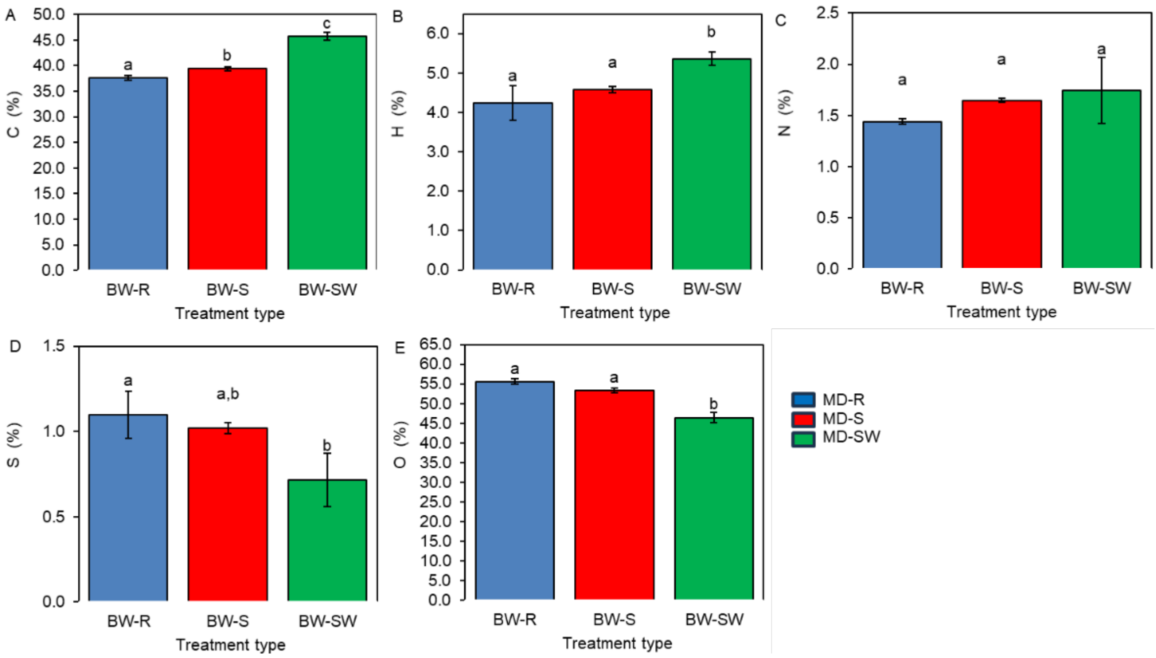

Figure 5. Mean values of carbon content (A), hydrogen content (B), nitrogen content (C), sulfur content (D), and oxygen content (E) of beach wrack samples. Mean values marked with different letters indicate significant differences according to Tukey's HSD post hoc test ($P < 0.05$). Error bars represent the standard deviation.

Effects of Sawdust Blending on Beach Wrack

Fig. 6 presents the results of the proximate analysis of the mixtures of beach wrack (BW-SW) with spruce sawdust. Spruce sawdust is characterized by an extremely low ash content (0.3%) compared to beach wrack, which contributes to a marked reduction in the overall ash content of the mixtures. Specifically, the ash content decreased to 6.9% in Mix50 and 4.0% in Mix30, indicating a substantial improvement in terms of ash-related combustion issues. In addition to reducing ash content, the incorporation of sawdust led to a notable decrease in volatile matter and a corresponding increase in fixed carbon content, compared to beach wrack alone. These changes are favorable for combustion stability and energy output. Furthermore, given that spruce sawdust has a significantly higher heating value (LHV > 19 MJ kg^{-1} and HHV > 20 MJ kg^{-1}), the mixtures also greatly improve their overall energy content. This makes the BW-sawdust blends more suitable for energy applications in conventional combustion systems.

