

Article

Assessment of Quality and Combustion Characteristics of Briquettes Derived from Giant Hogweed Biomass

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Abstract

The presence of Giant Hogweed (*Heracleum mantegazzianum*) in agricultural landscapes raises concerns due to its impacts on agroecology. Physically removed biomass can serve as a feedstock for solid biofuel, representing a viable strategy reducing reliance on herbicides. Giant Hogweed's bioenergy potential is currently underexplored, particularly regarding its seasonal variations in properties and the environmental impacts resulting from its use as a biofuel. This study assessed the processability of Giant Hogweed biomass into briquettes, to determine their mechanical durability and to evaluate their basic emission characteristics during combustion in a device commonly used at the household level. Biomass was sampled at two specific stages of plant development for a comparative study of briquette properties. For both summer- and autumn-harvested biomass, a high mechanical durability of the produced briquettes, approximately 97%, was achieved. Only carbon monoxide emissions from summer-harvested biomass exceeded the limits; nitrogen oxides concentrations were within the limits for both. Thermogravimetric analysis and differential scanning calorimetry revealed decomposition patterns. Autumn-harvested biomass showed better potential for briquetting, highlighting the advantages of later collection. The findings demonstrate the potential of plant and applied processing technology for valorisation as a solid biofuel, while certain aspects still need consideration.

Keywords: *Heracleum mantegazzianum*; plant biomass; briquettes; combustion gases; mechanical durability



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1. Introduction

Weeds are the foremost biological factor limiting crop growth and yield, and reliance on chemical herbicides contributes to resistance, pollution and adverse ecological impacts [1]. Consequently, physical removal of undesired plants for conversion into valuable products is encouraged and may serve as an effective control method [2]. Over recent decades, the use of weed plant biomass for the production of densified biofuels has emerged as a promising area of research [3,4], together with invasive weeds not commonly used for energy purposes such as problematic Bohemian and Japanese Knotweed [5–7] and Common Reed [8,9]. The findings of studies indicate that this approach of biomass utilization

represents good potential to be used as a feedstock in addition to typical biomass sources for bioenergy, such as agricultural and forestry residues. According to Nackley [10], supplying small amounts of invasive weed biomass to biomass-fired power boilers is sustainable and can significantly reduce their populations locally [10].

At present, the Giant Hogweed is among various other problematic weeds. *Heracleum mantegazzianum* is the most widespread invasive *Heracleum* species in the world, from the USA to New Zealand. It was officially reported in 33 European countries and garnered special attention due to its ability to induce severe skin phototoxic reactions in individuals upon their contact with fresh biomass [11,12]. The species has been detected as a weed in agricultural landscapes [13,14]. Müllerová [15] reported that biomass yields in stands of *H. mantegazzianum* fresh aboveground biomass may reach up to 94 t/h, corresponding to approximately 7 t/ha. This neophyte, due to its specific biological and ecological traits, has proven resistant to various control measures. Despite research into the use of biological methods (including herbicides, insects, fungi, and parasites), none have shown any real potential for effective eradication of populations [16]. Measures targeting this species without the use of herbicides, particularly the mechanical clearing of invaded sites from aboveground parts of plants, can result in large quantities of biomass within these sites [17]. This biomass can be utilized for bioenergy over the course of removal efforts, providing energy while contributing to its gradual eradication from the environment [18,19]. Gramauskas et al. [20] highlighted that invasive herbaceous biomass generation incurs no input costs through standard cultivation practices, such as sowing, fertilization, or maintenance. This suggests that the utilization of biomass as a feedstock could provide a low-cost solution for weed management.

Importantly, although currently information on the bioenergy potential of *H. mantegazzianum* is scarce, the species *Heracleum sosnowskyi* has already been the subject of research as a feedstock for bioenergy applications. Studies to date have primarily focused on solid biofuels in the form of pellets, exploring the optimal proportion of biomass as an additive to traditional feedstock for pellets [21], production of pellets with binders [22], and some properties of the pellets [23,24]. Given the similarities between species, findings from *H. sosnowskyi* may provide valuable information applicable also for *H. mantegazzianum* [16]. However, key data on certain properties of biomass important for bioenergy use are still lacking.

The deployment of bioenergy technologies is important as a pathway for climate change mitigation [25]. Biomass will become a leading renewable energy source capable of substituting fossil fuels in the future [26,27]. Therefore, there is a need for studies addressing the efficient and safe utilization of biomass for bioenergy applications.

Biomass from weeds is readily, widely available; however, raw biomass exhibits a low energy density [28]. Densification technology, according to Kabas et al. [29] and Gendek et al. [30], is an efficient method to enhance the mass and energy density of biomass per unit volume without requiring extensive effort or resources. Densified biomass products are applicable in energy production as well as in residential or commercial heating [31].

