

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Tropical AgriSciences



**Viability assessment of invasive hogweeds'
(*Heracleum* spp.) utilisation for energy purposes**

DISSERTATION THESIS

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Prague, May 2026

Declaration

I hereby declare that I have completed this thesis entitled “**Viability assessment of invasive hogweeds' (*Heracleum spp.*) utilisation for energy purposes**” independently, all texts in this thesis are original, and that all information sources have been quoted and acknowledged by means of complete references. I also confirm that this work has not been previously submitted, nor is it currently submitted, for any other degree, to this or any other university.

In Prague, 29.04.2026

.....

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Acknowledgements

To everyone who has greatly contributed to this research:

I am profoundly grateful to doc. Ing. Tatiana Alexiou Ivanova, Ph.D., prof. h.c., for her wise supervision and unwavering support throughout my academic journey. I sincerely appreciate all the opportunities that have been provided to me and the encouragement of my professional independence.

Special appreciation goes to Dipl.-Ing. Alexandru Muntean, Ph.D., and Ing. Veronika Chaloupková, Ph.D., for their willingness to share their knowledge and for the valuable skills and insights I gained over the period of our work together.

I would like to extend my appreciation to Dr. Miguel Fernández Llorente and his team at the Biomass Characterisation Laboratory of the Centre for the Development of Renewable Energy Sources (CEDER) in Spain for the hands-on experience I acquired under their mentorship.

I gratefully acknowledge the valuable help of Ing. Petr Hutla, CSc., and Ing. Petr Jevič, CSc., prof. h.c. in logistics and for offering expert guidance grounded in their exceptional competence.

My sincere thanks go to the entire Department of Sustainable Technologies for fostering an inspiring academic environment and for their commitment to making the world a better place.

The study was supported by the Internal Grant Agency of the Faculty of Tropical AgriSciences, CZU Prague [grant numbers 20253121, 20243101, 20233108, 20223110, 20213108]. and by the Czech Aid development project "Modernisation and raising the prestige of Higher Agricultural Education in Moldova" [project number 25-PKVV-005].

Abstract

Invasive alien species *Heracleum mantegazzianum* Sommier & Levier and *Heracleum sosnowskyi* Manden pose significant ecological risks when they spread beyond their native ranges. Invasions of giant hogweeds reduce native plant diversity and degrade local habitats. At invaded sites, these species form dense stands, resulting in a high accumulation of lignocellulosic biomass. Mechanical removal of plants aimed at controlling their spread provides the opportunity to obtain biomass from existing stands, which can be utilised as a feedstock for biotechnological applications.

The research aims to explore the viability of biomass from problematic invasive hogweeds as a feedstock for solid biofuels production. Given the comparable structural and physicochemical traits, both species mentioned above are treated as representative in this study. In the literature part, approaches to biomass valorisation in industrial sectors have been reviewed, with biofuel production emerging as a promising technology due to its processing capabilities. For the purpose of this research, biomass was sampled at two principal phenological phases (summer-harvested and autumn-harvested) and was thoroughly analysed to assess changes in fuel properties.

Based on the results for *Heracleum mantegazzianum*, properties of autumn-harvested biomass nearly comply with the requirements for the best A-class of non-woody solid biofuels, and harmful CO and NO_x emissions from combustion were found to be within permissible levels. Nevertheless, prioritising summer-harvested biomass utilisation is recommended as it prevents seed formation, thereby eliminating any risk of dispersal. Although summer-harvested biofuels are nearly compliant with B-class specifications, reaching a net calorific value of 14.22 MJ/kg as received with moisture content of 8.30 %; the ash content of 12.3 % dry and ash shrinkage starting temperature of 320 °C are critical parameters for practical combustion application.

Furanocoumarin content in biomass was analysed, accounting for variations across plant organs and harvesting periods. Briquettes and pellets produced under selected processing parameters exhibited high mechanical durability (surpassing 97 %), thereby ensuring reliable handling. Furthermore, the experimental data showed that torrefaction at 300 °C optimises the gross calorific value of summer-harvested biomass to 22.45 MJ/kg dry, though the resulting ash content of 22.32 % dry requires consideration for maintenance of equipment used for combustion.

Keywords: briquettes, pellets, combustion, furanocoumarins, weeds, giant hogweed, invasive plant management, GC-MS, slow pyrolysis, emissions

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List of Abbreviations

AC	Ash content
DPPH	2,2-Diphenyl-1-picrylhydrazyl
DT	Deformation temperature
DU	Mechanical durability
EPPO	European and Mediterranean Plant Protection Organization
FRAP	Fluorescence recovery after photobleaching
FT	Fluid temperature
GBIF	Global Biodiversity Information Facility
GC/MS	Gas chromatography–mass spectrometry
GCV	Gross calorific value
HPLC	High-performance liquid chromatography
HT	Hemisphere temperature
IEA	International Energy Agency
ISO	International Standardisation Organisation
NCV	Net calorific value
PUVA	Psoralen and ultraviolet
SEM	Scanning electron microscope
spp.	Species (plural)
ST	Shrinkage temperature
TBARS	Thiobarbituric acid reactive substances
TEAC	Trolox equivalent antioxidant capacity
TGA	Thermogravimetric analysis
TGA-DSC	Thermogravimetric analysis and differential scanning calorimetry
TLC	Thin layer chromatography
UV	Ultraviolet
VM	Volatile matter

1. Introduction

Currently, invasive alien plants are recognised as one of the major threats to biodiversity, contributing significantly to the disruption of ecosystems (Frigerio et al., 2024). The challenges of managing the spread and eradication of these plant species have been widely discussed in several recent studies, with particular emphasis on the problematic *Heracleum* spp.

The uncontrolled spread of two giant hogweeds - *Heracleum mantegazzianum* Sommier & Levier and *Heracleum sosnowskyi* Manden has become a serious environmental concern in affected regions. Nowadays, they are widely known for their rapid spread and ability to dominate in disrupted areas, posing a threat to biodiversity. Furthermore, the presence of thickets near populated invaded areas brings challenges such as serious health risks upon contact with human or animal skin because of phototoxic compounds in plant sap known as furanocoumarins. They are found predominantly in the aerial parts of the plant, particularly in the leaves and stems (Weryszko-Chmielewska & Chwil, 2012). Skin contact with the above-ground parts of the plant, followed by solar exposure, can cause dermatitis bullosa pratensis. Typical symptoms include swelling, pain, redness and heat of affected sites (Jakubowicz O et al., 2012; Tanirbergenov et al., 2018). The extent of symptoms depends on the depth of the burn, the area and the duration of exposure (Zdrojewicz et al., 2016). In the scientific literature, well-documented cases can be found, especially risk groups clinical examples of dermatitis caused by contact with the plant and the features of the disease in children (Tamrazova et al., 2019) or case reports of patients with immune deficiency experiencing delayed wound healing caused by exposure (Piersiala et al., 2019).

Historically, *H. sosnowskyi* is one of the plants that were originally selected, bred, and cultivated for agricultural purposes before

becoming invasive (Barney & DiTomaso, 2008). It spreads over great distances from the fields where it was initially cultivated. The analysis of genetic diversity in both native and invasive populations of *H. sosnowskyi* showed that success in the naturalisation is strongly associated with human activities since it has been used in agriculture (Osipova et al., 2021). Due to the similarity in ecological behaviour and chemical composition, contributing to a common invasive impact, the potential of the biomass of both of the above-mentioned species can be explored through the same methodology and joint research.

Currently used methods for the eradication of plants in invaded areas are showing limited long-term effectiveness. They often demand considerable financial and logistical resources. Efforts are being made to control the spread out of its native range through various methods, such as herbicide treatments, and mechanical plant removal (Egorov et al., 2020; Panasenko et al., 2013), or more experimentally, by thermal (Antipina & Maganov, 2018) or microwave treatment (Kabuce N. & Priede N., 2010). Herbicide-based control methods, while effective, can result in negative impacts on non-target species, soil health, and water quality in surrounding habitats. These plants remain a significant threat to the biodiversity and ecosystem (Nielsen et al., 2005).

In recent years, the attention of researchers has turned toward approaches that not only mitigate the spread of invasive species but also seek to utilise the biomass for biotechnologies. Recovering value from problematic vegetation aligns with the principles of sustainable land management as well as the circular bioeconomy.

The present study focuses on the viability assessment of invasive hogweeds' biomass utilisation for solid biofuels production. Although several studies have investigated some physico-chemical characteristics of invasive hogweed biomass, there remains a lack of comprehensive studies and complex evaluation of biomass in the context of established quality standards for solid biofuels whether the biomass

material meets the minimum requirements for effective practical use in pellet or briquette form.

For efficient and clean operation of biomass combustion systems, controlled conditions are essential. The behaviour of biomass is uneven, and it can lead to operational problems and pollutant emissions exceeding the limits (Pietka et al. 2019). Potentially turning the biomass of *H. mantegazzianum* into a feedstock for solid biofuel requires an understanding of combustion efficiency as well as compliance with environmental regulations for combustion of solid biofuels.

This thesis proceeds as follows: the Literature Review provides an extensive overview of the existing literature. Chapter reviews mainly recent studies on *H. sosnowskyi*, synthesising different technologies applied for the biorefinery of the plant biomass, including bioenergy use. Tested samples of biomass and applied methodology are described in the section Materials and Methods.

The very detailed assessment of the fuel-energy properties of hogweeds' biomass is presented in the section Results and Discussion based on the results of measurements. This evaluation encompasses key properties such as calorific value, ash and moisture contents, biomass chemical composition, elemental composition of ash, and its melting behaviour. A pyrolysis of biomass on a laboratory-scale level was performed as well to determine if the resulting biochar exhibits improved fuel quality. An analysis of furanocoumarin distribution in *H. mantegazzianum* biomass, examining their concentration across plant organs and whole plants sampled at different growth stages. The production of solid biofuels (briquettes, pellets) is presented, including their mechanical durability testing and profile of emissions released during combustion on a small-scale level. The findings of the research are summarised in the Conclusion section.

2. Literature Review

2.1. Plant Description

The genus *Heracleum* L. contains a large number of species (Bahadori et al., 2016a), from which *Heracleum mantegazzianum*, *Heracleum sosnowskyi*, and *Heracleum persicum* are a part of the plants' group called giant hogweeds, characterised by their towering height and expansive leaf size, earning them the term 'giants'. They rank among Europe's largest herbs, displaying an impressive appearance and forming dominant colonies (Nielsen et al., 2005).

H. mantegazzianum and *H. sosnowskyi* are morphologically very similar (Fig. 1), and it is difficult to differentiate between them (Jakubská-Busse et al., 2013); however, there is genetic evidence supporting that they are distinct species (Jahodová et al., 2007).



Figure 1 *Heracleum mantegazzianum* (left) and *Heracleum sosnowskyi* (right)
Source: Jakubská-Busse et al. (2013)

Both belong to the family Apiaceae, synonym Umbelliferae (Bahadori et al., 2016a). *H. sosnowskyi* is an endemic species found in meadows and forest edges in the Caucasus region of Eurasia and was first described by Mandenova (1950).

Hogweeds are monocarpic. The life cycle includes 6 main development stages, as described in Table 1 below.

Table 1 Growth stages of *H. sosnowskyi*

Growth stage	Description of the form of the root system and divisions of the lamina
Seed	-
Seedling	Taproot without branching, elongated seed-lobe
Juvenile	Taproot without branching, leaf with a crenate margin
Immature	Root system is slightly branched, leaves are simple with lobate margin
Vegetative adult	Root system apparently branched, leaves are pinnately compound
Generative	Root system apparently branched, leaves are pinnately compound, presence of inflorescence

Source: Dalke et al. (2015)

The above-ground part of the plant consists of a slightly tapered straight stem (with a height of up to 3 m) covered with trichomes, bearing inflorescence (terminal and satellite umbels) and leaves (Jakubska-Busse et al., 2013). The stem is hollow and deeply grooved or ridged. The leaves are arranged in a rosette pattern at the base of the plant, with each leaf connected to a stem. They are typically dark green in colour and can grow up to 1–2 m in length. The leaves are large, broad, and deeply incised. The edges of the leaves are sharply serrated and can be quite jagged (Satsyperova, 1984).

The flowering of umbels occurs from June to August (Nielsen et al., 2005) and lasts for 2–3 weeks (Jakubowicz et al., 2012). The white or occasionally pinkish flowers are clustered in an umbrella-shaped head (umbel) that can reach a diameter of up to 80 cm. Each compound umbel consists of 30–150 rays. Remarkably, a single plant can bear a total of over 80,000 flowers (Nielsen et al., 2005). Its pollination is done by diverse pollinators, including *Coleoptera*, *Diptera*, *Hemiptera*, and *Hymenoptera* (Grace & Nelson, 1981). Self-pollination is also observed, allowing a single plant to form a sizable population (Bogdanov et al., 2021).

The fruit has a strong aroma (Mishyna et al., 2015). As with all *Hera-
cleum* L. spp., the germination of mericarps requires a two-stage stratification period, ranging from 30 to 60–120 days (Tkachenko, 1989). Propagation is exclusively by seeds (Jakubska-Busse et al., 2013; Nielsen et al., 2005). The invasive triumph of this species is directly contingent on the abundance of propagules (Fig. 2) and their capacity to disperse (Dalke et al., 2015).



Figure 2 Umbel with seeds. Source: the website of the project Limitation of the occurrence of invasive plants in the Karlovy Vary Region

Seeds are released from late August to (Nielsen et al., 2005). According to estimates, the seed production ranges from 15,000 to 20,000 seeds/m². Seeds disperse through a mechanism involving both gravity and wind (Chadin et al., 2021). Typically, the seeds fall within a short distance from the parent plant. The majority of seeds germinate in the following growing season after undergoing a required cold period (0–5 °C), requiring stratification for about 3–4 months (Dalke et al., 2015).

2.2. Habitat and Distribution

Invasive hogweeds at present are 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 (Grosu (Dumitrescu) et al., 2024; Nasadiuk & Mamchur, 2024).

The *H. sosnowskyi* exhibits a rapid increase in both plant numbers and spread, estimated at 60 m per year (Baležentienė L. & Bartkevičius E., 2013). The invasion range of *H. sosnowskyi* lies between 48.6° N in the South and 72.6° N in the North, and it also occupies territories between 15.0° E on the West and 69.5° E in the East (Chadin et al., 2021). Invasions were evidenced in the following countries: Latvia, Estonia, Lithuania, Belarus, Ukraine, Poland, Hungary, and the former German Democratic Republic (Nielsen et al., 2005). *H. sosnowskyi* is present in a wide range of altitudes, latitudes, climates, and soil types. Habitat quality plays a crucial role in both establishment and subsequent spread. Typically, environments conducive to invasion are marked by ample sunlight, minimal active land use, human alterations to vegetation cover, and favorable water and soil nutrient levels (Nielsen et al., 2005). Only 20 % of *H. sosnowskyi* colonies successfully establish

themselves in natural habitats, while the remaining 80 % can be found in anthropogenised areas such as wastelands, roadsides, and housing areas (Baležentienė L. & Bartkevičius E., 2013) (Fig. 3).



Figure 3 Examples of habitats selected by hogweeds. Source: Grzędzicka (2023)

The development of methods for monitoring, mapping and modelling is crucial for accurate estimation of the expenses for control and risk evaluation. There are more and more methods that allow getting information about the territories of plant distribution. Methods for remote assessment of land plots overgrown with *H. sosnowskyi* using various indices (Bogdanov et al., 2021; Fomin & Chashchin, 2019; Morenko et al., 2019; Smirnov et al., 2020) have been developed. Satellite images of medium spatial resolution from the Sentinel-2 spacecraft are used to identify areas experiencing mass growth of *H. sosnowskyi* (Bogdanov V. et al., 2020; Tovstik et al., 2019), monitoring is possible with an unmanned aerial vehicle to obtain remote sounding data. In the study by Afonin et al. (2017), the ecological–geographical model was proposed based on the correlation between plant occurrence and the hydrothermal coefficient.

Maps of the distribution pattern of some specific regions of hogweeds are given in some works (Baležentienė L. & Bartkevičius E., 2013; Chadin et al., 2017; Jahodová et al., 2007; Koldasbayeva et al., 2022; Krivosheina M. G. & Ozerova N. A., 2019). Nowadays, the overview of the distribution can be found in several publicly available sources related to citizen science projects, like maps of occurrence records, for

example, Figure 4, which includes all bases of records: observation, machine observation, human observation, material sample, material citation, preserved specimen, fossil specimen, living specimen, and occurrence. It compiled from 22,471 georeferenced records from a publicly available checklist dataset of the Global Register of Introduced and Invasive Species of different countries - Invasive Species Specialist Group.