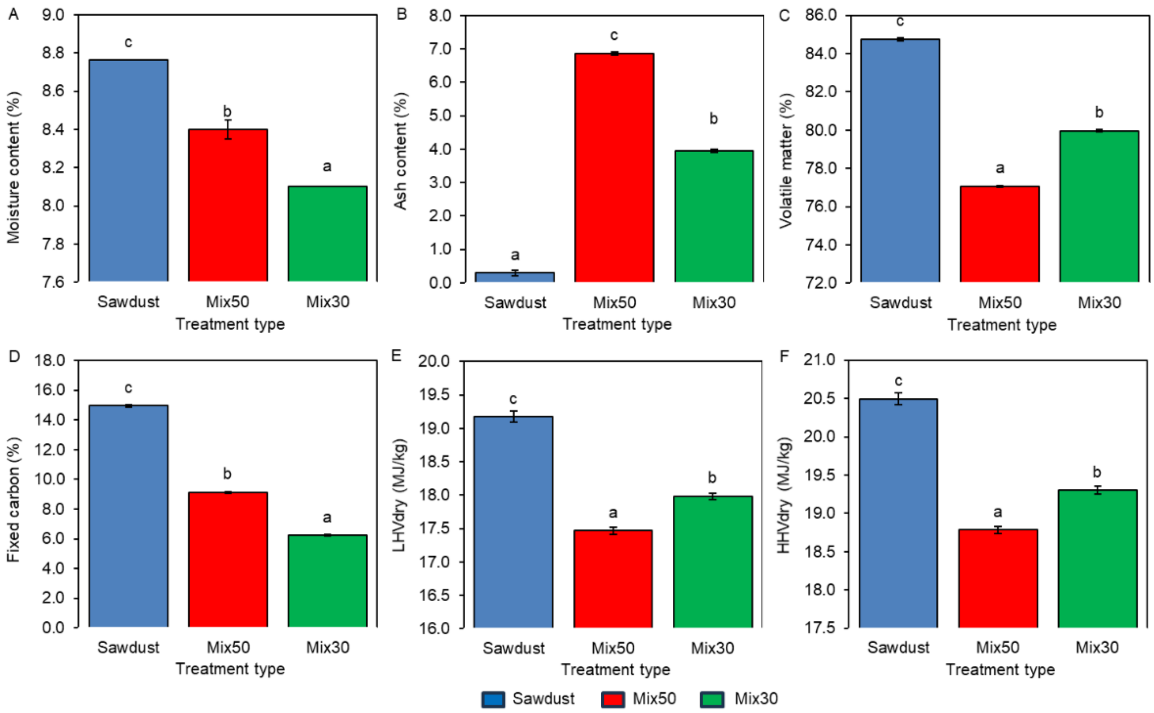

Figure 6. Mean values of moisture content (A), ash content (B), volatile matter (C), fixed carbon (D), lower heating value (E), and higher heating value (F) of mixtures of beach wrack with sawdust. Mean values marked with different letters indicate significant differences according to Tukey's HSD post hoc test ($P < 0.05$). Error bars represent the standard deviation.

Mixing beach wrack with sawdust significantly influences the results of the ultimate analysis (Fig. 7). Sawdust exhibits a significantly higher carbon content than raw and pretreated beach wrack, which contributes to improved fuel characteristics when blended. In particular, the Mix30 blend, composed of 70% sawdust and 30% beach wrack, achieved the highest carbon concentration at 48.6%, slightly higher than Mix50 (47.9%). However, the difference between the two mixtures was not statistically significant ($P > 0.05$). The hydrogen content remained consistent across all three materials (sawdust, Mix30, and Mix50), with no statistically significant differences observed ($P > 0.05$). In contrast, notable differences were found in nitrogen concentrations. Sawdust contained negligible nitrogen (0.1%), while Mix30 and Mix50 exhibited significantly higher values, averaging 0.6% and 0.9%, respectively. As highlighted in previous sections, nitrogen content is directly associated with NOx emissions during combustion. Nitrogen concentrations exceeding 0.6% may lead to elevated levels of nitrogen oxides, necessitating the implementation of proper emission control technologies in power plants (Obernberger et al., 2006). Similarly, sulfur was nearly absent in sawdust but present in higher concentrations in both blends, following the pattern observed for nitrogen. The oxygen content was also significantly higher ($P < 0.05$) in the mixtures than in sawdust alone, reflecting the influence of beach wrack's oxygen-rich marine biomass component. Based on the obtained results, blending sawdust with beach wrack leads to a notable improvement in fuel quality, specifically by increasing the carbon and hydrogen content, which are key contributors to higher heating value, and by reducing nitrogen and sulfur levels associated with pollutant emissions.