Another issue is that combustion of raw herbaceous biomass is also associated with elevated levels of emissions [28]. Carbon monoxide (CO) and nitrogen oxide (NO_x) emissions from the combustion of solid biofuels are subject to the regulated limits due to their potential to negatively affect air quality. Both are associated with harmful impacts on respiratory and cardiovascular health [32]. Noteworthy, NO_x emissions contribute significantly to the formation of acid rain [33,34]. The combustion properties of weed biomass that have not been investigated may lead to undesirable effects during use. Evaluating emissions released during combustion of such biofuels is necessary.

The study aims to evaluate the viability of *Heracleum mantegazzianum* biomass as a feedstock for briquettes production and to perform their combustion under operating conditions representative of those typical for household use. The biomass of the plants at two different developmental stages was processed separately for further determination of mechanical durability, combustion and thermogravimetric analysis. The emission concentrations of CO and NO_x were evaluated as a function of the coefficient of excess air and flue gas temperature.

2. Materials and Methods

2.1. Sample Collection and Production of Briquettes

Above-ground biomass of *Heracleum mantegazzianum* Sommier et Levier from the invaded site was selected as the target material for this study. A sampling site with a population of *H. mantegazzianum* was identified using species occurrence records provided by the publicly available online Species Occurrence Database maintained by the Nature Conservation Agency of the Czech Republic. The site is located at the edge of the field margin in the Central Bohemian region near the Prague district Zličín. The monospecific stand, consisting of naturally established plant individuals, was selected.

According to Prochnow et al. [35], the chemical composition and physical properties of biomass vary with vegetation stage because studies indicate that delaying harvest is associated with improved biofuel characteristics, for example, higher lignin-derived carbon content. Therefore, the collection process of biomass samples for briquette production involved two harvests from the single selected stand, aligned with critical phases of the species' life cycle. The biomass sample was collected at peak biomass yield in mid-July during flowering (hereafter referred to as summer-harvested). The autumn-harvested post-senescent biomass sample was obtained in mid-November (hereafter referred to as autumn-harvested) (Figure 1). Biomass of *H. mantegazzianum* within the stand was used in the first year, and the second harvest was conducted on the biomass of the same species that had naturally emerged in the same stand the following year.



Figure 1. Plants of *Heracleum mantegazzianum* on the site.

Manual loppers were used to cut the plants and chop them into manageable lengths for transportation in sealed bags of 100 L volume. The collected biomass was air-dried under sheltered conditions and was mechanically shredded with a hammer mill 9FQ-40 (5.5 kW), using a sieve with openings of a diameter of 8 mm for the production of briquettes.

A sample sets of briquettes for testing was prepared using a hydraulic briquetting press (Figure 2a), BrikStar model CS 25 (manufactured by the Brikli company, Malšice, Czech Republic). This equipment is designed for small- to medium-scale applications and operates with a compression of 18 MPa. The diameter of the compression cylinder is 65 mm (which defines the cross-sectional size of the prepared briquettes). The biomass

used for briquette production was composed entirely of untreated plant material, with no additives introduced during processing. The moisture content of the material for briquette production was around 8–9%. Each biomass harvest resulted in 66 produced briquettes.



Figure 2. Briquetting press (a) and rotation drum (b).

2.2. Determination of Mechanical Durability

The mechanical durability (DU) of the produced briquettes was determined according to ISO 17831-2:2015 [36], using a standardized automatic rotating abrasion drum (BT 105, manufactured by RIAE, Prague, Czech Republic) (Figure 2b).

A test sample weighing 2 ± 0.1 kg of briquettes was placed in the drum, where the test sample was exposed to impacts caused by collisions with each other and with the drum's inner wall at a rotation speed of 21 ± 0.1 rpm for 5 min. The DU was determined based on the mass retained after removal of the abraded particles. The final value was expressed as the average of two replicates.

The mechanical durability of briquettes was calculated using the following formula:

$$DU = \frac{m_1}{m_2} \times 100\%, \quad (1)$$

where DU is the mechanical durability (%), m_1 is the mass of the test sample before the test (g), and m_2 is the mass of the test sample after testing and sieving (g).

Following the mechanical durability determination, the briquettes were subjected to combustion and emissions measurement.

2.3. Combustion Tests of Briquettes

Combustion tests were conducted using a manually fed combustion device equipped with a fixed grate, emulating combustion of the prepared briquettes in a device commonly used for domestic heating (manually operable local space heater). The unit has a rated thermal output of 8 kW, with a standard fuel consumption of 2.5 kg/h, as specified by the manufacturer of the combustion device. The conditions were maintained manually during measurements.

During combustion, emissions were measured using a Madur GA-60 flue gas analyser (Madur Polska Sp. Z. O.o., Zgierz, Poland). The probe was inserted into the exhaust pipe. The analyser recorded flue gas temperature along with O_2 , CO, and NO_x concentrations. The combustion tests were conducted under controlled operating conditions flue gas temperature (T_{fg}) and excess air ratio (n). The sensor signals were proportional to the volume concentration of the monitored components, expressed in ppm. The concentrations of the dry flue gas components were recalculated to standard conditions (0 °C and 101.325 kPa) and expressed in $mg \cdot m^{-3}$, referenced to a flue gas oxygen content of 13% by volume [37].