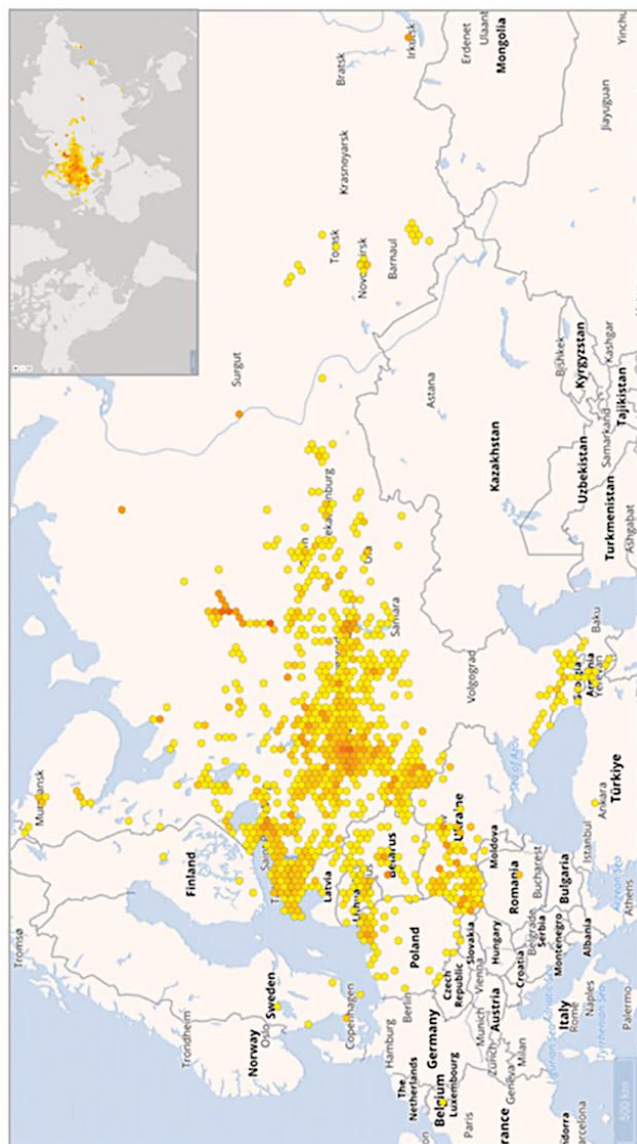


Figure 4 *Heracleum sosnowskyi* occurrence records map for the period 1900–2024 from a publicly available dataset. Source: GBIF (2023)

2.3. Management Efforts Towards Invasion and Spread

Due to the rapid increase in quantity and spread of hogweeds, which poses significant negative consequences for both human (Fig. 5) and native ecological systems, there is an urgent need to mitigate the impacts of species biological invasion by identifying effective control measures (Baležentienė & Bartkevičius, 2014).



Figure 5 Phytophotodermatitis caused by sap. Source: website of the project Limitation of occurrence of invasive plants in the Karlovy Vary region.

The decision regarding the implementation of eradication techniques for *H. sosnowskyi* depends on the size of plant populations (EPPO Data Sheet on Invasive Alien Plants, 2009). Because plants are seed-propagated (Jakubská-Busse et al., 2013; Nielsen et al., 2005), the most effective eradication technique is to prevent the plants from fruiting. This can be achieved through both chemical and mechanical means. During the period of *H. sosnowskyi* cultivation, its regular mowing was conducted to prevent the plants from flowering and fruiting (Bogdanov et al., 2010; Chernyak, 2013). This activity can be combined with the simultaneous stocking of its above-ground parts to obtain valuable products (Shakhmatov et al., 2014, 2016). Nowadays,

the most effective method for eliminating hogweeds is the chemical control using herbicides, as mechanical techniques often do not ensure complete plant suppression (Egorov et al., 2020). A systematic approach is also required when using herbicides, as a single chemical treatment does not kill the plant (Panasenکو et al., 2013). Correct and repeated application of herbicides is necessary for plant spread control to achieve satisfactory results, regardless of the management method.

More environmentally friendly methods for eradication have been tested and proposed in the literature. A thermal treatment method using hot water (90–100 °C) weekly on seedlings was suggested (Antipina & Maganov, 2018). Another method involves thick-layer mulching using wood residues (coniferous barks) on sites with massive *H. sosnowskyi* growth. Sporadic seeds falling on the surface of the bark from adjacent sites germinate, but seedlings die (Antipina et al., 2020). The plants were also effectively treated with microwaves (Słowiński et al., 2022); 10 and 15 min of microwave irradiation resulted in 100 % hogweed destruction. Another approach – afforestation in some regions has been proposed as an effective approach (Kabuce & Priede, 2010).

To manage weeds, herbicides are widely used. However, there is an increased concern about the risks to people and the environment associated with synthetic herbicides (Hagner et al., 2020). Measures targeting hogweeds, without the use of herbicides, particularly mechanical clearing of invaded sites, can result in large quantities of biomass within individual invaded sites (Tanke et al., 2019). Available data on the biomass yield of *H. mantegazzianum* are limited. As documented by Müllerová (2024), in stands of fresh aboveground biomass may reach up to 94 t/ha. Dry matter yields ranging from 6 to 7 t/ha and which corresponds to 6.04 ± 0.89 t/ha in the study done by Van Meerbeek et al. (2015). However, due to considerable variation in plant population density across invaded sites, it is currently difficult to accurately estimate the quantity of biomass.

The biomass from *H. sosnowskyi* can achieve a range of 2.3–4.6 kg/m² (Abramova et al., 2021). Even at a minimal yield of 2 kg/m², we can obtain 20 tons of biomass per hectare can be obtained from *H. sosnowskyi*.

The large areas affected by thickets of *H. sosnowskyi* led to the search for opportunities to use its biomass. The study of the chemical structure of components of *H. sosnowskyi* is crucial for assessing its potential application (Makarova et al., 2016). The spread of *H. sosnowskyi* can be limited not only through the use of herbicides. Targeted, integrated processing of biomass into products needed by society can be applied (Pavlov & Solovyov, 2021).

Particular attention should be paid to the actual circumstance that the scope of research regarding *H. sosnowskyi* is broader than that of *H. mantegazzianum*. This is due to more extensive experience historically gained in regions with the most affected areas since the plant's use as a fodder crop. For this reason, a more diverse range of studies on *H. sosnowskyi* can be observed in the following subsections in the Literature Review of the present Thesis.

2.4. Phytochemical Constituents

The chemical composition of the green mass of *H. sosnowskyi* is diverse and includes 20–25 % carbohydrates, about 10 % sugars, up to 16 % proteins, up to 14 % carotenes, 17 amino acids, tannins, essential oils, glutamine, vitamins C and P, folic acid, polysaccharides, coumarins, macro- and micronutrients (Ivanova et al., 2015).

According to available data, the most interesting biologically active compounds of *H. sosnowskyi* are primarily dominated by furanocoumarins, mainly of the psoralen type, and to a lesser extent, angelicin derivatives (Kulikov et al., 2022). Coumarins, including angelicin, bergapten, imperatorin, isobergapten, isopimpinellin, marmezin,

osthole, (+)-oxypeucedanin, pangelin, pimpinellin, psoralen, sphondin, umbelliferone, and methoxalen, were documented in early studies (Abyshev & Denisenko, 1973; Malikov & Saidkhodzhaev, 1998; Politowicz et al., 2017). The presence of the majority of coumarins in the seed extract of *H. sosnowskyi* was confirmed in the study by Politowicz et al. (2017). On the other hand, Jakubska-Busse et al. (2013) identified only pimpinellin, isopimpinellin, psoralen, bergapten and methoxalen in the essential oil from seeds of *H. sosnowskyi*.

Substances of coumarin nature, causing the phototoxic effect, are located on the surface of the petioles and leaf plates of the plant within the trichomes (Fig. 6) (Usik A.V., 2020; Weryszko-Chmielewska & Chwil, 2017). According to Weryszko-Chmielewska & Chwil (2012), the highest density of trichomes is observed on the abaxial leaf surface.

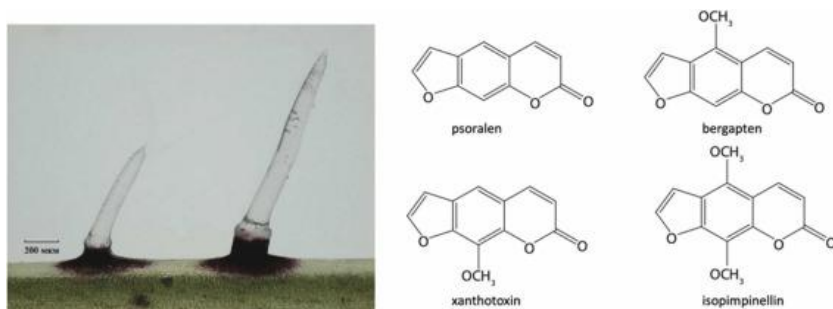


Figure 6 Trichomes on petioles of leaves of *H. sosnowskyi* containing coumarins (microscopically) and structures of some furanocoumarins found in *Heracleum* species. Source: Usik (2020), Jakubowicz et al., (2012).

Furocoumarins in *H. sosnowskyi* serve as protective agents against fungi, bacteria, and plant growth regulators (Mishyna et al., 2015). In the above-ground part of the plant, the greatest accumulation of extractives occurs during the flowering phase. Research has indicated that the amount of coumarins present in plants is influenced by their habitat and geographical location (Jakubska-Busse et al., 2013). Plants grown in northern regions exhibit higher levels of coumarin content

compared to those found in the central part of Russia and the Far Eastern region (Andreeva, 2021). Enhanced levels of soluble flavonols, anthocyanins, and furanocoumarins, such as xanthotoxin, isopimpinellin, and bergapten, contribute to improved heat tolerance in Sosnowsky's hogweed (Rysiak et al., 2021).

Besides the furanocoumarins, the tissues of *H. sosnowskyi* contain various biologically active compounds, including esters and phenolic compounds, with a chemical composition closely resembling that of giant hogweed (*H. mantegazzianum*), as indicated in the study of Jakubska-Busse et al. (2013). Different parts of *H. sosnowskyi* plants also yield essential oils, primarily consisting of aliphatic esters and monoterpenes, showcasing a diverse array of biological activities (Burgiel Z. et al., 2008; Hpoo et al., 2020; Synowiec & Kalemba, 2015; Tkachenko, 2007). Synowiec & Kalemba (2015) analysed the chemical composition and quantity of the essential oil obtained from *H. sosnowskyi* seeds through hydrodistillation utilising a Clevenger-type apparatus. The yield of essential oil from *H. sosnowskyi* seeds was 5.1 %, and a total of sixty-two compounds were identified, constituting 96 % of the total oil. The primary compounds found in the seed essential oil were coumarins, furanocoumarins, hydrocarbons, alcohols, esters, and aldehydes. The predominant components of the oil were aliphatic esters (82.9 %), followed by aliphatic alcohols (11 %). The oil was mostly composed of octyl acetate (39.5 %), hexyl 2-methylbutanoate (14.4 %), hexyl 2-methylpropanoate (6 %), hexyl butanoate (5.4 %), and octanol (8.6 %). Other components included octyl 2-methylbutanoate (4 %), hexyl 3-methylbutanoate (2.6 %), octyl 2-methylpropanoate (2.4 %), hexanol (1.3 %), hexyl acetate (1 %), and octanal (0.7 %) (Synowiec & Kalemba, 2015).

Seeds' essential oils from *H. sosnowskyi* and *H. mantegazzianum* were also studied by Jakubska-Busse et al. (2013). Besides

coumarin derivatives, they identified various toxic compounds, such as isobutyl isobutyrate, isoamyl butyrate, hexyl hexanoate, 1-hexadecanol, and others, in the essential oils. These compounds found could potentially lead to eye irritation, skin irritation, respiratory discomfort, dizziness, breathing problems, and nausea (Jakubska-Busse et al., 2013). The composition of *H. sosnowskyi* essential oil, obtained from the seeds using a Clevenger-type apparatus, was also evaluated by Kwasny et al. (2012) with similar results. The composition of essential oil from *H. sosnowskyi* fruits, together with *H. mantegazzianum* and *H. persicum* fruits, obtained via hydrodistillation using a Deryng apparatus, was presented by Politowicz et al. (2017). This study demonstrated an absence of furanocoumarins in the studied essential oils, which is in contradiction to the commonly held opinion, as well as assertions in certain publications, suggesting that burns may result from furanocoumarins not only through direct contact with the plant but also via exposure to volatiles emanating from the plant during hot days (Jakubowicz et al., 2012). Moreover, no significant differences were detected in the chemical profile of the evaluated fruit essential oils of *H. sosnowskyi*, *H. persicum*, and *H. mantegazzianum*, which supports the assumptions of a close relationship of these species (Politowicz et al., 2017). And the composition of solvent extracts from *H. sosnowskyi* seeds was identified by Tomaszekiewicz-Potępa & Vogt, (2010). Tkachenko (2009) reported the composition of the root essential oil of *H. sosnowskyi*, together with another 18 *Heraclium* species; the results showed that the composition varied at different vegetation phases.

2.5. Methods for the Extraction of Bioactive Compounds

Extraction and purification of bioactive compounds from wild plants like *H. sosnowskyi* is a complex and time-intensive process (Kenari et al., 2020; Liu et al., 2024). This encompasses initial screening and identification, extraction, and proceeding to isolation and

characterisation. According to literature sources (Baležentienė, 2012; Politowicz et al., 2017; Synowiec & Kalembe, 2015; Tkachenko, 2007), bioactive compounds from *H. sosnowskyi* are derived from stems, leaves, seeds, flowers and roots. There is no universally recognised standard method for extracting bioactive compounds from plants, and, in some cases, the use of several methods is required (Azmir et al., 2013). Generally, we can categorise them into three main types: basic extraction techniques, advanced extraction techniques, and sophisticated or super-advanced extraction techniques (Patra et al., 2018). In the case of *H. sosnowskyi*, the use of advanced extraction techniques is prevailing.

In the literature, conventional laboratory settings, such as the hydro-distillation method using Clevenger apparatus (Kwasny et al., 2012; Synowiec & Kalembe, 2015), Ginsberg's apparatus (Tkachenko, 2007), Deryng's apparatus (Politowicz et al., 2017), or the steam distillation method (Tkachenko, 2009), are commonly presented. Additionally, liquid-liquid extraction (Kulikov et al., 2022) and solid-liquid extractions, including aqueous extractions (Baležentienė, 2012) and solvent extractions (Jakubska-Busse et al., 2013; Karmanov et al., 2020) have been reported for *H. sosnowskyi*.

In recent years, new methods have also been employed for several *Heracleum* species; however, the data for *H. sosnowskyi* remain limited. Advanced extraction techniques, such as accelerated solvent extraction process (ASE), the phytonics process, solid phase micro-extraction (SPME), supercritical fluid extraction (SFE) and microwave assisted extraction (MAE) processes have gained popularity (Azmir et al., 2013; Patra et al., 2018). The last one mentioned was used for *H. persicum* by Kenari et al. (2020) and Gharachorloo et al. (2017). MAE, among others, has seen advancements and modifications aimed at enhancing its performance, including nitrogen-protected microwave-assisted extraction (NPMAE), vacuum microwave-

assisted extraction (VMAE), dynamic microwave-assisted extraction (DMAE), solvent-free microwave-assisted extraction (SFME), ultrasonic microwave-assisted extraction (UMAE), etc. (Chan et al., 2011). The UMAE method was applied for leaves of *Heracleum vicinum* Boiss. by Liu et al. (2024) and Wu et al. (2023). This method and other MAE methods offer considerable green benefits for industrial and large-scale applications, including reduced extraction time, minimised solvent use, low energy consumption and increased yield (Kadam et al., 2013).

Several parameters, like extraction temperature, liquid–solid ratio, volume fraction of solvent, equipment power, and extraction time, as well as the properties of initial plant material, are investigated in order to optimise extract yield and quality (Chan et al., 2011; Liu et al., 2024). In the study of Tomaszewicz-Potępa & Vogt, (2010) regarding *H. sosnowskyi*, the efficiency of extraction of morphologically different parts of the plant (seeds, stems, leaves), with different degrees of maturity (green, semi-mature and mature) and different storage methods (dried, frozen), was compared. The results clearly indicated that the desired extraction effects can be achieved from dry mature seeds. Considering the bioactivity, a 2-year plant at the flowering stage showed the highest phytotoxicity, compared to other plant materials taking into account their plant age, part used and phenophase (Baležentienė, 2012).