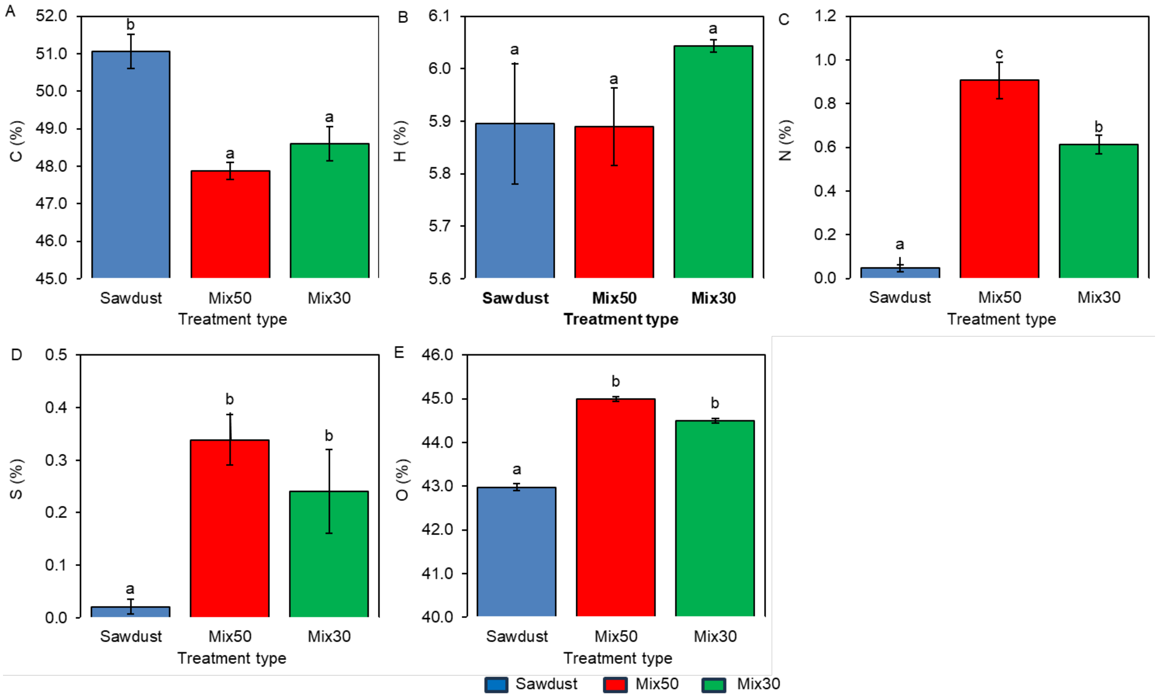

Figure 7. Mean values of carbon content (A), hydrogen content (B), nitrogen content (C), sulfur content (D), and oxygen content (E) of mixtures of beach wrack with sawdust. Mean values marked with different letters indicate significant differences according to Tukey's HSD post hoc test ($P < 0.05$). Error bars represent the standard deviation.