The results of emission measurements were processed using regression analysis (Microsoft Excel 2309, Microsoft 365) to convey the dependence of CO and NO_x on excess air

ratio and flue gas temperature. Polynomial functions of the second degree were selected as the most suitable means of representing this dependence.

2.4. Thermogravimetric Analysis and Differential Scanning Calorimetry

A thermogravimetric analyser Setaram Setsys Evolution model S60 (Setaram Instrumentation, Tours, France) was used for thermal decomposition of the biomass (heating rate of $10\text{ }^{\circ}\text{C min}^{-1}$ under an air atmosphere). Dry analytical samples (23.2 mg of summer-harvested and 10.7 mg of autumn-harvested) were used for thermogravimetric analysis, where the loss in mass of the biomass was studied as a function of temperature and heat flow. The outputs were expressed as TGA graphs. The blue curve represents the heat rate, and the green curve the weight loss (TG) as a function of temperature [38].

3. Results and Discussion

3.1. Mechanical Durability

Densified biomass of *H. mantegazzianum* intended for energetic use in the form of briquettes (diameter of 65 mm, length 46.32 ± 10.01 mm) for combustion was tested. The suitability of briquetting technology (particularly using the hydraulic press) for the processing of the studied biomass was investigated by means of standardized procedures. Summer-harvested and autumn-harvested types of biomass were separately used for briquette production.

The aspects of biomass briquettes' practical applicability, such as mechanical durability, are of particular importance due to the growing interest in replacing hard coal, which is recognized to be less prone to damage during handling [39]. For this reason, briquettes made from biomass should be characterized by the highest possible mechanical durability. According to [40], the mechanical durability is a key indicator of solid biofuel quality, as insufficient mechanical strength of briquettes may cause them to break apart or crumble back into raw material during handling and storage.

The briquettes derived from *H. mantegazzianum* summer-harvested biomass exhibited a mechanical durability of 97.39%, whereas the briquettes produced from autumn-harvested material exhibited a mechanical durability of 97.8%. The obtained closely similar results indicate that the physical properties influencing the bonding behaviour of *H. mantegazzianum* biomass did not change substantially throughout plant development, specifically from flowering to senescence.

With values exceeding 95%, the results align with the commonly accepted guiding value for briquettes [41]. As an illustration, Figure 3 shows that the briquettes retained their original form with only minor losses of material.



Figure 3. Sample batch after one of the replicates of testing (autumn-harvested biomass).

Furthermore, the obtained results are comparable to the value of testing briquettes made from industrial hemp (size of particles less than 3.8 mm) of 97.7% as reported by Ivanova et al., 2014 [42]. Compared to briquettes made from woody material, for example, Platan chips, the DU was achieved 96.7% with 7.7% MC [43].

The fraction of feedstock is among the critical factors for the briquetting process as it affects the costs of material grinding [39]. A particle size of 8 mm was adopted for biomass grinding in this study, resulting in briquettes exhibiting satisfactory mechanical strength for both types of *H. mantegazzianum* biomass.

Gramauskas et al. [20] reported on the mechanical durability of briquettes made from biomass compositionally similar to the studied material, *H. sosnowskyi*, using a screw briquetting press, achieving a weight loss of 1.26%.

Based on the results of testing, the biomass of *H. mantegazzianum* appeared to facilitate the formation of strong interparticle bonds when applying the conditions mentioned in the present study. These findings are consistent with results reported for biomass like cotton stalks, eucalyptus sawdust, and bamboo fibre [44].

3.2. Assessment of Combustion Behaviour of Briquettes

Considering the densified biomass of *H. mantegazzianum* for thermal conversion in combustion units, there is a need for insight into emission-related combustion behaviour. Biomass typically shows uneven behaviour during combustion, which may result in operational problems and pollutant emissions exceeding the limits [45–47].

The CO and NO_x emissions released during the combustion of prepared briquettes are summarized in Table 1. The excess air ratio and flue gas temperature were taken into consideration during measurement for each type of emissions.

Table 1. Summary of emissions concentrations from combustion of *H. mantegazzianum* biomass briquettes converted to reference oxygen content 13% vol. in flue gas and normal gas conditions.

	T _{fg}	n	CO	NO _x
	(°C)	(-)	(mg·m ⁻³)	(mg·m ⁻³)
Summer-Harvested Biomass				
Mean	396.38	2.72	4850.46	246.11
SD	9.72	0.14	188.95	13.03
Max	443.00	4.60	5970.28	363.00
Min	308.10	1.85	1696.45	163.37
Autumn-Harvested Biomass				
Mean	308.69	2.10	1750.06	144.16
SD	3.00	0.03	49.91	2.76
Max	340.00	2.52	2419.83	165.49
Min	269.10	1.74	1280.06	38.47

T_{fg} = Flue gas temperature; n = excess air coefficient; CO = carbon monoxide; NO_x = oxides of nitrogen; SD—standard deviation.