Followed the extraction, for the isolation of the bioactive compounds, a number of different separation techniques, such as column chromatography, flash chromatography, Sephadex chromatography, TLC and HPLC, are utilised to produce pure compounds (Azmir et al., 2013; Patra et al., 2018; Sasidharan et al., 2011). Column chromatography was used by Kulikov et al. (2022) to isolate furanocoumarins from *H. sosnowskyi* and to evaluate their bioactivity.

Nowadays, the sustainability in extracting and purifying bioactive compounds is crucial (Herrero et al., 2015). There's a shift towards eco-friendly techniques over traditional methods for their efficiency and quality. Moreover, these scalable techniques have advantages in a biorefinery framework, enhancing their benefit over conventional methods (Quitério et al., 2022).

2.6. Bioactivity

Generally, plants generate an array of secondary metabolites, which seem to be not necessary for plant development (Yang et al., 2018) and which play a crucial role in the plant's defense mechanism against both pathogenic attacks and environmental stresses. The secondary metabolites serve as defenses, either directly or indirectly, against ultraviolet radiation exposure, fungal, microbial, vertebrate, invertebrate or insect attacks, and, even other competing plants (Rattan, 2010; Vengurlekar et al., 2012; Wallace, 2004; Yang et al., 2018).

The biological activity of plants is closely associated with the chemical profile of their extracts. The chemical composition, which is influenced by several factors including geographical location, environmental and agronomic conditions, the developmental stage of the plant material, and the method of extraction (Barra, 2009). The synergistic or antagonistic effects among components within plant extracts could play a pivotal role in the bioactivity of essential oils and other plant extracts (Torbaty et al., 2014).

In traditional medicine, several *Heracleum* species are employed for treating a spectrum of ailments encompassing neurological, gastrointestinal, respiratory, rheumatological, and urinary tract disorders (Souri et al., 2004). It was discovered that Caucasian hogweeds possessed elevated concentrations of biologically active compounds in their tissues, potentially contributing to their invasiveness (Budarin S. & Kondratyev M., 2014; Synowiec & Kalemba, 2015), which are

responsible for a wide range of pharmacological properties, including anti-inflammatory, antimicrobial, anticholinesterase, antioxidant, antiviral, cytotoxic, and anticarcinogenic activities (Bahadori et al., 2016b). Biological activities of *H. sosnowskyi* are summarised in the following subchapters.

2.7. Allelopathic Activity

As mentioned, the invasive nature of *H. sosnowskyi* could be attributed to a significant concentration of bioactive substances within its tissues, as discovered (Budarin & Kondratyev, 2014; Synowiec & Kalemba, 2015). *H. sosnowskyi* exhibits high allelopathic activity towards various plant species, potentially providing a competitive edge in new territories through the utilisation of allelochemicals (Baležentienė & Bartkevičius, 2014; Bochkarev et al., 2011). The identified phytotoxicity attributed to allelochemicals may shed light on the underlying reasons for their high aggressiveness (Baležentienė & Bartkevičius, 2014).

The tissues of *H. sosnowskyi* contain various biologically active compounds, including coumarins, esters and phenolic compounds (Jakubska-Busse et al., 2013). Generally, as the main compounds responsible for plant's allelopathic potential are phenolic compounds (Dash et al., 2007; Hura et al., 2006). In the case of *H. sosnowskyi*, the phenolic compounds are present in all parts of plant, however the highest amounts (92.61 mg/mL) are found in the leaves and the lowest quantities (1.99 mg/mL) in the roots (Baležentienė, 2012; Baležentienė & Bartkevičius, 2014). It corresponds with the finding of Synowiec & Kalemba (2015), who also identified the primary location of the total phenolic content of *H. sosnowskyi* as being in its leaves. Baležentienė & Bartkevičius (2014), in a set of bioassays, demonstrated that the phenolic compounds found in the aqueous extracts of *H. sosnowskyi* hindered the germination of rapeseed (dicot) and perennial

ryegrass (monocot). Therefore, invasive species such as *H. sosnowskyi* and *H. mantegazzianum* could significantly contribute to the reduction of species diversity or the displacement of native plants in local habitats (Baležentienė, 2015).

Studies by Budarin & Kondratyev (2014) have demonstrated the use of active substances from this hogweed as growth regulators for certain plant species in agriculture, including camomile (*Matricaria chamomilla* L.), wheat (*Triticum aestivum* L.), pea (*Vicia sativa* L.), barley (*Hordeum vulgare* L.) and tutsan (*Hypericum perforatum* L.). Pesnya et al. (2011) reported that aqueous extracts of *H. sosnowskyi* inhibited the growth of *Allium cepa*. Baležentienė (2012) evaluated the herbicidal effect of aqueous extract from the stem, leaves, flowers and seeds of *H. sosnowskyi* against seeds of energy oil rapeseed (*Brassica napus* L.) cv. Kasimir and perennial ryegrass (*Lolium perenne* L.) cv. Sodrė, using Petri-dish bioassay. The study confirmed that the phytotoxic effects of *H. sosnowskyi* aqueous extracts on seed germination varied based on several factors: the concentration of the extract (ranging from 0.02 % to 0.2 %), the age of the plant (either 1-year or 2-year), the specific parts of the plant used (including stem, leaf, blossom, seed; and root), and the plant's growth stage (from rosette to ripening).

Besides aqueous extracts, another source of allelopathic compounds could be provided by essential oils. Synowiec & Kalemba (2015) using the Petri-dish bioassay, evaluated *H. sosnowskyi* seed essential oil (at tested concentrations 0.2 – 7.2 g/L), obtained from its seeds, as a potential agent for a natural herbicide against *Bromus secalinus*, *Amaranthus retroflexus*, *Centaurea cyanus* and *Avena fatua*; on the other hand, *Echinochloa crus-galli* and maize were resistant at the tested concentrations of essential oils.

2.8. Antimicrobial Activity

Various antimicrobial activities of extracts, essential oils, and constituents of the *Heracleum* genus have been documented in the literature. Nonetheless, the antimicrobial efficacy is closely related to chemical composition, thus it varies depending on factors such as geographical location, plant parts utilised, extraction methods, and experimental protocols employed (Barra, 2009).

As recent studies show, *H. sosnowskyi*'s extracts have a potential for the future development of novel biofumigants (Hpoo et al., 2020). Essential oil of *H. sosnowskyi* fruits exhibited heightened effectiveness against certain fungi, such as *Penicillium funiculosum* and *Fusarium oxysporium* f. sp. *lycopersici* (FOL) race 1 (Hpoo et al., 2020), particularly due to n-octanol. N-octanol played a significant role in the antimicrobial activity, while octyl acetate was identified as the key determinant of its antifungal action. Possibly tested compounds themselves can replace methyl bromide or other fumigants and fungicides; however, these compounds might be implemented into components of a new management strategy (Hpoo et al., 2020).

Furthermore, it was discovered that lignins obtained from *H. sosnowskyi* biomass are capable of strong binding of T-2 mycotoxin and thorium radionuclide (Th^{232}) from the aqueous media. So, there is the possibility of creating biomedical multifunctional preparations for efficient therapy on the basis of this biopolymer (Karmanov et al., 2020). Burgiel Z. et al. (2008) examined the antifungal capacities of *H. sosnowskyi* essential oil and discovered robust biological activity against *Fusarium culmorum*; the mycelium of *F. culmorum* was completely inhibited in the presence of essential oil.

Politowicz et al. (2017) evaluated the antimicrobial activity of essential oils and furanocoumarin fractions of *Heracleum* species using the disc diffusion method. The study showed no antimicrobial activity of

essential oils and moderate activity of furanocoumarin extracts from *H. sosnowskyi*, *H. mantegazzianum* and *H. persicum* against the following pathogens: *Staphylococcus aureus*, *Staphylococcus pseudintermedius*, *Streptococcus agalactiae*, *Bacillus subtilis*, *Escherichia coli*, *Pectobacterium atrosepticum* as well as against yeast *Candida albicans*, at a concentration of 70 µg/mL.

Essential oil from *H. sosnowskyi* fruits and roots, together with essential oils from *H. antasiaticum*, *H. dissectum*, *H. lehmannianum*, *H. ponticum* and *H. stevenii* showed anti-influenza activity, *in vivo*, against Types A and B influenza (Tkachenko, 2007). This study also reported that the essential oils from the mentioned plants could be used as a disinfectant for sanitation purposes of lodgings and other materials. The study has revealed that essential oils derived from *H. lehmannianum*, *H. ponticum*, and *H. aconitifolium* demonstrated higher levels of antiviral effectiveness than *H. sosnowskyi*. Moreover, root-sourced essential oils were more potent in antiviral activity than those extracted from fruits (Tkachenko, 2007).

2.9. Antioxidant Capacity

In recent years, plant extracts as herbal antioxidants gained scientific interest, especially in food science and medicine, due to concerns over the potential harm of synthetic antioxidants to human health (Shahidi & Ambigaipalan, 2015). The antioxidant activity of the plant extracts is attributed to the presence of active polyphenolic compounds (Yazdan-Bakhsh et al., 2021). However, contrarily, it was demonstrated that the presence of this type of component is not necessary for the antioxidant activity of *H. sprengelianum* Wight and Arnott (Karuppusamy & Muthuraja, 2011).

In the literature, the antioxidant potential was evaluated for several *Heracleum* spp. Antioxidant capacity of *H. lasiopetalum* Boiss extract, obtained using an ultrasonic bath, was evaluated by

DPPH free radical scavenging method and iron reduction assay in multilayer nanoemulsion with biopolymer coating to control oxidative stability of sunflower oil (Yazdan-Bakhsh et al., 2021). Karuppusamy & Muthuraja (2011) isolated essential oil by hydrodistillation from the leaves, seeds and rhizomes of *H. sprengelianum* Wight and Arnott and assessed its antioxidative potential via TBARS assay. Concentrations 250 and 500 mg/L were comparable to those of α -tocopherol and butylated hydroxytoluene (BHT). Essential oil from *H. persicum* aerial biomass, obtained through hydrodistillation and microwave-assisted hydrodistillation, was evaluated by Gharachorloo et al., (2017) using DPPH and Oven test method. Their results indicated that the percentage of inhibition increased with increasing of essential oil concentration. Hydroalcoholic fruit extract was confirmed by clinical trials as a safe antioxidant supplement with minimal coronary artery disease (Panahi et al., 2016). Fruit, leaves and root hexane extracts of *H. verticillatum*, *H. sibiricum*, *H. angustisectum*, and *H. ternatum* were tested by Ozek et al. (2019). The extracts from the leaves and fruits of *H. angustisectum* showed the most potent DPPH activity and TEAC values; meanwhile, the root extracts of *H. verticillatum* and *H. angustisectum* emerged as the most effective inhibitors of acetylcholinesterase, and, the extracts exhibited either no activity or a weak inhibitory effect on α -amylase.

H. transcaucasicum and *H. anisactis* roots essential oils (Torbati et al., 2014) showed high antioxidant activity via TLC-bioautography and DPPH assay. Essential oil of *H. rawianum* fruits, obtained by hydrodistillation, demonstrated a high antioxidant action via DPPH and FRAP methods (Hasheminya & Dehghannya, 2021). Dash et al. (2007) determined a significant antioxidant capacity of the methanol extract of *H. nepalense* D.Don roots via DPPH method, Hydroxyl radical scavenging activity and Superoxide scavenging activity.

These results revealed a suitable potential for use in the food and medicinal industries. While the antioxidant activity of essential oils or other extracts from the *Heracleum* family has been investigated in various literature, as indicated above, there are limited studies specifically focusing on the antioxidant activity of *H. sosnowskyi* itself. According to the study of Karmanov et al., (2020) , *H. sosnowskyi* lignin has significant biomedical potential due to high phenolic hydroxyl content. The lignin in that study was isolated by the organic solvent method by treating the ground raw material with a dioxane–water mixture (9:1) in the presence of HCl (0.7 %) at the boiling temperature. The purified lignin was isolated from low molecular weight impurities through a process involving two successive reprecipitations; first from dioxane to diethyl ether, afterwards, it underwent freeze-drying. The analysis revealed that hogweed lignin exhibited notable antioxidant potential, comparable to that of well-known antioxidants (such as ascorbic acid and rutin).

2.10. Further Potential Application in the Pharmaceutical Industry

Regardless of well-proven risks for the health of animals in nature and humans, while imprudent handling with *H. sosnowskyi*, it can be a source of useful components even in medicine. *H. sosnowskyi*, possessing a high photosensitising effect due to its content of bergapten, psoralen, and xanthotoxin, can be utilised in dermatology. Alongside *Ammi majus*, it serves as raw material for the preparation of herbal remedies for dermatitis (Budarin S. & Kondratyev M., 2014). Furanocoumarins can also be applicable in phototherapeutic drug production due to the hydrophobic properties of furanocoumarins obtained from the raw material of the plant. Photosensitisers derived from natural sources are currently being researched and applied in clinical practice, since they represent a potential alternative to phthalocyanines in combating cancer and other diseases that necessitate the utilisation

of photoactive materials (Kulikov et al., 2022). They are also suitable for use in the production of photosensitisers for PUVA therapy (Ageev et al., 2022). On the other hand, Autier et al., (1997) discovered that psoralen furanocoumarin could serve as a carcinogenic causative agent in melanoma.

Pectin gel made of *H. sosnowskyi* may be considered a promising biomaterial for tissue engineering. These gels were stronger than the gel obtained from the commercial apple pectin (Patova et al., 2017). The degradation and swelling of *H. sosnowskyi* hydrogel in physiological solutions have not been investigated yet (Popov et al., 2022). The water extract of the plant (leaves and petiole) oppresses mitosis, induces chromosomal mutations, and causes apoptosis, and these effects directly depend on the concentration of the extracts (Pesnya et al., 2011).

According to Gurina et al., (2023), the pharmacological potential of *H. sosnowskyi* has been insufficiently studied. There is no evidence base that is necessary to obtain safe and effective medicines based on it. At the same time, in order to obtain the dosage forms of *H. sosnowskyi*, it is necessary to develop safe methods of harvesting and processing raw materials.

2.11. Use in the Food Industry

Traditionally, the majority of *Heracleum* species are utilised as food additives, spices, and flavoring agents in folk cuisine (Bahadori et al., 2016). Nowadays, it has been demonstrated that *H. sosnowskyi* can be used as an alternative source of low methoxyl pectin. *H. sosnowskyi* pectin can be used as a thickening or gelling agents in low-calorie foods, in delivery systems for bioactive compounds. The investigation of yield, chemical composition, thermal stability and rheological properties of pectins obtained from fresh, frozen, air-dried hogweed raw materials revealed that freezing was not a suitable storage method

before utilisation. It is supposed to perform optimisation of the method of hogweed pectin extraction according to the requirements of the food and pharmaceutical industries. Further research is required to explore the gelling ability of *H. sosnowskyi* pectin in the presence of other components (low molecular weight substances, polysaccharides, proteins) and to ensure the biological safety of the obtained products (Patova et al., 2017).

2.12. Utilisation as a Packaging Material

Aside from energy use, the chemical composition also allows obtaining cellulose utilising biotechnological approaches to process plant raw material as an alternative to the traditional wood-base method (Mironova et al., 2022). *H. sosnowskyi* was found to be a promising material for cardboard production (Musikhin & Sigayev, 2006). The yield of cellulose as a semi-finished product can range from 49.5 % to 49.7 %. The redox-organosolvent method, with preliminary alkaline treatment, can be used, and the obtained cellulose should be classified as short-fiber. The analysis of cellulose showed that it is comparable in characteristics to GOST 28172–89. The average fiber length is 0.70 mm, and the average fiber width is 20.4 microns (Vurasko et al., 2022). Nanocrystalline cellulose has been produced from a lignocellulosic mass of *H. sosnowskyi* by sulfuric acid hydrolysis as well as hydrolysis in a mixture of nitric and hydrochloric acids (Zakharov et al., 2020). Mironova et al. (2022) evaluated the business model for cellulose production. The profitability point of cellulose production starts with around 309 ha of hogweed processed by the plant.

Vegetable plastic without resins, based on *H. sosnowskyi*, was obtained through the hot flat pressing in closed molds. Regression dependencies of plastic properties depending on the pressing temperature and moisture of the press raw material have been identified. The possibility of obtaining a material with satisfactory physical and

mechanical properties suitable for use has been demonstrated (Ershova et al., 2020), along with the modeling of production processes (Korsakova & Savinovskikh, 2020).