Challenges and considerations in the use of beach wrack as a biofuel

The qualitative analysis of beach wrack underscores the need for pretreatments to enhance its suitability as a fuel. Raw beach wrack contains excessively high concentrations of sand and salt, resulting in elevated ash content and reduced heating values. Among the pretreatment methods, sieving alone proves insufficient; combining sieving with washing is essential to improve the fuel's characteristics significantly. Based on the results, pretreated beach wrack could be used in medium- to large-scale power plants (500 kW to 5 MW) employing grate or fluidized bed combustion systems. Blending beach wrack with sawdust offers an effective solution to lower the excessive ash content found in beach wrack alone. As previously reported in the literature, co-combustion of agricultural residues and other biomass materials with forestry by-products such as sawdust has been shown to significantly enhance fuel characteristics, combustion performance, and contribute to a reduction in carbon emissions (Nie et al., 2022; Mencarelli et al., 2025). However, for beach wrack to be considered a viable and stable biomass resource, further studies are needed to quantify its composition, variability, and seasonal availability across different coastal areas. This information is essential for developing reliable supply chains and integrating them into energy systems.

It is important to note that beach wrack is not composed solely of organic materials such as algae, tree leaves, and wood branches (Vincevica-Gaile et al., 2022). It may also include anthropogenic waste, such as metals and, notably, plastics (Martins et al., 2024). For example, Vincevica-Gaile et al. (2022) detected approximately 3.0% of plastic and wood debris in the beach wrack of the Baltic Sea.

The presence of such waste requires careful consideration, as combustion could lead to the release of harmful air pollutants. Burning plastic produces a variety of air pollutants, including gases (e.g., NOx, CO, VOCs), particulate matter, and toxins. The types of pollutants released are influenced by the specific types of plastic being burned and the conditions under which combustion occurs, including temperature, airflow, and residence time (Song & Hall, 2020). Therefore, using beach wrack for energy production must be accompanied by adequate abatement systems to minimize environmental impact.

While the characteristics of beach wrack after pretreatment make it an interesting option for energy generation, economic viability remains a significant limitation. Beach wrack can contain up to 80% sand, dramatically reducing the proportion of usable material. Additionally, washing decreases the usable fraction by removing residual salt and sand. Mechanical treatments (sieving and washing) and thermal treatments (drying) represent significant costs, which can substantially impact the overall economic feasibility of the process (Vincevica-Gaile et al., 2022; Preethi et al., 2023; Martins et al., 2024).

CONCLUSIONS

The presented study evaluated the qualitative characteristics of beach wrack through proximate analysis, heating value determination, and ash melting behavior. In addition, it investigated the effects of different pretreatment strategies, including sieving, washing, and the combination of beach wrack with sawdust (at 30% and 50% ratios), on these fuel-relevant parameters. Beach wrack has potential as a bioenergy feedstock but requires pretreatment to enhance its fuel characteristics.

Raw beach wrack was characterized by an excessively high ash content (44.6%) and low heating values (9.8–11.1 MJ kg^{-1}), making it unsuitable for direct combustion. Sieving removed 82.5% of the sand by weight and reduced the ash content to 25.0%, yet this was not sufficient to meet typical biomass fuel standards. The combination of sieving and washing (BW-SW) proved to be a critical step, significantly lowering the mean ash content to 13.8% and increasing the heating value to 17.1–18.4 MJ kg^{-1}. However, the ash content of BW-SW remains considerably higher than that of terrestrial biomass, limiting its use in conventional combustion systems. Blending BW-SW with sawdust proved highly effective, reducing the ash content to 6.9% in Mix50 and 4.0% in Mix30. These blends also showed improved carbon content and heating values, along with reduced nitrogen and sulfur contents, which are important for minimizing emissions.

Overall, beach wrack can be valorized for energy purposes, especially when mixed with woody biomass like sawdust, but its use is more suitable for medium- to large-scale plants equipped with advanced pollution control systems. Further research is needed to refine pretreatment methods and evaluate the economic and environmental sustainability of beach wrack-based fuels, particularly in coastal areas where this biomass is readily available.

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