The carbon monoxide concentrations in the flue gas of combusted summer-harvested biomass reached up to 6000 mg·m⁻³ (Figure 4a,b). As presented in Table 1, the average value exceeded the prescribed CO emission limits established by relevant regulations (at 2000 mg·m⁻³) [48]. According to [49], under conditions of a low excess air coefficient, incomplete combustion occurs and high concentrations of carbon monoxide are found.

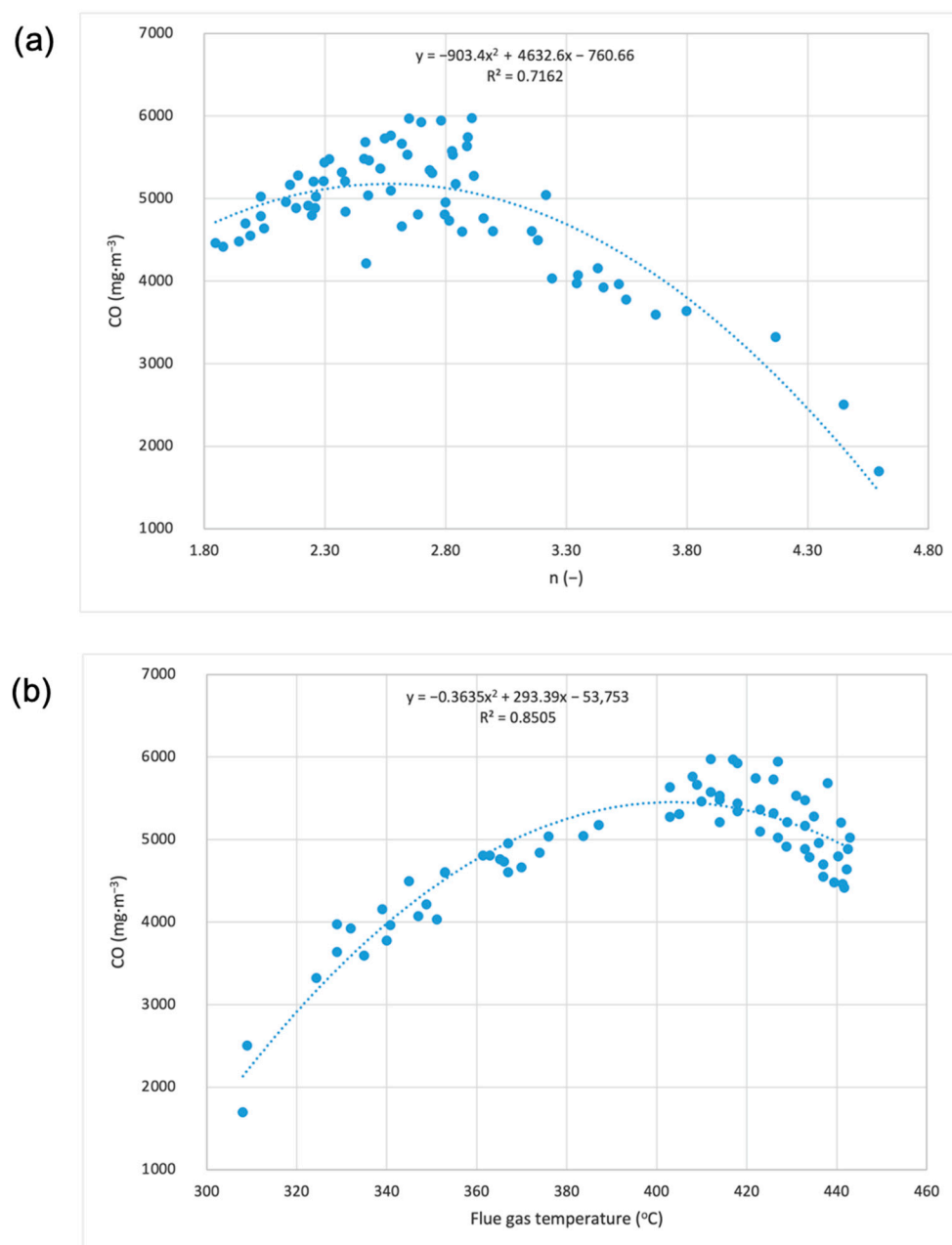


Figure 4. CO emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (summer-harvested biomass).

The elevated CO emissions from summer-harvested biomass observed underscore the importance of harvest timing planning for the processing of solid biofuels. To ensure the safe and environmentally acceptable use of Giant Hogweed biomass as fuel, attention is required for combustion optimization and emission mitigation techniques.

The NO_x concentrations in flue gas of summer-harvested biomass increase with a higher excess air ratio, but temperature decreases because of cooling (see Figure 5a,b). The requirement for average emission concentrations of NO_x, where the limit value is 500 mg·m⁻³ [48] under the same conditions, was met as listed in Table 1.