2.13. Application as Construction Materials

The industry has recently adopted a modern approach of utilising waste vegetable materials for producing building materials. Considering the issue of existing additives to concrete and energy efficiency in construction, dried *H. sosnowskyi* can be efficiently used as a plant-based additive to obtain heat-resistant, cost-effective material for enclosures (Musorina et al., 2019). Experiments to enhance the biostability of the raw material obtained from stems were conducted by Stepina et al. (2021) to determine the optimal conditions for modifying plant raw materials, resulting in an absolutely biostable material suitable for heat-insulating material production. The raw material was treated with monoethanolamine (N→B) trihydroxyborate-based compositions (usually used as modifiers for wood protection of building structures) in order to modify the surface, for example, against fungi. In the study by Melnichenko & Galceva (2021), the material of *H. sosnowskyi* was modified and mixed with gypsum for the production of papercrete. The studies showed the effectiveness of modifying the plant filler with a hydrophobisant, flame retardant, as well as an additional process of vacuuming and powdering with intercalated graphite. The modified filler can be used in the production of building materials.

2.14. Further Use in Other Industry Sectors

The residual solid material obtained after extraction from *H. sosnowskyi* has demonstrated its ability for the sorption of gold ions from solutions, as evidenced by SEM and UV spectrophotometry analysis (Ivanova et al., 2017). Ivanova et al. (2015) also determined optimal

conditions for the production of hogweed extracts with selective modifying properties valuable to float gold-bearing sulfide minerals.

There is a particular research interest in the scientific literature regarding the treatment of biomass to derive carbon. The *H. sosnowskyi* biomass represents a promising and affordable raw material for the production of graphene nanosheets, a crucial nanocarbon material demanded across various branches of science and industry (Voznyakovskii et al., 2020). Using the self-propagating high-temperature synthesis (SHS) technology in the study by Karmanov et al. (2023), the potential of *H. sosnowskyi* stems to be a material for the adsorption of uranium and T-2 mycotoxin was demonstrated. Additionally, Dubinov et al. (2022) have developed and patented a method for obtaining a sorbent for collecting oil and petroleum products.

Many *H. sosnowskyi* compounds consist of cyclic carbon structures with various functionalities, which have recently been considered as potential precursors of 2D nanocarbon-graphene materials with a high specific surface area of 179.1 m²/g (Voznyakovskii et al., 2020). The possibility of using *H. sosnowskyi*-based hard carbons in real batteries is demonstrated in the study by Lakienko et al. (2022). Pavlov et al. (2021) discovered the potential of the application of *H. sosnowskyi* essential oils in rubber formulation for expanding the temperature range while using it when the ambient temperature is below freezing. The physico-mechanical characteristics of promising composite friction material with added seeds of *H. sosnowskyi* for the production of frost-resistant brake pads for railway transport were found to comply with the established standards for these products (Pavlov et al., 2021).

The structures of *H. sosnowskyi* pectic polysaccharides, isolated from stem callus tissue, have been characterised. The considerable yield of the pectins opens up an opportunity to utilise *H. sosnowskyi* as a potential source of the said class of polysaccharides, which can stimulate the growth of seedlings and roots of other species, such as *Triticum*

aestivum L. (Gordina, Kuznetsov, et al., 2019; Gordina, Zlobin, et al., 2019).

The green mass of *H. sosnowskyi* can serve as a raw material for bioethanol production due to its high yield and the high sugar content in green mass with the use of *Saccharomyces cerevisiae*. Depending on the harvest season, preliminary calculations show that bioethanol yield from 2,500 L/ha can be obtained (with a yield of 50 t/ha and 10 % of sugars) and 29,000 L/ha (with a yield of 200 t/ha and 31 % of sugars) – and even higher. It is recommended to collect green mass in the period from the end of budding to the mass flowering of plants since this period contains the highest number of sugars) (Dorzhiev & Pateeva, 2011). The high carbohydrate content in *H. sosnowskyi* allows for the production of various alcohols, forming the basis of biofuels. On average, it contains 32.1 % crude protein, 12.5 % crude fiber and 21.2 % sugar per unit of absolute dry matter, which is more than in winter rape and cereal crops (barley, corn, etc.) (Keldysh & Pomazkov, 2009). The study of Shakhmatov et al. (2014) focused on characterising the chemical structure of polysaccharides obtained from the aerial parts of *H. sosnowskyi* through water extraction. Mironova et al. (2022) in their study considered and compared possible business models for processing hogweed using the proposed technology to produce bioethanol. The investigation of Zihare & Blumberga (2017) evaluated the economic and environmental impact of biobutanol production from *H. sosnowskyi*.

Presently, there are advancements in hogweed processing aimed at producing bioethanol (Dorzhiev & Pateeva, 2011). By employing contemporary biotechnological methods such as enzymatic processing of raw materials and screening yeast strains, along with optimising nitrogenous nutrition in terms of type, quantity, and application time, there exists potential to substantially enhance the bioethanol yield per unit mass of the plant (Verardi et al., 2020).

Besides bioethanol production, the study conducted by Dubrovskis et al. (2011) in Latvia demonstrated the potential of utilising *H. sosnowskyi* for biogas production. The average biogas yield and energy potential per unit area, based on calculations, resulted in 2,96 L/kg_{vos} and 38 GJ/ha (less than greater burdock and largeleaf lupin biomass). But the investigated average methane content was higher (76.4 %). This study proposed that *H. sosnowskyi* could be completely removed and replaced with another energy crop species (largeleaf lupin) to provide a stable biomass supply for bioenergy production. This transition could be achieved within an average of four years.

Table 2 summarises the potential applications of giant hogweed biomass identified in the literature review.

Table 2 Industrial sectors and potential applications of *H. sosnowskyi* (considered in the present study)

Sector	Applications	References
Agrochemical	Herbicidal product	Pesnya et al. (2011), Baležentienė (2012), Synowicz & Kalemba (2015)
	Biofumigant	Burgiel et al. (2008), Hpoo et al. (2020)
Pharmaceutical	Herbal remedies of dermatitis	Budarin & Kondratyev (2014)
	Antiviral drug	Tkachenko (2007)
	Disinfectant	Tkachenko (2007)
	Antibacterial drug	Politowicz et al. (2017)
	Phototherapeutic drug	Kulikow et al. (2022)
	Photosensitisers for PUVA therapy	Ageev et al. (2022)
	Pectin gel for tissue engineering	Patova et al. (2017)
	Water extract oppressing mitosis	Pesnya et al. (2011)
	Biopolymer for gastrointestinal tract	Karmanov et al. (2020)
Food	Low methoxyl pectin – gelling agent in low-calorie food	Patova et al. (2017)

Energy	Bioethanol production	Dorzhiev & Pateeva (2011)
	Biobutanol production	Zihare & Blumberga (2017)
	Biogas production	Dubrovskis et al. (2011)
	Solid biofuels production	Zihare et al. (2018), Polina et al. (2021), Dorzhiev & Pateeva (2011)
Construction and Manufacturing	Cellulose production	Musikhin & Sigayev (2006), Vurasko et al. (2022), Zakharov et al.
	Vegetable plastic production	Ershova et al. (2020), Korsakova & Savinovskiyh (2020)
	Modified filler for production of building material additive to heat-insulating material	Musorina et al. (2019)
	Papercrete production	Melnichenko & Galceva (2021)
	Extract with selective modifying properties valuable to float gold-bearing sulfide minerals	Ivanova et al. (2015), Ivanova et al. (2017)
	Graphene nanosheets	Voznyakovskii et al. (2020)
	Carbon for batteries	Lakienko et al. (2022)
	Carbon nanomaterials – adsorbents	Karmanov et al. (2023)
	Sorbent for collecting of oil from water	Dubinov et al. (2022)
	Additive to rubber, frost-resistant brake pads	Pavlov et al. (2021)
	Pectic stimulator for growth of seedlings and roots	Gordina et al. (2019)

2.15. Use for Production of Solid Biofuels

As previously noted, it is essential to emphasise that literature regarding the valorisation of *H. mantegazzianum* biomass is limited, particularly concerning its potential for conversion into solid biofuels. Research on *H.sosnowskyi* is more prevalent due to the long-standing history of investigating species in affected regions.

Some recent studies exploring the potential of *H.sosnowskyi*, for example, Polina et al., (2021) produced and examined pellets and found their properties to be comparable to pellets made of coniferous wood material, which is often used for the manufacturing of commonly used good-quality pellets. Although biomass fuel-energy properties are being investigated, they are usually just partially verified against standards for solid biofuels. Priedniece et al. (2024) explored *H. sosnowskyi* biomass as one of the alternative locally available biomass sources for pellets production. Some properties of biomass were compared to requirements for EN plus B-class wood pellets, demonstrating conformity. The authors stated that there are no critical parameters of biomass that can be problematic for standardised pellet production and their utilisation, for instance, ash content on a dry basis in the study resulted in 1.92 %. In comparison, the ash content of *H.mantgazzianum* was determined and the value was reported in the present study, varying 9.10 % and 12.3 %, being unfavourable, especially for pellet production. Gramauskas et al. (2023) reported the calorific value of *H. sosnowskyi* biomass (harvesting season is not specified) to be 15.86 MJ/kg, which is comparable to the calorific value of *H. mantegazzianum* autumn-harvested biomass (the data provided in this study in the Results and Discussion section). Both, briquettes (made with screw press and heated to 70-90 °C during production) and pellets were produced and characterised and tested. Dorzhiev & Pateeva (2011) provided recommendations to valorise solid residues left after pressing of *H. sosnowskyi* biomass for bioethanol production for conversion to briquettes and pellets; however, there is still

no evidence of such a type of residue processing in the literature. Another type of study on hogweed biomass was carried out by Zihare et al. (2018), where the authors demonstrated energy characteristics of *H. sosnowskyi* biomass (collected in October) being better than those of another problematic invasive plant, Canadian goldenrod (*Solidago canadensis*). This study was focused more on the possibilities of optimisation with different binders and testing of blends on a laboratory scale level, comparing the resulting GCV and AC.

Overall, existing research focuses primarily on *H. sosnowskyi*, suggesting that hogweed biomass possesses favorable properties with the potential to be processed into high-density pellets and briquettes, offering a calorific value comparable to that of traditional wood-based solid biofuels. Moreover, compliance of biomass properties with standards for solid biofuels has been addressed for *H. sosnowskyi* biomass. The same methodology remains to be extended to *H. mantegazzianum*.

The deployment of bioenergy technologies is crucial as a pathway for mitigating climate change (Pathak et al., 2022). Biomass will become a leading renewable energy source capable of substituting fossil fuels in the future (Jeníček et al., 2025; Nakimuli et al., 2025). The greatest advantage of using biomass for biofuels is the potential to achieve a balance of carbon dioxide (CO₂) that is released during combustion. Additionally, it offers lower emissions of sulfur dioxide (SO₂), nitrogen oxides (NO_x), and carbon monoxide (CO) (Piętka et al., 2019). Therefore, there is a need for studies addressing the efficient and safe utilisation of biomass for bioenergy applications.

In the comparative analysis of biomass feedstocks, herbaceous plants offer several strategic advantages over woody biomass. As noted by McKendry (2002), herbaceous species reach maturity within a single growing season, whereas forests require decades to regenerate. From a logistics and carbon-neutrality perspective, the localised nature of herbaceous biomass is a major advantage. Stolarski et al. (2013)

pointed out that herbaceous biomass can be harvested using standard agricultural machinery, which lowers the initial investment costs compared to specialised forestry equipment.

The current industrial landscape for herbaceous biomass utilisation is diverse, covering a wide range of dedicated energy crops and residues from agriculture. According to Angelini et al. (2009), perennial grasses like miscanthus (*Miscanthus x giganteus*) and switchgrass (*Panicum virgatum*) are among the most studied and utilised materials due to their high biomass yield and low nutrient requirements.

Beyond dedicated energy crops, agricultural residues such as cereal straws (wheat, barley and rye) represent the largest volume of herbaceous biomass currently used for densification. Monedero et al. (2015) discussed the widespread production of straw pellets in countries with intensive grain farming, noting that while straw has a high ash content, it remains a low-cost and abundant energy source.

In addition to traditional grasses, industrial hemp (*Cannabis sativa L.*) has emerged as a potential herbaceous feedstock. The similarity in stalk structure between industrial hemp and large herbs like giant hogweed suggests that the technologies and parameters developed for hemp densification can be effectively adapted for the processing.

The biomass of invasive weeds holds great underutilised potential and is of particular interest for energy purposes (Čerevková et al., 2020). The chemical composition of hogweed presents an opportunity to explore it as a potential source for alternative energy, diverging from conventional resources like petroleum (Mironova et al., 2022). But there is still little attention given to the potential of invasive species that can be considered as a resource of biomass-for-bioenergy already present in the environment, compared to the assessment of the invasiveness of new bioenergy crops to prevent new introductions (Van Meerbeek et al., 2015).

Biomass from weeds is readily and widely available; however, raw biomass exhibits a low energy density (Ibitoye et al., 2021). Densification technology, according to Kabas et al. (2024) and Gendek et al. (2018), 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 (Bajwa et al., 2018).

Over recent decades, the use of weed plant biomass for the production of densified biofuels has emerged as a promising area of research (Guil-Guerrero et al., 2014; Sharma & Pant, 2019), together with invasive weeds not commonly used for energy purposes, such as problematic Bohemian and Japanese knotweed (Brunerova et al., 2017; Halmová & Fehér, 2009; Jezerska et al., 2018) and common reed (Demko et al., 2017; Ivanova et al., 2017). Lantana camara, a woody shrub, has invaded millions of hectares of forest and pasture land, has been investigated for its energy potential. Priyanka and Joshi (2012) demonstrated that lantana can be converted into high-quality charcoal and briquettes, offering a viable solution for forest management in infested regions. Common ragweed (*Ambrosia artemisiifolia*) is also being considered as a bioenergy source. Vujevic et al. (2012) conducted research on the energy value of ambrosia, noting that its high biomass productivity makes it a suitable candidate for combustion, provided that the harvest occurs before the pollen-release stage to prevent allergies. Furthermore, thistle (*Cynara cardunculus*), often considered a weed in Mediterranean climates, has been successfully commercialised as an energy crop. Fernandez et al. (2006) showed that this plant can be harvested annually for more than ten years without replanting, producing both oil from seeds and solid fuels from stalks. The use of gorse (*Ulex europaeus*) and broom (*Cytisus scoparius*) has also been documented in hilly regions (Mediavilla et al. 2017, Mediavilla et al. 2020). Nunes et al. (2019) argued that the systematic removal of these

invasive shrubs for pellet production is a strategy for forest fire prevention. This management by utilisation model, supported by Ruan et al. (2019), suggests that the high cost of weed control can be partially offset by the energy value of the harvested biomass. The findings of studies indicate that this approach of biomass utilisation represents good potential to be used as a feedstock in addition to typical biomass sources for bioenergy, such as agricultural and forestry residues. Nackley (2015) stated that supplying small amounts of invasive weed biomass to biomass-fired power boilers is sustainable and can significantly reduce their populations locally.

According to Ibitoye et al. (2021), a significant barrier to the widespread use of raw biomass as biofuel is its low bulk density, which complicates logistical operations (handling, storage and transport). To address these challenges, densification technologies have emerged as an efficient and cost-effective strategy (IEA, 2019). The briquetting relies on various pressing technologies, including piston, hydraulic, screw, and roller presses. Pellet production typically utilises ring or flat die systems. The choice of densification technology plays a critical role in the energy balance. Generally, briquetting and pelletising require different levels of energy investment. According to Hu et al. (2014), the specific energy consumption for piston-type briquetting machines is often lower than that of the ring-die pelletiser, as briquetting requires less intensive grinding. While pelletising demands the biomass to be ground to a particle size of less than 6 mm, briquetting systems can often process material with a particle size of 10-50 mm, which significantly reduces the energy spent during the mechanical pretreatment stage.

The amount of energy recoverable from biomass is primarily determined by its calorific value (Erol et al., 2010). According to Vassilev et al. (2010), the typical gross calorific value for raw herbaceous biomass ranges between 17 and 19 MJ/kg, which is slightly lower than that of

woody biomass, which generally falls between 18.5 and 21 MJ/kg. McKendry (2002) reported that wheat straw and miscanthus have these values of approximately 18.5 MJ/kg. Prade et al. (2011) found that industrial hemp stalks can reach up to 19 MJ/kg.