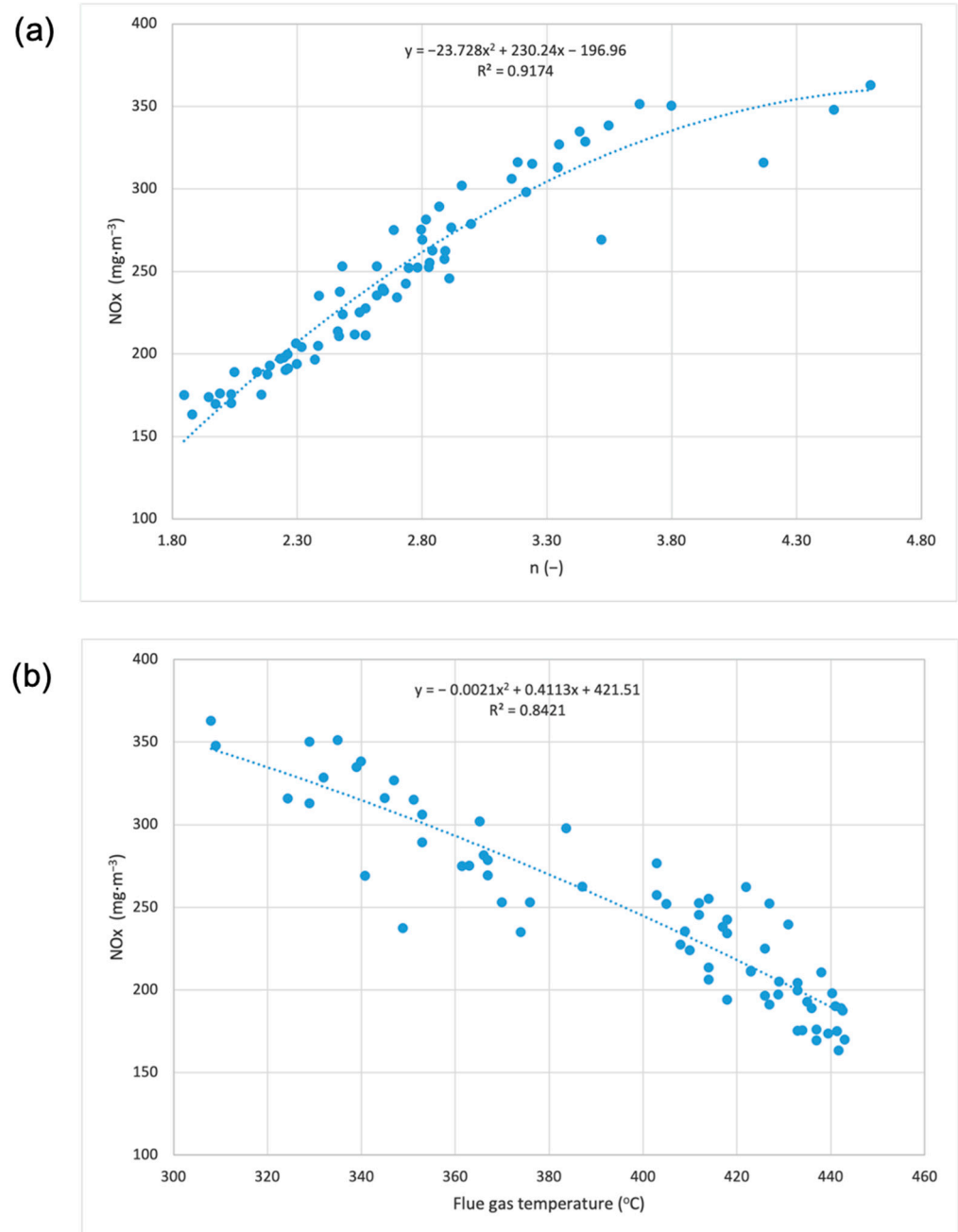


Figure 5. NO_x emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (summer-harvested biomass).

The concentration is lower than that of the commonly used energy crop *Miscanthus*, with a mean value of 473.51 mg·m⁻³ [50], and corresponds to the results obtained for briquettes made from Switch Grass [51].

Testing of the autumn-harvested sample resulted in the increasing trend in carbon monoxide concentration in the flue gas, depending on n, with decreasing flue gas temperature (Figure 6a,b). This trend and the average values of CO concentrations are similar to those obtained by [50] for briquettes made from energy crop *Miscanthus*. According to [51], the average value is similar to hardwood (Maple) and non-woody material (Hay).

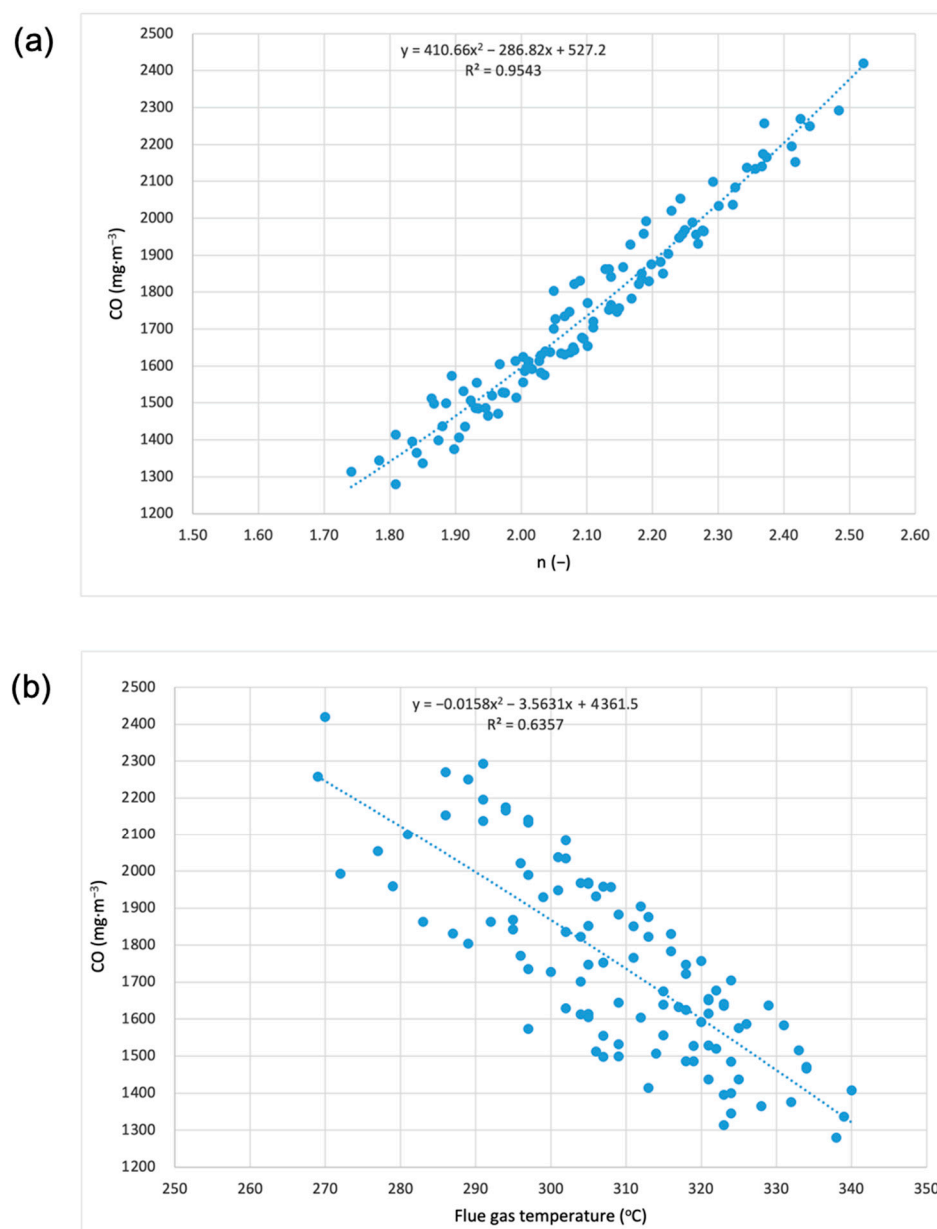


Figure 6. CO emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (autumn-harvested biomass).

The coefficients of determination for regression equations presenting NO_x emissions during combustion of autumn-harvested biomass (both air excess ratio and flue gas temperature) indicated a weak correlation between the variables (Figure 7a,b). This suggests that other factors likely influence the emission levels beyond those included in the analysis [52].

All the values of measured NO_x emission concentrations are below the established level [53]. The average value is similar to the value measured for sawdust briquettes in the study performed by Roy et al. [51].

In general, low CO emissions demonstrate improved combustion efficiency, and the overall performance of combustion units [34,54,55] of the autumn-harvested biomass is preferable to use for combustion.