When energy from biomass is obtained via complete thermal degradation, the inorganic solid residue remains in the form of ash. Obernberger and Thek (2004) conducted extensive research on various solid biofuels feedstocks and concluded that this higher mineral concentration in grasses and stalks is a result of their faster growth cycle and nutrient uptake mechanisms. The ash content is an important parameter because its high concentration represents a significant technical barrier to efficient biomass combustion (Munawar et al. 2021). The logistics of ash disposal and management are both labor-intensive (James et al. 2012). Van Loo and Koppejan (2008) pointed out that herbaceous ash is rich in alkali metals (especially potassium) and silica, whereas wood ash is predominantly composed of calcium. For invasive species, Styles et al. (2008) noted that wild herbaceous plants like Knotweed can accumulate high levels of minerals depending on soil composition.

For the investigation and application of biomass materials as biofuel, the initial step is characterisation of the proximate and elemental composition of the material (Malat'ák et al., 2020a). There is limited knowledge of the properties of biomass of invasive plants, which may either limit or promote their effective use for further processing, such as for example thermochemical conversion of lignocellulosic biomass (Okoro et al., 2020).

To improve the fuel properties of herbaceous material and solid biofuels made from this type of material, thermochemical treatment methods such as torrefaction have been proposed. Basu (2013) describes torrefaction as a mild pyrolysis process that increases the carbon content and energy density of the biomass while making it hydrophobic.

Furthermore, the chemical „homogenisation“ of the feedstock is a key benefit mentioned in the literature. Phanphanich and Mani (2011) observed that while different herbaceous species may have varying mechanical properties in their raw form, torrefaction tends to equalise these differences, producing a consistent solid fuel. By applying torrefaction, as suggested by Medic et al. (2012), producers can ensure a standardised product with predictable energy output, effectively bridging the gap between low-quality biomass wastes and high-grade industrial coal. Bridgeman et al. (2008) showed that torrefied wheat straw and reed canary grass reached gross calorific values of 21.5 MJ/kg and 23 MJ/kg, respectively.

Combustion of raw herbaceous biomass is associated with elevated levels of emissions (Ibitoye et al., 2021). Carbon monoxide (CO) and nitrogen oxide (NO_x) emissions from the combustion of solid biofuels are subject to regulated limits due to their potential to negatively affect air quality. Both are associated with harmful impacts on respiratory and cardiovascular health (Mao et al., 2019). Notably, NO_x emissions contribute significantly to the formation of acid rain (Boningari & Smirniotis, 2016; Siegmund et al., 2024). The combustion properties of weeds biomass that have not been investigated may lead to undesirable effects during use. Evaluating emissions released during the combustion of such biofuels is necessary.

In conclusion, although the potential for utilising biomass of invasive hogweed is recognised, its specific application for solid biofuels production is not yet fully characterised. Based on the literature review, unlike *H.sosnowskyi*, the fuel characteristics of *H.mantegazzianum* remain insufficiently explored. Since the impacts of various physical and chemical biomass properties on solid biofuel quality are well-established, these criteria can be reliably used to evaluate the energy potential of invasive hogweed biomass. Beyond biofuel quality, it is crucial to assess the safety, considering whether biomass conversion into

energy poses increased risks to human health and to the environment during processing and combustion. The possible practical challenges should be addressed as well. Furthermore, there is a notable absence of systematic comparisons between characteristics of *H.mantegazzianum* biomass harvested in different seasons.

3. Objectives

3.1 Main objective

The main objective of the Thesis was to assess the viability of problematic giant hogweed biomass for conversion into solid biofuels as a management solution for existing unmanaged biomass.

3.2 Specific objectives

1. To review current studies on the potential applications of the giant hogweed biomass.
2. To conduct a detailed characterisation of the biomass fuel properties and evaluate the impact of torrefaction on quality improvement.
3. To compare characteristics of the biomass and biofuels across the distinct biomass harvesting seasons.
4. To assess the compliance of determined biomass properties with current solid biofuels standards.
5. To determine variations in furanocoumarin content during the growing season and its distribution within the giant hogweed plant.
6. To evaluate the quality of solid biofuels produced from the giant hogweed biomass, including their combustion behaviour and emissions released.

4. Materials and Methods

4.1. Material Collection

The above-ground biomass of *Heracleum mantegazzianum* Sommier et Levier (hereafter referred to as *H. mantegazzianum*) obtained from a representative invaded site was subjected to comprehensive characterisation as a potential feedstock for solid biofuel production (with focus on briquettes). The study utilised only naturally occurring wild-growing plants.

Physical properties and chemical composition of herbaceous biomass vary with vegetation stage. Studies indicate that delaying harvest is associated with improved biofuel characteristics (Prochnow et al., 2009). Therefore, harvesting of biomass was conducted at two key phenological stages to account for the physiological changes in *H. mantegazzianum*. While the feedstock for briquettes production was sourced in sufficient amounts from two harvests, the analytical phase in the laboratory involved analysis of more types of biomass samples (specified in the following sections).

To ensure environmental safety during material collection, the plants were harvested before the seed-setting stage to prevent accidental seed dispersal during transportation. Harvesting was timed to mid-July during flowering (Fig. 7), representing a period when the peak of above-ground biomass accumulation can be observed (hereafter referred to as summer-harvested).



Figure 7 Summer-harvested biomass of *H. mantegazzianum* in-situ before collection

The post-senescent biomass sample was obtained in mid-November (hereafter referred to as autumn-harvested) (Fig. 8). Biomass of *H. mantegazzianum* on 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 8 Autumn-harvested biomass of *H. mantegazzianum* in-situ prior to collection

The stand, consisting of naturally established plant individuals, was selected for biomass harvesting (Fig. 9). The 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 of Zličín.

The following harvesting procedure was carried out identically for both summer- and autumn-harvested material. To cut the plants and chop them into manageable lengths for transportation, manual loppers were used. Appropriate safety measures were implemented (eye protection, protective work gloves and clothing) due to the toxic nature of the species. Immediately after harvesting, the biomass was packed into heavy-duty sealed 100 L plastic bags and transported for further processing.



Figure 9 General view of the sampling site

The harvested biomass was air-dried under sheltered conditions (Fig. 10) and was mechanically shredded with a hammer mill 9FQ–40

(5.5 kW, equipped with Lenze MDERAXX132-12J electric motor), using a different sieves with openings of a diameter of 8 mm for the briquette production and 6 mm for pellets production.



Figure 10 Preliminary drying of summer-harvested biomass (left) and internal view of hammer mill with sieve (right)

The preparation of analytical biomass samples followed the protocols outlined in ISO 14780:2017. The samples underwent mechanical grinding followed by sieving to a fraction of less than 1 mm. Laboratory mill Foss Cyclotec 1093 (Foss, Denmark) was used.

4.2. Biomass Characterisation

A systematic methodology, based on international standards established by the International Organisation for Standardisation for solid biofuels, was adopted for the *H. mantegazzianum* biomass characterisation in this thesis. Access to standards was provided by the library of the Czech University of Life Sciences Prague. Table 3 provides an overview of the ISO standards used.

Table 3. Summary of standards for analytical methods applied in the thesis

Parameter	Reference Standard	Standard Number and Year of Revision
GCV, NCV	Solid biofuels — Determination of calorific value	ISO 18125:2017
AC	Solid biofuels — Determination of ash content	ISO 18122:2022
Total S and Cl	Solid biofuels — Determination of total content of sulfur and chlorine	ISO 16994:2016
Total C,H, N	Solid biofuels — Determination of total content of carbon, hydrogen and nitrogen	ISO 16948:2015
Major elements	Solid biofuels — Determination of major elements — Al, Ca, Fe, Mg, P, K, Si, Na and Ti	ISO 16967:2015
Minor elements	Solid biofuels — Determination of minor elements	ISO 16968:2015
Ash melting behaviour	Solid biofuels — Determination of ash melting behaviour	ISO 21404:2020
DU	Solid biofuels — Determination of mechanical durability of pellets and briquettes. Part 2: Briquettes	ISO 17831-2:2015
Fuel quality class	Solid biofuels — Fuel specifications and classes. Part 6: Graded non-woody pellets	ISO 17225-6:2021
	Solid biofuels — Fuel specifications and classes. Part 7: Graded non-woody briquettes	ISO 17225-7:2021

Specific analytical techniques, equipment, technical details, and requirements for maintaining measurement precision are elaborated in the following subsections.

The biomass characterisation phase was performed in the Laboratory of Biomass Characterisation at the Centre for the Development of Renewable Energy Sources (CEDER-CIEMAT), a National Reference Research Centre in Spain providing a rigorous testing environment for reliable research on solid biofuels.

4.2.1. Calorific Value Determination

The gross calorific value (GCV) was determined following ISO 18125:2017 using an automatic bomb calorimeter Parr 6400 (Parr Instrument Company, Moline, IL, USA). An analytical sample in the form of a pellet with a diameter of 10 mm was placed in a combustion bomb (Fig.11), where it was ignited in an oxygen atmosphere at constant volume. The repeatability of the calorimetric measurements was maintained within the permissible limits defined by the ISO standard mentioned above. Specifically, the absolute difference between replicate measurements did not exceed 120 J/g.



Figure 11 Combustion bomb (not to scale) (left) and automatic isoperibol calorimeter (right)

The net calorific value was calculated from the GCV obtained by calorimetry.

The following formula was used:

$$Q_{\text{net}} = Q_{\text{gr}} - 24.42 \times (w + 8.94 \times H^a)$$

where:

Q_{net} is the net calorific value in J/g;

Q_{gr} is the gross calorific value in J/g;

24.42 is the coefficient corresponding to 1 % of the water evaporated from the sample at 25 °C;

W is the moisture content in the sample in %;

8.94 is the coefficient for conversion of hydrogen to water;

H^a is the hydrogen content in the sample (%).

4.2.2. Ash Content Determination

Ash content (AC) was determined gravimetrically based on the ISO 18122:2022. Samples of biomass were placed in a ceramic crucible. The procedure involved heating the analytical sample incrementally, raising it to 550 °C. The heating was continued until a constant mass of inorganic residue was reached. AC was expressed as a percentage of the original mass of the sample on a dry basis. LECO TGA 701 (LECO Corporation, St. Joseph, MI, USA) was employed for the measurement. Instrument stability and measurement precision were maintained through the use of a blank sample. For each sample, the absolute difference between two parallel determinations, performed under the same conditions, was kept within the required threshold of 0.2 % (absolute) for samples with ash content above 10 % and 0.1 % for those below 10 %.

4.2.3. Determination of the Total Content of Carbon, Hydrogen, and Nitrogen

The elemental analysis for CHN was performed in accordance with ISO 16948:2015. The measurements were carried out using an automated high-temperature furnace TruSpec LECO (LECO Corporation, St. Joseph, MI, USA) connected to a computer running the manufacturer's operating software TruSpec CHNS. Approximately 0.1 mg of finely ground biomass sample was weighed into tin capsules for analysis. The samples were combusted at high temperature in the TruSpec furnace, converting carbon, hydrogen, and nitrogen into measurable gases. The generated gases were quantified using thermal conductivity detection, and each sample was measured in triplicate to ensure reproducibility.

4.2.4. Determination of the Total Content of Sulfur and Chlorine

The content of sulfur and chlorine was evaluated according to ISO 16994:2016. The procedure involved combustion of the analytical sample in a bomb calorimeter (mentioned above in sub-section 4.2.1. Calorific Value Determination), followed by lixiviation of the combustion residues from the oxygen bomb to prepare a solution for ion chromatography. The analysis was completed using an 883 Basic IC Plus (Metrohm, Herisau, Switzerland) connected to a computer running software. An automated injection system was utilised to ensure high precision and reproducibility of analytical samples delivery into the chromatographic column.

4.2.5. Determination of Major and Minor Elements

The analytical procedure for major and minor elements requires the decomposition of samples. Biomass ashes, which were obtained at 550 °C, were acid digested in a microwave furnace Ethos Pro system (Milestone, Sorisole, Italy) using nitric acid (HNO₃), hydrogen

peroxide (H_2O_2) and hydrofluoric acid (HF) as a first step and boric acid (H_3BO_3) as a second step before being further analysed.

To determine the content of major elements (Al, Ca, Fe, Mg, P, K, Si, Na, Ti), the samples were analysed by Coupled Plasma Atomic Emission Spectroscopy ICP-OES (IRIS AP, Thermo Jarrell Ash, Madrid, Spain) (Fig. 12) using the methodology of ISO 16967:2015. The concentrations of major elements were also converted into their oxide forms.



Figure 12 Atomic emission spectrometer

The detection of minor elements (As, Cd, Cr, Cu, Ni, Pb, Zn) was carried out in accordance with ISO 16968:2015 by the iCAP Q - Inductively Coupled Plasma Mass Spectrometry system (ICP-MS) (Thermo Scientific, Waltham, Massachusetts, USA), whereas Mercury (Hg) was detected separately using a direct mercury analyser DMA 80 (Milestone, Sorisole, Italy) via thermal decomposition, gold amalgamation, and absorption spectrophotometry.

4.2.6. Volatile Matter Determination

Content of volatile matter (VM) was determined according to EN ISO 18123:2015 standard as the loss in mass during calcination of the sample

in a thermogravimetric analyser with carousel for multiple samples LECO TGA 701 (LECO Corporation, St. Joseph, MI, USA) at 900 °C for a period of 7 minutes. The precision of the results was maintained within the repeatability limit of 0.3 % (absolute), ensuring the consistency of measurements.

4.2.7. Determination of Ash Melting Behaviour

Optical heating microscope Hesse HT15 (Hesse instruments, Osterode am Harz, Germany) connected to the computer running the manufacturer's software for data acquisition (Heating Microscope Measurements and Evaluation) (Fig. 13) was used for the analysis of the ash melting behaviour on a laboratory scale following the standard ISO 21404:2020.

A cylindrical pellet (3 mm in diameter and 3 mm in height) was prepared from the ash of a biomass analytical sample and subjected to a gradual increase in temperature (from the room temperature to 1,400 °C in an air atmosphere).

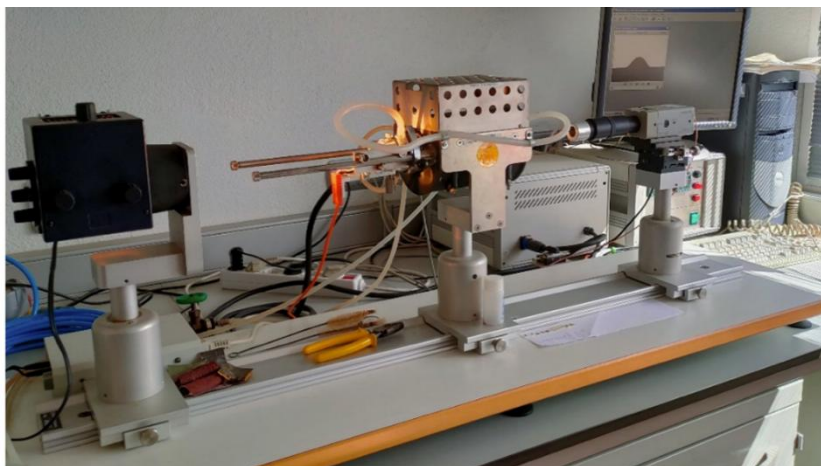


Figure 13 Optical heating microscope

The assessment of this parameter relies on detecting morphological changes in the testing ash pellet (Fig. 14).

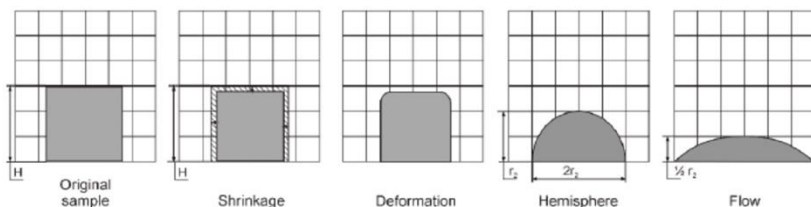


Figure 14 Phases which can occur in the ash melting process according to ISO 21404:2020

The characteristic temperatures during ash melting analysis are described as follows:

1. Shrinkage starting temperature (ST) corresponds to the stage where the area of the test piece falls below 95 % of the original test piece area due to the shrinking of the pellet;
2. Deformation temperature (DT) is characterised by the first signs of melting, like rounding of the edges;
3. Hemisphere temperature (HT) is detected when the test pellet forms approximately a hemisphere, i.e., when the height is half of the base diameter;
4. Fluid temperature (FT) reached when ash spreads out over the supporting tile in a layer and height of which is half the height of the test piece at the hemisphere temperature.

4.3. Thermochemical Conversion of Analytical Samples and Their Characterisation

The analytical samples were thermally treated in an inert atmosphere to convert them into biochar samples in an automatic thermogravimetric analyser, LECO TGA 701 (LECO Corporation, St. Joseph, MI, USA) in Fig. 15. The analyser was used as a programmable multiple sample furnace connected to a computer running the manufacturer's

operating software. An inert atmosphere was maintained by purging the furnace with N₂.

Thermochemical conversion of *H.mantegazzianum* biomass (both harvests) was investigated at four distinct temperatures: 200, 300, 400, and 500 °C.



Figure 15 TGA used as a programmable furnace (left) and carousel for samples (right)

An instrumental method of ash content determination, which is also compliant with the ISO standard, was employed using the thermogravimetric analyser mentioned above.

The obtained samples were also subjected to calorific value determination and C, H, N content determination according to the aforementioned methodology (4.2.1. Calorific Value Determination and 4.2.3. Determination of Total Content of Carbon, Hydrogen, and Nitrogen, respectively).

The elemental composition was visualised using a Van Krevelen diagram to show an expected improvement in the energy density of the material (indicating a shift towards lower H/C and O/C ratios).

For the calculation of the oxygen content (by difference), the following formula was used: $O = 100 - (C + H + N + S + \text{Ash})$, where the sulfur content for treated samples was assumed to be equal to that of the non-treated material.

For the calculation of atomic ratios, the following formulas were used:

$$H/C = \frac{H/1.008}{C/12.011}$$

where:

H is the total hydrogen content of the sample (%),

C is the total carbon content of the sample (%),

1.008 is the relative atomic mass of hydrogen,

12.011 is the relative atomic mass of carbon

$$O/C = \frac{O/15.999}{C/12.011}$$

where:

O is the oxygen content of the sample (%),

C is the total carbon content of the sample (%),

15.999 is the relative atomic mass of oxygen,

12.011 is the relative atomic mass of carbon

Methodology and areas of typical composition of biomass, peat, lignite, coal and anthracite depicted in the diagram for comparison were taken from Van Loo & Koppejan (2008).

4.4. Analysis of Furanocoumarins

4.4.1. Extraction of Furanocoumarins

Preparation of samples for extraction involved dry plant material grinding using a knife mill, Retsch Grindomix GM 200 (Retsch GmbH, Haan, Germany). The material was also homogenised by sieving to a particle size of less than 1 mm.

In total, six different samples were collected and examined. The first three samples represented individual parts of 3 randomly selected plants within a sampling radius of approximately 10 m, harvested at the end of their flowering phase (in mid-July). No seeds were observed at the time of sampling. The samples for analysis were labeled as follows: Stem, Leaves, and Umbel (inflorescence).

The three remaining samples represented whole plants (mixed material from 3 random plants collected within a radius of 10 m) captured *H. mantegazzianum* during three distinct stages of its reproductive cycle: July (flowering phase (main shoot): full flowering: 50% of flowers open, first petals may have fallen), August (ripening or maturity of fruit and seed: fully ripe), and September (senescence or beginning of dormancy and dieback).

Extraction was done in flasks equipped with cellulose extraction thimbles. Using the analytical balance KERN 572 (KERN & SOHN GmbH, Balingen, Germany) with 0.001g readability, prepared *H. mantegazzianum* samples were individually weighed. Approximately 150 g of each sample was extracted with 50 mL of methanol. Extraction was performed by an automatic solvent extractor SER 158 Series (Velp Scientifica, Usmate Velate, Italy) in Figure 16. Extraction conditions were based on a modified version of the AOAC 2003.06.

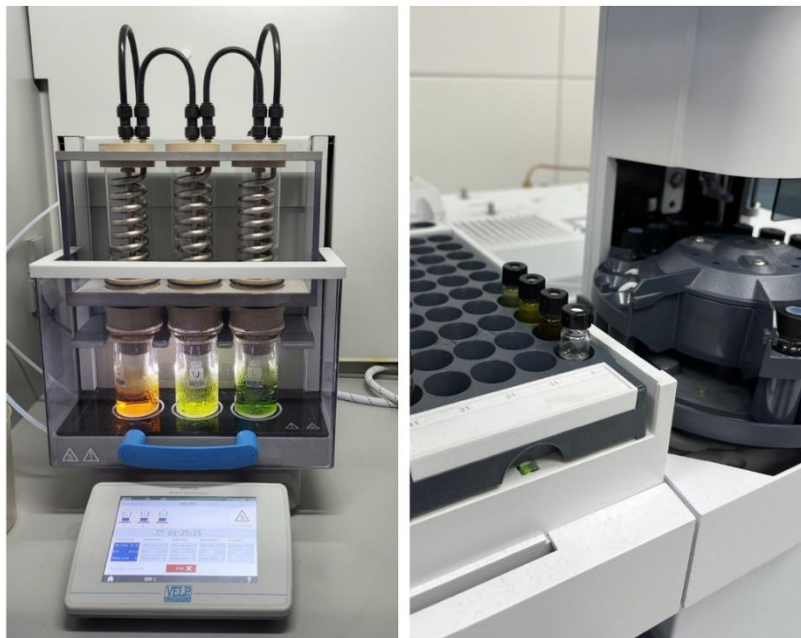


Figure 16 Extraction (left) and samples prepared for GC/MS analysis (right)

4.4.2. Determination of Furanocoumarins Content

Gas Chromatography/Mass Spectrometry analysis was performed using an Agilent 7890B/5977a GC/MSD system (Agilent Technologies, Santa Clara, CA, USA) equipped with an HP-5 capillary column (30 m $\times$ 0.25 mm, film thickness 0.25 μ m; Agilent 19091s-433). GC-MS was selected due to its high sensitivity and suitability for the analysis of relatively low-molecular-weight, non-polar, and thermally stable furanocoumarins, allowing their analysis without additional chemical modification (Peroutka et al. 2007, Sajjadi et al. 2017, Vickackaite et al. 2025).

Evaporated extracts were diluted with methanol to a final concentration of 20 μ g/mL. Injection volume was 1 μ L, with the GC inlet maintained at 250 $^{\circ}$ C under splitless mode. The oven temperature program

was set as follows: an initial temperature of 70 °C was held for 2 min, followed by a temperature ramp of 10 °C/min to 280 °C and a final hold at 280 °C for 10 min.

Helium (He) served as the carrier gas at a flow rate of 1 mL/min. The MS transfer line temperature was set at 250 °C, and the electron ionisation energy was 70 eV. Spectra were collected over an m/z range of 30–600 with a scan time of 1 second.

Compound identification was based on comparison of mass spectra with the NIST 2.2.f library (National Institute of Standards and Technology, USA). The use of mass spectral matching provides reliable structural identification based on characteristic fragmentation patterns. Data processing and peak integration were conducted using MassHunter Workstation Software Qualitative Analysis B.07.00.

Due to the absence of authentic reference standards and calibration curves, quantitative results were interpreted on a semi-quantitative basis using relative peak area normalization, a commonly applied approach in GC-MS phytochemical analysis (Adams, 2007). This approach enables comparison of the relative abundance of compounds within and between samples but does not provide absolute concentrations.

All analyses were performed under identical instrumental conditions to ensure reproducibility of retention times and relative peak areas.

4.5. Production and Testing of Briquettes

4.5.1. Solid Biofuel Production and Mechanical Durability Determination

A sample sets of briquettes for testing was prepared using a hydraulic briquetting press BrikStar model CS 25 (Briklis, Malšice, Czech Republic), shown in Figure 17.

This type of press 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).



Figure 17 Hydraulic briquetting press (left) and briquetting of material (right)

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 9 %.

The mechanical durability (DU) of the produced briquettes was determined according to ISO 17831-2:2015, using a standardised automatic rotating abrasion drum (BT 105, manufactured by Research Institute

of Agricultural Engineering, Prague, Czech Republic) and weight measurements were carried out using electronic balance KERN KB 2400-2N (KERN & SOHN GmbH, Balingen, Germany) (readability 0.01 g) (Fig. 18). 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.



Figure 18 Rotating drum

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 following formula was used:

$$DU = \frac{m_2}{m_1} \times 100$$

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 (g).

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

4.5.2. Combustion Tests of Briquettes

Combustion tests were conducted using a manually fed combustion device (Fig. 19) 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 solid fuel consumption of 2.5 kg/h, as specified by the manufacturer of the combustion device. The conditions were maintained manually during measurements.



Figure 19 Combustion unit (left) and burning briquettes made from *H.mantegazzianum* (right)

During combustion, emissions were measured using a Madur GA-60 flue gas analyser (Madur Polska Sp. Z. O.o., Zgierz, Poland). The sampling probe of the analyser was inserted into the exhaust pipe of the combustion device. Flue gas temperature, along with O₂, CO, and NO_x concentrations, was recorded. The combustion tests were conducted under controlled operating conditions, with flue gas temperature (T_{fg}) and excess air ratio (n) as parameters. The sensor signals were proportional to the volume concentration of the monitored components, expressed in parts per million (ppm). The concentrations of the dry flue gas components were normalised to standard conditions (0 °C and 101.325 kPa) and expressed in mg/m³, referenced to a flue gas oxygen content of 13 % by volume.

In line with the previously reported approach to biomass combustion tests using similar equipment, which also considers the nonlinear behaviour of CO and NO_x emission formation processes (Malat'ák et al., 2020), second-degree polynomial functions were applied. For the experimental investigation of the relationships between briquettes combustion parameters and gaseous emissions, the measurement data were processed using Microsoft Excel 2309 (Microsoft 365), where CO and NO_x emissions were dependent variables, while excess air coefficient and flue gas temperature were used as independent variables. Model performance was evaluated using the coefficient of determination (R^2), indicating the goodness of fit.

4.5.3. Thermogravimetric Analysis and Differential Scanning Calorimetry

A thermogravimetric analyser was used for thermal decomposition of the biomass analytical samples in an air atmosphere and at a heating rate of 10 °C/min in the Setaram Setsys Evolution model S60 (Setaram Instrumentation, Tours, France) (Fig. 20). The loss in mass of the biomass sample 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.



Figure 20 Thermogravimetric analyser for TGA DSC. Source: Setaram Instrumentation official website

4.6. Test Production of Pellets and Mechanical Durability Determination

To demonstrate the pelletisation potential and evaluate the practical application of giant hogweed biomass (without additional binders), the summer-harvested sample was used to produce pellets.

Milled material with particle size less than 6 mm (methodology outlined previously, the used sieve was adjusted to 6 mm) was pelletised with a low-power (4 kW) biomass granulator with a horizontal matrix Green Energy JGE 120 (Pest Control Corporation, s.r.o., Vlčnov, Czech Republic) (Fig. 21, left). The granulator had a capacity of 75-100 kg/h. The pellets were produced with a standard diameter of 6 mm, consistent with industrial requirements for residential heating systems. The material used for pelletisation was stored at room temperature before production.

After pelletisation, the produced pellets underwent a cooling phase, being left at an ambient temperature of 8 °C for 15 min to stabilise

their structure (the pellets were evenly distributed in a single layer on a plastic surface).

The ISO 17831-1:2015 standard was used to determine the mechanical durability of the produced pellets. The tester PT 500 (manufactured by RIAE, Prague, Czech Republic), designed in compliance with the requirements of the mentioned ISO standard, was employed (Fig. 21, right).



Figure 21 Biomass granulator (left) and pellets tester (right)

Two samples of pellets (approximately 500 g as prescribed by the standard) were subjected to testing. After the procedure in the tester, the samples of pellets were sieved through a 3.15 mm screen to remove the dust and small particles. Weight measurements were done using an electronic balance KERN KB 2400-2N (KERN & SOHN GmbH, Balingen, Germany) (readability 0.01 g)

The following formula was used:

$$DU = \frac{m_2}{m_1} \times 100$$

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 sieved test sample after testing (g).

5. Results and Discussion

This chapter presents and discusses in detail the results of the *H. mantegazzianum* biomass characterisation.

During the biomass material preparations, it was observed that harvested plants possess favourable physical characteristics for mechanical processing. This is mainly due to the specific morphology of the plant (such as a hollow stem), which characterises inherent friability.

5.1. Biomass Characterisation

Through a series of laboratory measurements, the study focused on evaluating the giant hogweed biomass's potential to be processed into solid biofuel and utilised.

5.1.1. Calorific Value, Ash Content, and Volatile Matter

The energy potential of the studied biomass was determined through bomb calorimetry. The autumn-harvested biomass sample exhibited a gross calorific value (GCV) of 18.65 MJ/kg (d.b.), aligning with the energy performance of dedicated energy crops like miscanthus. When biomass is harvested in summer to prevent seed spread, the biomass maintains a high GCV of 16.91 MJ/kg (d.b.). Compared to another problematic invasive species, Japanese knotweed (*Fallopia japonica*), Jezerska et al. (2018) reported a GCV of 14.61 MJ/kg (d.b.) for *F. japonica*. From a waste-to-energy perspective, *H. mantegazzianum* offers a higher energy recovery potential. Obtained values are being found to align closely with the properties of established non-woody energy crops, confirming the viability of biomass as a material for solid biofuels production. In terms of lifecycle and physical structure, giant hogweed biomass can be compared to material sourced as an agricultural residue, namely cotton stalks. Since it is already widely utilised as an easily available bioenergy source and demonstrates a

calorific value of 16.55 MJ/kg (Elshareef et al. 2025), a similar approach for hogweed biomass valorisation can be applied.

Following the release of energy, the non-combustible mineral solid constituents of the biomass remain as ash. Determination of this inorganic fraction is important in terms of maintenance requirements for combustion equipment. In the study done by Zajac et al. (2018), it is emphasised that the ash content is a variable characteristic of biomass, determined by a set of factors including the presence of impurities during handling. The site-specific characteristics, timing, and conditions of harvest affect the ash content of biomass.

Seasonal variation impacted the ash content of the studied material, which dropped from 12.3 % dry in mid-summer to 9.1 % dry in late summer.

A key indicator of biomass ignition behaviour is volatile matter content. For the studied biomass samples, the volatile matter was recorded at 73.5 % dry and 74.3 % dry for summer-harvested and autumn-harvested biomass, respectively. This parameter remained relatively stable across different biomass harvest periods, showing a minor increase.

5.1.2. Elemental Composition

The properties, quality, potential applications, and environmental problems associated with any fuel are determined by the elemental composition (Malaťák et al., 2020). To evaluate the impact of harvest timing on fuel quality, a comprehensive elemental analysis was conducted focusing on the variation of constituents between summer- and autumn-harvested biomass samples. The measurement results are presented in Table 4.

Table 4 Content of major elements in biomass samples of *H.mantegazzianum* (%)

Elements	Summer-harvested biomass	Autumn-harvested biomass
Aluminium, Al	0.06	0.18
Barium, Ba	0.02	0.04
Calcium, Ca	6.70	17.00
Iron, Fe	0.04	0.13
Potassium, K	31.30	33.00
Magnesium, Mg	1.20	1.60
Manganese, Mn	0.01	0.02
Sodium, Na	0.10	0.15
Phosphorus, P	2.20	3.00
Sulfur, S	0.67	1.00
Silicon, Si	1.10	1.50
Strontium, Sr	0.01	0.04
Titanium, Ti	0.01	0.01

It can be seen that the dominant elements in biomass are K, Ca, and P. The potassium content in the biomass reached 33 % in autumn biomass (it just slightly changed with later biomass harvesting), such a high concentration raises a concern regarding ash melting behaviour. Ash melting issues, such as lower ash melting temperatures leading to sintering or slag formation, are likely to occur when K concentrations exceed 7 % dry (Obernberger et al., (2006), Endriss et al. (2023)).

Notably, it can be observed that the percentage of calcium content increased from 6.70 % in summer to 17 % in autumn. Obernberger et al. (2006) stated that Ca concentrations below 15 % negatively affect ash melting behaviour. Thus, this rise had a positive effect on the ash

behaviour of autumn-harvested biomass. There is a potential to mitigate the negative effect of high K content.

The concentrations of Al, Ba, Fe, Mg, Mn, Na, S, Si, Sr, and Ti were found to be low. These elements are expected to have no impact on the biomass ash.

The presence of these constituents can be attributed to both plant uptake and contamination. Since the biomass was collected by hand and packed on-site, the possibility of getting soil into the samples was minimised.

The technical difficulties typical for herbaceous biomass are manageable by utilising specialised combustion technologies and regulated operating temperatures.

The chemical composition of the *H.mantegazzianum* biomass ash, expressed as oxides, is summarised in Table 5. The variations in these inorganic constituents are critical for understanding the ash melting behaviour observed in different harvest seasons.