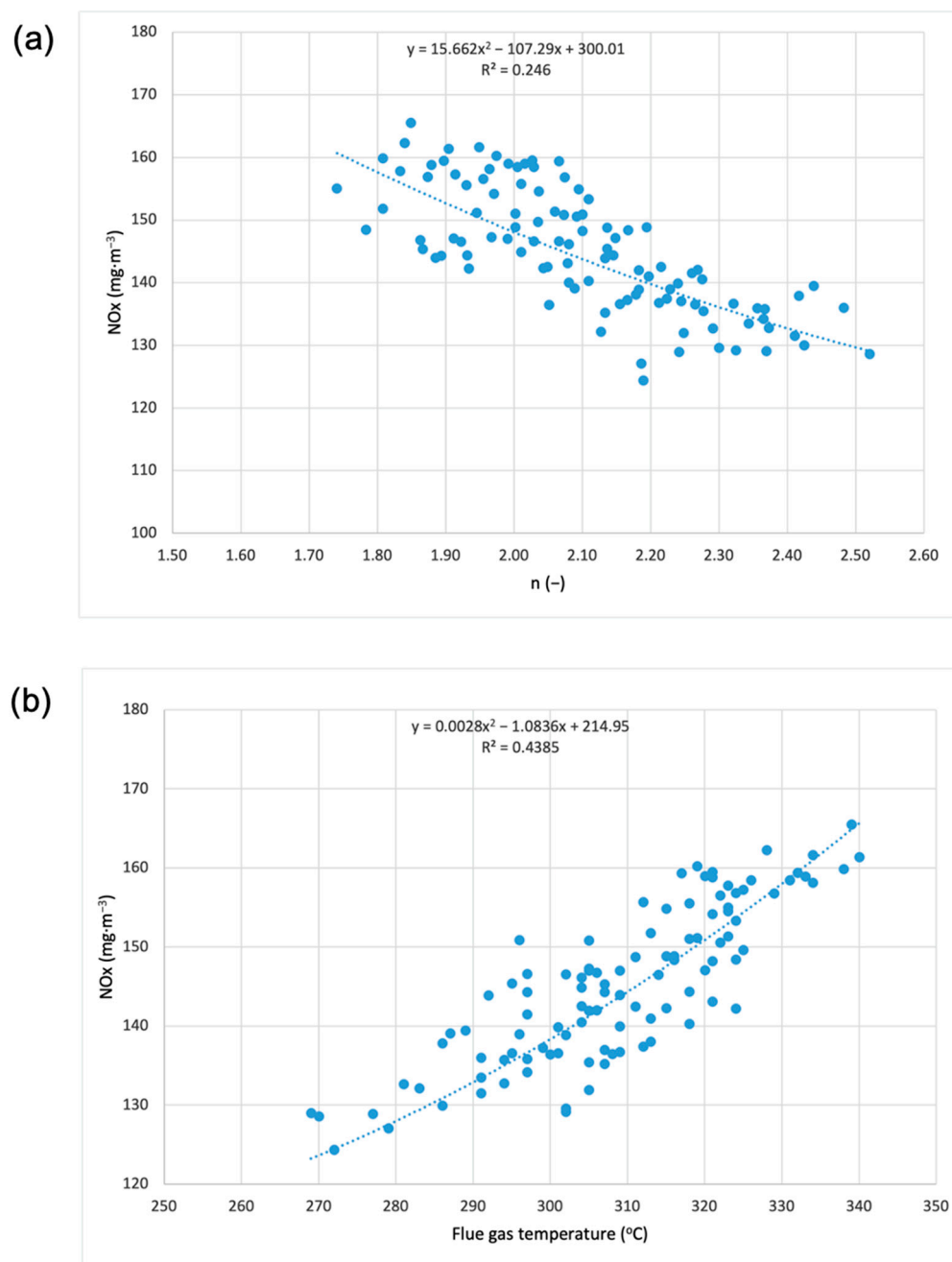


Figure 7. NO_x emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (autumn-harvested biomass).

3.3. Evaluation of Thermogravimetric Analysis and Differential Scanning Calorimetry

The thermal decomposition of biomass samples was observed through weight loss over several stages to compare summer- and autumn-harvested samples and reveal differences in their decomposition characteristics. In particular, to qualitatively evaluate the main components of biomass, such as cellulose, hemicellulose and lignin, they can be distinguished based on thermal decomposition behaviour from the course of weight loss intensity of biomass [56,57].

The dehydration stage, reflected by the initial mass loss, was nearly identical in both samples and occurred up to 150 °C (see Figure 8), as is commonly observed [58]. The next stages of decomposition under an oxidative environment, according to [59], are described as follows: at low temperatures (160–400 °C), the devolatilization of the sample takes place

(hemicellulose and cellulose are assumed to decompose during this stage), leading to char formation. Then, the oxidation of the sample occurs at temperatures higher than 400 °C.