Table 5 Ash composition of *H.mantegazzianum* samples (%)

Oxides	Summer-harvested biomass	Autumn-harvested biomass
Aluminium oxide, Al ₂ O ₃	0.12	0.34
Barium oxide, BaO	0.02	0.06
Calcium oxide, CaO	9.50	24.00
Iron(III) oxide, Fe ₂ O ₃	0.06	0.18
Potassium oxide, K ₂ O	37.70	39.00
Magnesium oxide, MgO	2.00	2.70
Manganese(III) oxide, Mn ₂ O ₃	0.02	0.03

Sodium oxide, Na ₂ O	0.09	0.21
Phosphorus pentoxide, P ₂ O ₅	5.00	6.10
Sulfur trioxide, SO ₃	1.68	2.60
Silicon dioxide, SiO ₂	2.40	3.30
Strontium oxide, SrO	0.02	0.05
Titanium dioxide, TiO ₂	0.01	0.02

The comparative analysis of the ash composition harvested in summer and late autumn reveals that constituents demonstrated an upward trend with varying intensity. The dominant potassium oxide (K₂O) remained stable, showing comparable values across both samples and remained critically high despite the positive trend in CaO (more than twofold increase was observed).

The natural plant losing its organic mass may be the main reason for the increase in concentrations.

5.1.3. Ash Melting Behaviour

Understanding of studied biomass ash melting behaviour is important for the reliable operation of combustion units, as the formation of slag can lead to reduced efficiency and even mechanical damage. The characteristic temperatures of ash fusion reflect the complex melting behaviour of the biomass mineral matter under increasing temperatures. In Table 6, detected characteristic temperatures of the *H. mantegazzianum* ash melting process are summarised.

Table 6 Characteristic ash melting temperatures (°C)

<i>H.mantegazzianum</i> sample	ST	DT	HT	FT
Summer-harvested biomass	320	790	nd	>1,450
Autumn-harvested biomass	620	740	770	>1,450

Note: nd – not determined

Comparative analysis of the melting behaviour of ashes obtained from summer- and autumn-harvested biomass led to the following findings.

The summer samples showed a wide melting range with low shrinkage temperature (ST). The lower shrinkage and deformation temperatures are more disadvantageous, as it indicates a high propensity for slagging at low operating temperatures. The typically higher alkali metal content is found in green biomass before the natural leaching process in late autumn. The shrinkage starting temperature rose from 320 for summer biomass to 620 °C for the autumn-harvested sample. Notably, the hemisphere temperature (HT) for the summer sample was not determined. The ash maintained a state without a distinct hemispherical condition before reaching the fluid stage. The ash melting behaviour of autumn-harvested biomass is characterised by a rapid phase transition from deformation to hemispherical being more predictable.

Despite an observed increase in calcium oxide content from 9.5 % to 24 % (see the subsection above), the fluid temperature (FT) was identical for both samples, exceeding 1,450 °C. The ash resulting from the combustion of solid biofuels made from *H. mantegazzianum* biomass is unlikely to form a fully liquid slag under standard combustion conditions for both tested types of biomass. However, ash of summer-harvested biomass exhibited lower thermal stability.

In comparison, for a representative of energy crops, hemp, the following temperatures were reported: 1,079 °C (ST), 1,418 °C (DT),

1,490 °C (HT) and 1,496 °C (FT), being comparable to woody biomass ash and suitable for biofuel production (Čepauskine et al. 2018). Ash from woody biomass (pine, eucalyptus), which is used for good quality solid biofuels, typically shows initial melting when the temperature reach approximately 1,100 °C, demonstrating the thermal stability of this type of ash (Fernández & Carrasco, 2005). An evaluation of ash melting behaviour of the solid biofuels made from *H. sosnowskyi* biomass was done by Gramauskas et al. (2023); the stability of ash was nearly identical to that of woody biomass was exhibited in the study. Specifically, the study recorded temperatures as follows: 1,316 °C, 1,435 °C, 1451 °C, and 1,467 °C as ST, DT, HT and FT, respectively. Although this parameter was investigated for *H. sosnowskyi* in a previous study, the harvesting conditions and ash composition were not reported, nor was the equipment used. This lack of data limits the comparability of their results with our findings.

The obtained experimental data for *H. mantegazzianum* ash obtained in this study highlight the need for further optimisation for utilisation. Among possibilities to improve ash melting behaviour is the use of mineral additives (Steenari et al. 2009, Schmitt & Kaltschmitt, 2013) or employing biomass pretreatment methods such as leaching (Fernández et al. 2022). Additives commonly applied to reduce ash-related problems include lime (CaO , Ca(OH)_2), calcite (CaCO_3), kaolin, and feldspars (Niu et al. 2016).

5.2. Evaluation in Accordance with ISO Standard Limit Values for Solid Biofuels

The quality of solid biofuels is broadly defined by the compliance of parameters with established requirements. Over a decade ago, the international ISO standards specifically for solid biofuels were developed, and since then, this approach has become central to the solid biofuel industry. The assessment of biomass properties and comparison to established international standards clearly shows whether the biomass meets industry requirements for performance and safety of potential practical use. Furthermore, a specific quality class is assigned to the briquettes and pellets (woody and non-woody) depending on how their fuel-energy parameters meet the limit values. The following section presents a direct comparison of the obtained results against the requirements of the ISO 17225 series (Fuel specifications and classes). The applied standards employ specifically adapted value limits which account for the natural chemical composition of non-woody biomass, including herbaceous plants, which, for example, contain higher levels of ash and nitrogen compared to woody biomass.

The results obtained for both summer-and autumn-harvested biomass of *H. mantegazzianum* are presented in Table 7, where ISO standard limit values are added for direct comparison with results.

Table 7 *H.mantegazzianum* biomass characterisation and standards limit values for selected parameters

Parameter	Unit	Summer-harvested biomass	Autumn-harvested biomass	Non-woody briquettes classes (ISO 17225-7:2021)				Non-woody pellets classes (ISO 17225-6:2021)			
				A1	A2	B	A	A	B	A	B
Ash, AC	% dry	12.30	9.10	≤3	≤6	≤10	≤6	≤6	≤10	≤6	≤10
Net calorific value	MJ/kg ar	14.22	15.90	≥14.5	≥14.5	≥14.5	≥14.5	≥14.5	≥14.5	≥14.5	≥14.5
Nitrogen, N	% dry	1.31	0.91	≤1.5	≤1.5	≤2	≤1.5	≤1.5	≤2	≤1.5	≤2
Sulphur, S	% dry	0.10	0.08	≤0.20	≤0.20	≤0.30	≤0.20	≤0.20	≤0.30	≤0.20	≤0.30
Chlorine, Cl	% dry	0.17	0.12	≤0.10	≤0.20	≤0.30	≤0.10	≤0.10	≤0.30	≤0.10	≤0.40
Arsenic, As	mg/kg dry	<0.10	0.10	≤1	≤1	≤1.5	≤1	≤1	≤1.5	≤1	≤1.5
Cadmium, Cd	mg/kg dry	0.020	0.038	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5
Chromium, Cr	mg/kg dry	<1.0	<1.0	≤50	≤50	≤50	≤50	≤50	≤50	≤50	≤50
Copper, Cu	mg/kg dry	4.0	4.1	≤20	≤20	≤20	≤20	≤20	≤20	≤20	≤20
Lead, Pb	mg/kg dry	<0.20	<0.20	≤10	≤10	≤10	≤10	≤10	≤10	≤10	≤10
Mercury, Hg	mg/kg dry	0.006	0.005	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1
Nickel, Ni	mg/kg dry	<1.0	<1.0	≤10	≤10	≤10	≤10	≤10	≤10	≤10	≤10
Zinc, Zn	mg/kg dry	12	19	≤100	≤100	≤100	≤100	≤100	≤100	≤100	≤100

The results of biomass characterisation demonstrate inconsistent compliance of *H.mantegazzianum* samples with established ISO standards for solid biofuels.

Compared to the results for summer-harvested, the autumn-harvested sample characteristics align more closely with quality standards, meeting the very important required value limits for NCV (a.r.) (compliant for all Classes of non-woody briquettes and pellets) and AC (compliant for B Classes of non-woody briquettes and pellets).

Notably, despite failing to meet certain thresholds, the summer-harvested sample was nearly compliant with standard requirements, showing good results for non-woody material.

The net calorific value as received of the summer sample was 14.22 MJ/kg, which almost meets the required value for all classes for non-woody types of feedstocks (≥ 14.5 MJ/kg). The autumn-harvested biomass consisted of hogweed stems, exhibits good result of 15.9 MJ/kg (a.r.).

AC of summer-harvested biomass fails to meet the requirements for any quality class of non-woody solid biofuels, while the autumn sample showed the suitability for Class B (for both briquettes and pellets).

For both types of tested biomass samples, N and S content were found to be low and consistently met the requirements for all classes of non-woody briquettes and pellets.

Regarding the Cl content in the samples, which was 0.17 % dry and 0.12 % dry for the summer and autumn samples, respectively, the values exceed the stricter limit (0.10 %) set for Class A pellets, while remaining compliant for Class B non-woody pellets and briquettes.

Testing biomass for elements As, Cd, Cr, Cu, Pb, Hg, Ni and Zn is a mandatory part of fuel certification for both domestic and industrial

applications. Compliance with limits is necessary to confirm fuel quality with safe resulting ash, which can be safely disposed of or reused. The concentrations of the mentioned elements were found to represent only a fraction of the maximum values permitted by ISO standards for non-woody solid biofuels, remaining well within safe limits in both harvesting seasons, as shown in Table 7 above.

These findings suggest that while both harvesting seasons are viable for combustion, autumn biomass provides a more potent material for bioenergy production.

Summer harvesting of *H.mantegazzianum* biomass remains critical for biological control. Non-compliance with quality classes does not preclude the utilisation of biomass for solid biofuels production; rather, it necessitates the use of specialised combustion equipment.

5.3. Thermochemical Treatment of Samples

Enhancing the fuel properties via thermochemical conversion, specifically pyrolysis, requires the understanding of *H.mantegazzianum* biomass behaviour during treatment in the absence of oxygen. This section evaluates the changes of key parameters, including ash content (AC), gross calorific value (GCV), and elemental composition (C, H, N) across the selected temperature range to assess the quality of the resulting biochar samples (Fig. 22).



Figure 22 Illustration of the analysed product of *H. mantegazzianum* biomass thermochemical conversion

The results of AC determination are presented in Figure 23. The thermochemical conversion of giant hogweed biomass is influenced by a characteristic feature of herbaceous biomass – the high ash content of the initial material, and it undergoes a progressive increase with the temperature, reflecting the concentration of inorganic elements.

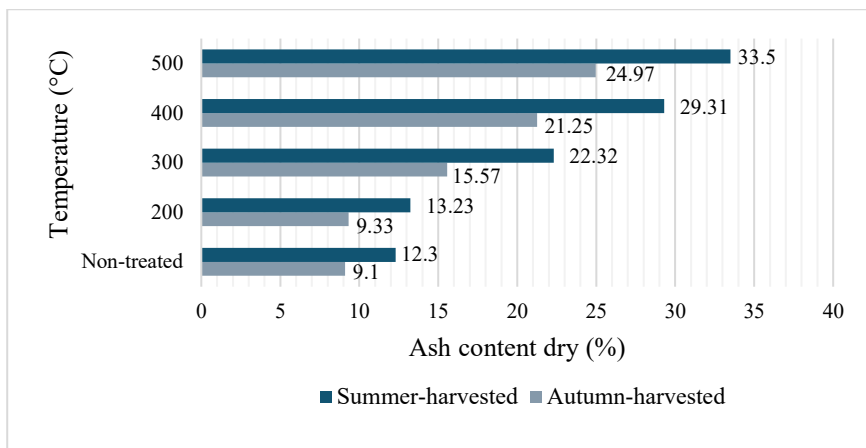


Figure 23 Values of ash content dry of non-treated and treated biomass samples

An increase in AC values was observed, particularly between 300 °C and 400 °C, for both samples, rising from 22.32 % to 29.31 % and 15.57 % to 21.25 % for summer- and autumn-harvested biomass, respectively. This behaviour is consistent with the study done by Neves et al. (2011), where it was demonstrated that the most substantial organic mass loss occurs within this specific temperature range and it is due to intensive thermal decomposition of cellulose and lignin degradation.

Across the entire tested range of temperatures, the elevated AC of samples suggests limitations for effective conventional combustion. In case of high AC of biochar, its utilisation may be more effective when blended with lower-ash biomass in co-firing applications to mitigate potential furnace problems.

The following data describes the evolution of energy content in relation to conversion temperature. The results of the GCV (d.b.) determination are presented in Figure 24.

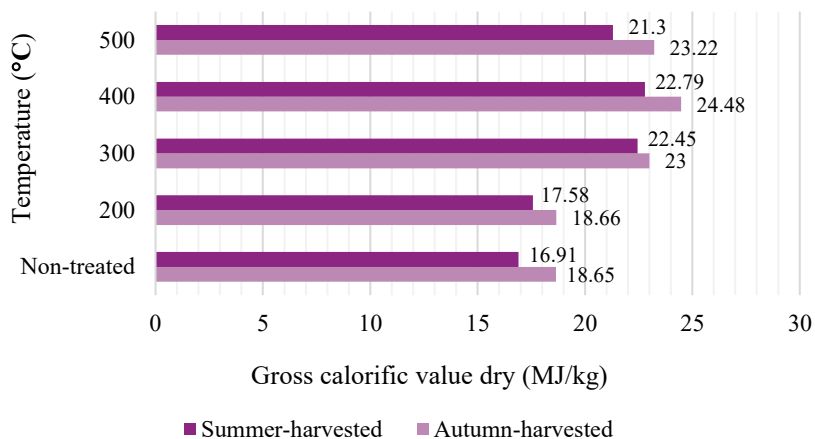


Figure 24 Values of gross calorific value dry of thermally treated and non-treated biomass samples

Overall, the GCV of biochars of both samples represented an energy upgrade over non-treated biomass. While the autumn-harvested biomass processed at 400 °C exhibited the maximum calorific output, reaching 24.48 MJ/kg, other biochars of both harvesting seasons produced at temperatures of 300–500 °C are comparable to traditional fossil fuels, as values fall within the range of GCV of high-quality lignite 20–25 MJ/kg, according to Vassilev et al. (2010). These findings represent the great potential for valorisation of the invasive plant biomass, demonstrating high energetic viability.

The observed decline in GCV for the samples treated at 500 °C is attributable to their high AC, being 33.5 % and 24.97 % for summer- and autumn-harvested biomass, respectively. In this case, the accumulation of ash in the samples offsets the increase in fixed carbon content.

An elemental analysis of the produced biochars was conducted. The results for two distinct sample types are documented separately in Tables 8 and 9.

At 200 °C, the samples showed minimal effect of thermochemical treatment.

For both summer- and autumn-harvested biomass samples, the peak N content was observed at 300 °C, being disadvantageous for fuel applications due to an increase in the potential for NO_x emissions during combustion. However, at this conversion temperature, high N content in biomass material makes the product a valuable nutrient-rich soil amendment.

Table 8 Total contents of C, H, and N of thermochemically treated summer-harvested *H.mantegazzianum* biomass (% , dry)

Element	Non-treated	200 °C	300 °C	400 °C	500 °C
Carbon, C	43.60	44.70	56.30	58.80	59.90
Hydrogen, H	5.20	5.30	4.50	3.60	2.30
Nitrogen, N	1.31	1.28	1.97	1.68	1.54

The analysis revealed that summer biomass reaches the same C content as autumn-harvested 300 °C This finding suggests that the earlier harvesting does not compromise the carbon enrichment of the biochar produced at this temperature.

Table 9 Total contents of C, H, and N of thermochemically treated autumn-harvested *H.mantegazzianum* biomass (% , dry)

Element	Non-treated	200 °C	300 °C	400 °C	500 °C
Carbon, C	46.70	45.00	56.30	63.50	60.40
Hydrogen, H	5.40	5.80	5.00	3.70	2.80
Nitrogen, N	0.91	0.96	1.25	1.23	1.01

A slight decrease in C content at 200 °C compared to the raw material can be observed for the autumn sample. This may indicate the release of carbon-rich organic volatiles. At this temperature, this loss of compound probably outweighs the biomass carbon enrichment process.

The C, H, N content values were used to calculate the atomic ratios, which were then plotted on a Van Krevelen diagram. The diagram allows for a comparison between the produced biochar and traditional solid biofuels. The different elemental contents of the treated biomass at different temperatures affect the resulting combustion behaviour. The biochars produced from biomass of *H.mantegazzianum* according to their O/C and H/C atomic ratios are plotted in Figure 25.