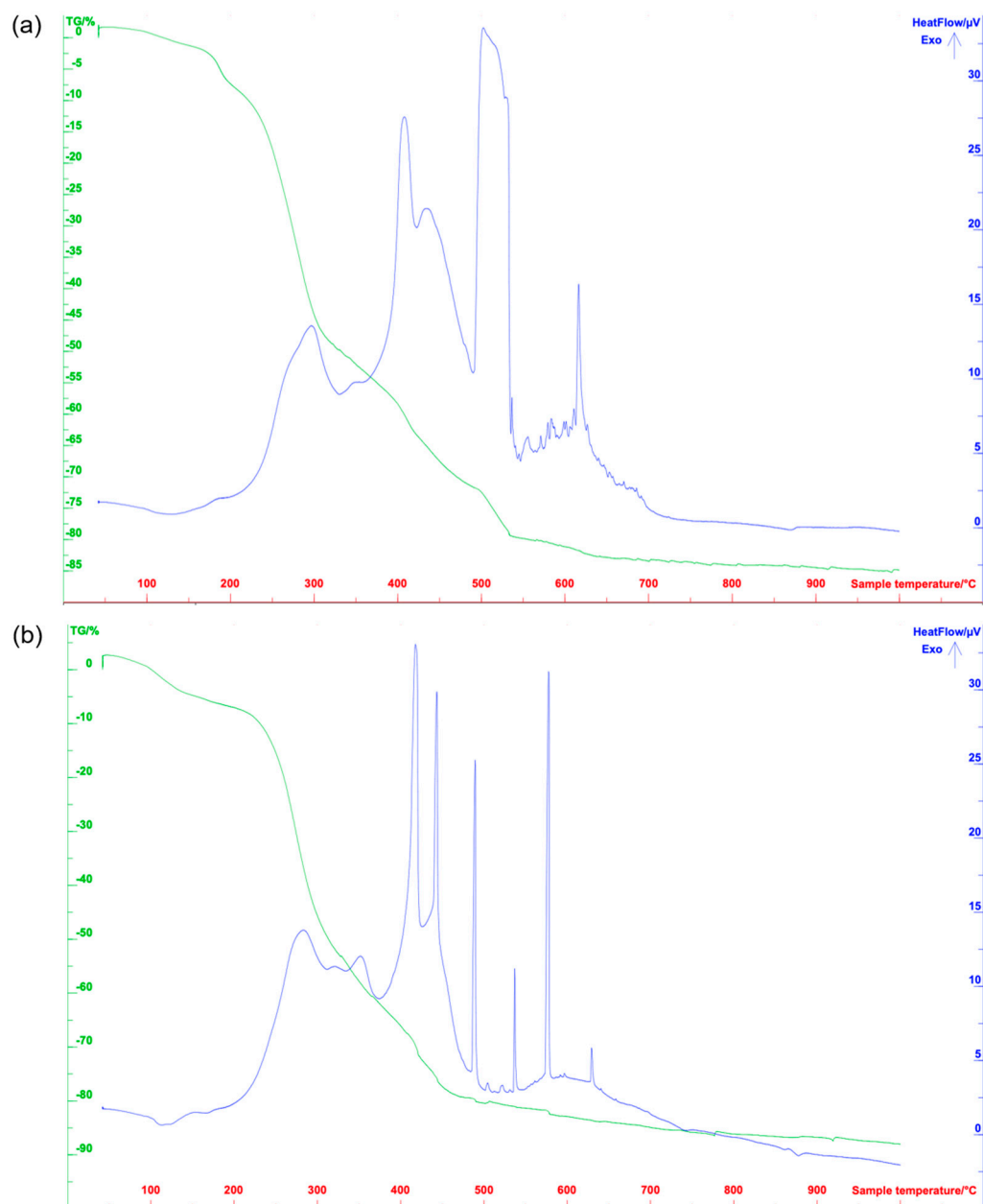


Figure 8. TGA-DSC graphs of the studied biomass: summer-harvested (a) and autumn-harvested biomass (b).

The weight loss curve indicates that between 150 °C and 300 °C weight loss of both samples was similar, with similar amounts of hemicellulose content. From 300 °C, the autumn-harvested biomass lost more weight. Above 550 °C, the difference is more stable until the end of the measurement.

The first peak on the heat flow curve showing the reactivity of biomass seems to be similar for both samples. Rather than the typical two clear peaks [60], the profile exhibited a series of narrow peaks, as can be seen on the heat flow curve of both tested samples. There are different behaviors of autumn and summer samples between 300 °C and 400 °C.

Another variation in the reactions includes the reaction of autumn-harvested at 400–500 °C, which is more intensive than the summer-harvested one; at 500 °C, the autumn

sample demonstrated a quick and intensive reaction, but the summer sample took longer at 500–550 °C.

A series of peaks in the higher temperature range suggests the presence of multiple thermal events, possibly due to sample heterogeneity or a complex decomposition mechanism [61]. The obtained results suggest that, based on the thermal decomposition process for both samples of *H. mantegazzianum*, efficient combustion can be expected.

The weight loss curves show that the autumn-harvested biomass had a lower ash content, with around 90% mass loss by the end of the measurement, compared to about 85% for the summer-harvested one.

4. Conclusions

Biomass of Giant Hogweed was obtained from the invaded site and processed into briquettes using a hydraulic briquetting press. The mechanical durability of the produced briquettes was determined using the standardized rotating drum method.

The biomass showed good processability into briquettes without the addition of binders, indicating that its natural composition is sufficient for densification. For both summer- and autumn-harvested biomass, produced briquettes exhibited high mechanical durability, demonstrating that the densification process effectively produced robust solid biofuel regardless of harvest stage. However, combustion tests revealed notable differences in emissions concentration characteristics between harvests. Carbon monoxide emissions from the summer-harvested material exceeded established limits, indicating incomplete combustion. The results from the combustion tests detected elevated CO emission concentrations from the combustion of summer-harvested biomass, compromising its applicability for small-scale energy use and posing air quality risks in the vicinity of the combustion unit. In contrast, CO emissions from the biomass harvested later (in autumn) were within acceptable limits, suggesting that delayed harvest improves combustion efficiency of briquettes. Nitrogen oxides concentrations were within limits for both harvest stages, reflecting that nitrogen content was not critically affected by harvest timing.

TGA and DSC analysis provided insights into the thermal behaviour of Giant Hogweed biomass. The obtained results can be used for the optimization of the parameters of biomass processing.

While the biomass shows promising characteristics for solid biofuel production, certain limitations must be considered when produced.

Further studies should address the energy balance of the biomass to biofuel process, as well as evaluate mechanized harvesting approaches and the economic viability of the produced briquettes. A comprehensive life cycle assessment should be conducted.

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