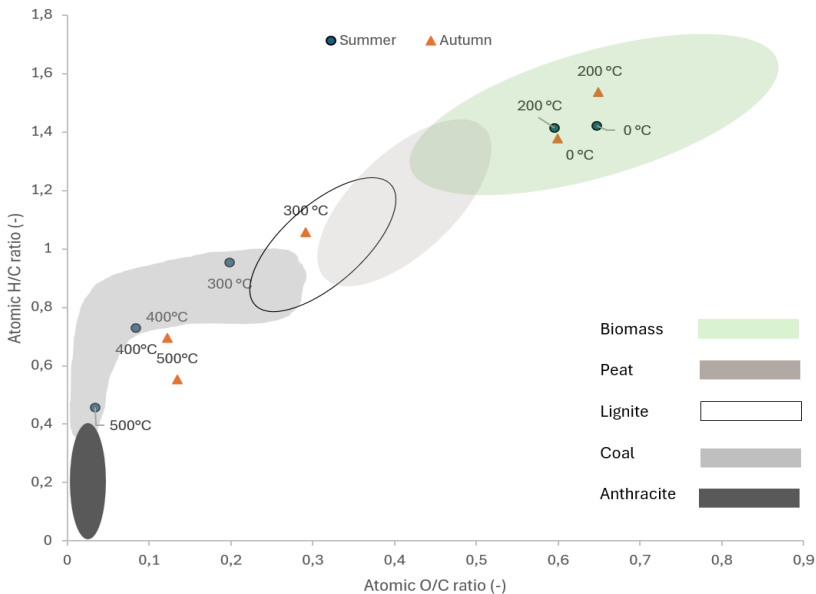


Figure 25 Van Krevelen diagram for biomass sampled at different seasons and treated at different temperatures

The diagram identifies the 200 °C samples as chemically unaltered biomass. The thermochemical treatment at this temperature is insufficient for structural conversion.

None of the samples exhibited ratios corresponding to those of peat and anthracite.

The autumn-harvested biomass treated at 300 °C displayed a marked similarity to lignite.

Biochar produced from summer-harvested biomass is displayed structurally closer to coal than autumn-harvested. However, its energy potential is limited by high AC and N content.

5.4. Content of Furanocoumarins

Analysis of *H. mantegazzianum* biomass samples resulted in the identification of four main furanocoumarins: angelicin, methoxsalen, pimpinellin, and bergapten. Additionally, significant amounts of fatty acids—particularly palmitic acid and oleic acid—were detected.

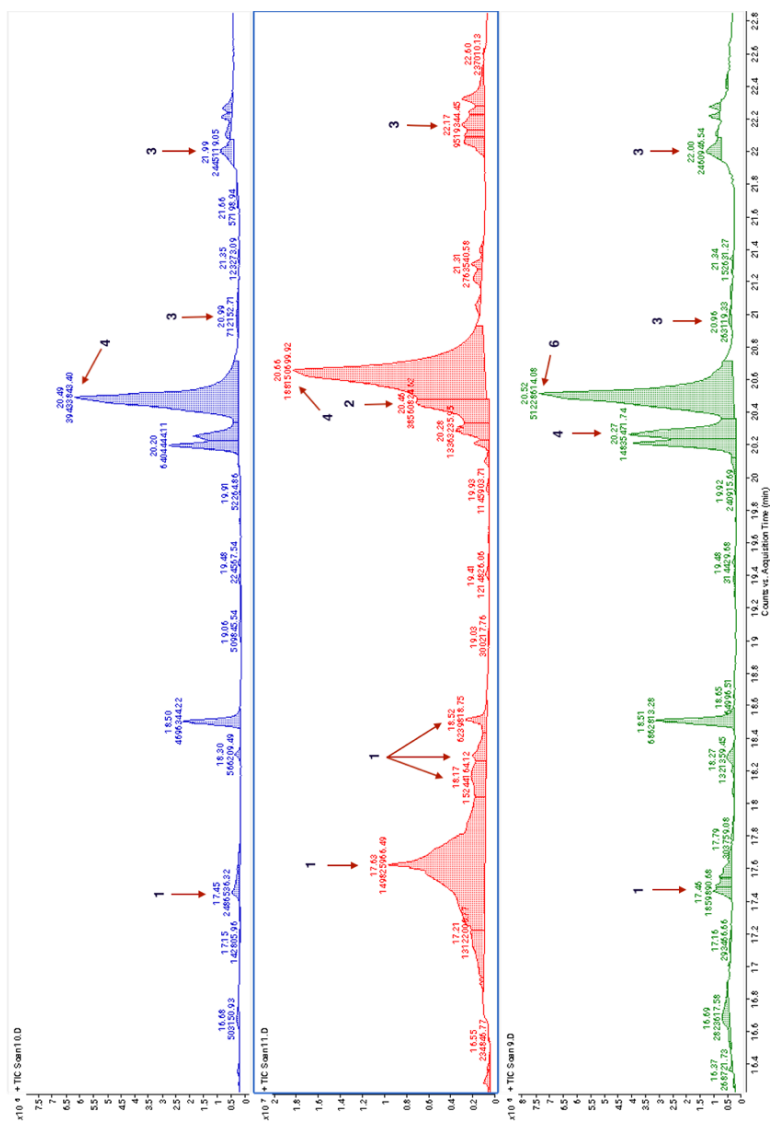
5.4.1. Distribution in Plant Organs

The comparative analysis of different plant parts revealed distinct compound profiles. Table 10 and Figure 26 show that the leaf sample exhibited the highest total concentration of phototoxic compounds (43.21 %), with angelicin being the dominant component, followed by methoxsalen (6.85 %) and pimpinellin (4.51 %). The leaf sample also showed a high content of palmitic acid (33.45 %).

In contrast, the stem contained a lower overall concentration of furanocoumarins (6.98 %), consisting of 4.85 % angelicin and 2.13 % pimpinellin. Notably, oleic acid (20.27 %) was detected exclusively in the stem. The umbel had the lowest total amount of furanocoumarins (6.72 %), with angelicin at 2.94 % and pimpinellin at 3.78 %, but it contained the highest level of palmitic acid among all samples (46.59 %). Methoxsalen was not detected in either the stem and umbel samples.

Table 10 Distribution of furanocoumarins and fatty acids in organs of summer-harvested *H. mantegazzianum*

Compound	Chemical formula	Stem	Umbel	Leaves
(Relative Area Sum %)				
Angelicin	C ₁₁ H ₆ O ₃	4.85	2.94	31.85
Pimpinellin	C ₁₃ H ₁₀ O ₅	2.13	3.78	4.51
Methoxsalen	C ₁₂ H ₈ O ₄	nd	nd	6.85
Palmitic acid	C ₁₆ H ₃₂ O ₂	5.35	46.59	33.45
Oleic acid	C ₁₈ H ₃₄ O ₂	20.27	nd	nd



The peaks correspond to the following identified compounds: (1) angelicin, (2) methoxsalen, (3) pimpinellin, (4) palmitic acid, (6) oleic acid

5.4.2. Seasonal Variation of Furanocoumarins

Seasonal dynamics of compound distribution were evaluated by comparing samples collected in July, August, and September (see Table 11 and Figure 27). The August sample exhibited the highest total furanocoumarin content (44.73 %) and the greatest compound diversity. It was the only sample in which bergapten (19.19 %) was detected. The same sample also contained 15.45 % angelicin, 8.81 % pimpinellin, and 1.28 % methoxsalen, along with 26.71 % palmitic acid.

In July, the total content of phototoxic compounds was intermediate, with methoxsalen (10.3 %) being the most abundant, followed by angelicin (6.49 %) and pimpinellin (4.51 %). Palmitic acid accounted for 30.79 %.

The September sample had the lowest levels of furanocoumarins (1.75 %). Neither palmitic acid nor methoxsalen was detected. However, this sample contained oleic acid (20.28 %).

Table 11 Identification of compounds in different months

Compound	Chemical formula	July	August	September
(Relative Area Sum %)				
Angelicin	C ₁₁ H ₆ O ₃	6.49	15.45	1.25
Pimpinellin	C ₁₃ H ₁₀ O ₅	4.51	8.81	0.50
Bergapten	C ₁₂ H ₈ O ₄	nd	19.19	nd
Methoxsalen	C ₁₂ H ₈ O ₄	10.30	1.28	nd
Palmitic acid	C ₁₆ H ₃₂ O ₂	30.79	26.71	nd
Oleic acid	C ₁₈ H ₃₄ O ₂	nd	nd	20.28

nd: not detected

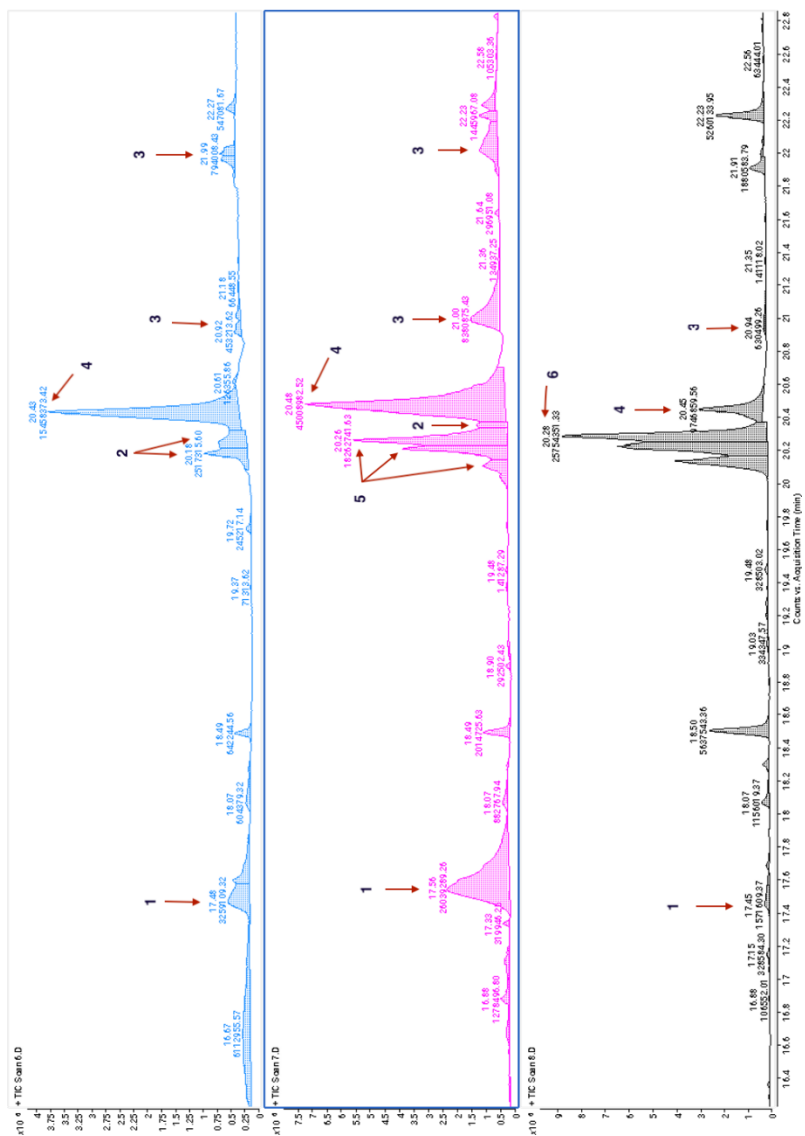


Figure 27 Chromatograms of samples July (blue), August (pink), September (black)

The peaks correspond to the following identified compounds: (1) angelicin, (2) methoxsalen, (3) pimpinellin, (4) palmitic acid, (5) bergapten, (6) oleic acid

The findings align with previous research. Pira et al. (1989) and Knudsen (1983) found higher phototoxic compound levels in seeds and leaves compared to stems, which is consistent with our observation that leaves contained the highest concentration of furanocoumarins.

Berenbaum (1981) noted that methoxsalen and angelicin are leaf-specific; in our study, methoxsalen was found only in leaves, while angelicin was also detected in other organs. This pattern supports the idea of chemical defense through furanocoumarin accumulation in photosynthetically active tissues (Zangerl & Berenbaum, 2005).

Malikov & Saidkhodzhaev, (1998) reported the presence of angelicin, bergapten, methoxsalen, and other coumarins in both *H. mantegazzianum* and *H. sosnowskyi*, with imperatorin and psoralen being specific to *H. mantegazzianum*. Our results suggest the presence of additional furanocoumarins as well.

Zobel & Brown, (1990) found that *Heracleum lanatum* accumulates furanocoumarins seasonally, with peak concentrations in spring and a sharp resurgence in autumn, particularly on leaf surfaces. In contrast, our study on *H. mantegazzianum* identified August as the peak for furanocoumarin content, especially bergapten, with a decline by September. While both studies confirm leaves as the primary accumulation site, *H. mantegazzianum* showed angelicin as dominant, unlike *H. lanatum*, where xanthotoxin prevailed. These differences reflect species-specific seasonal dynamics and chemical profiles.

August was found to have the highest toxicity, likely due to maximum biomass and the presence of seeds, known to contain high toxin levels (Dodd et al., 1994).

In addition to furanocoumarins, significant amounts of palmitic and oleic acid were detected. Palmitic acid is common in both animal fats and vegetable (Brody, 1999), while oleic acid plays a key role in pharmaceutical formulations (Choulis, 1997). Their seasonal decline may be due to volatility at high temperatures and reduced biomass (Daho et al., 2012). Similar trends have been described in other plant families (Stuhlfauth et al., 1985).

The observed seasonal peak in August likely corresponds to both optimal metabolic activity and the onset of seed development, when protective secondary metabolites may be upregulated. In contrast, the decline in September may reflect senescence and reduced biosynthesis.

5.5. Briquettes

5.5.1. Mechanical Durability of Briquettes

Densified biomass of *H. mantegazzianum* intended for energetic use in the form of briquettes (diameter of 65 mm, length of 46.32 ± 10.01 mm) for combustion was tested. Both harvests of biomass resulted in 65 produced briquettes. Summer-harvested and autumn-harvested types of biomass were used for briquette production separately.

The suitability of briquetting technology (particularly using the hydraulic press) for the processing of the studied biomass was investigated by means of standardised procedures.

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 recognised to be less prone to damage during handling (Dyjakon et al., 2020). For this reason, briquettes made from biomass should be characterised by the highest possible mechanical durability. According to Olugbade et al. (2019), 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 closely similar results obtained indicate that the physical properties influencing the bonding behavior 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 (Kpalo et al., 2020). As an

illustration, Figure 28 shows how the briquettes retained their original form with only minor losses of material.



Figure 28 Mechanical durability determination

Furthermore, the obtained results are comparable to the value of testing briquettes made from industrial hemp (particles with a size of less than 3.8 mm) of 97.7 %, as reported by Ivanova et al. (2014). Compared to briquettes made from woody material, for example, platan chips, the DU was achieved 96.7 % with 7.7 % MC (Brožek, 2016).

The fraction of feedstock is among the critical factors for the briquetting process as it affects the costs of material grinding (Dyjakon et al., 2020). 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. (2023) 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 (Brunerová et al., 2018).

5.5.2. 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 (Huang et al., 2023; Piętko et al., 2019; Williams et al., 2012).

The CO and NO_x emissions released during the combustion of prepared briquettes are summarised in Table 12. The excess air ratio and flue gas temperature were taken into consideration during measurement for each type of emissions.

Table 12 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} (°C)	n (-)	CO (mg/m ³)	NO_x (mg/m ³)
Summer-harvested biomass				
Mean	396.38	2.72	4,850.46	246.11
SD	9.72	0.14	188.95	13.03
Maximum	443.00	4.60	5,970.28	363.00
Minimum	308.10	1.85	1,696.45	163.37
Autumn-harvested biomass				
Mean	308.69	2.10	1,750.056	144.16
SD	3.00	0.03	49.91	2.76
Maximum	340.00	2.52	2,419.83	165.49
Minimum	269.10	1.74	1,280.06	38.47

Notes: T_{fg} – flue gas temperature; n – excess air coefficient; CO – carbon monoxide; NO_x – nitrogen oxides; SD – standard deviation

The carbon monoxide concentrations in the flue gas of combusted summer-harvested biomass reached up to 6,000 mg/m³ (Figure 29a,b). As presented in Table 12, the average value exceeded the prescribed CO emission limits established by Commission Regulation (EU) 2015/1185 of 24 April 2015 Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Solid Fuel Local Space Heaters, European Union (2015) at 2,000 mg/m³. According to a study done by Malat'ák et al. (2017) under conditions of a low excess air coefficient, incomplete combustion occurs, and high concentrations of carbon monoxide are found.

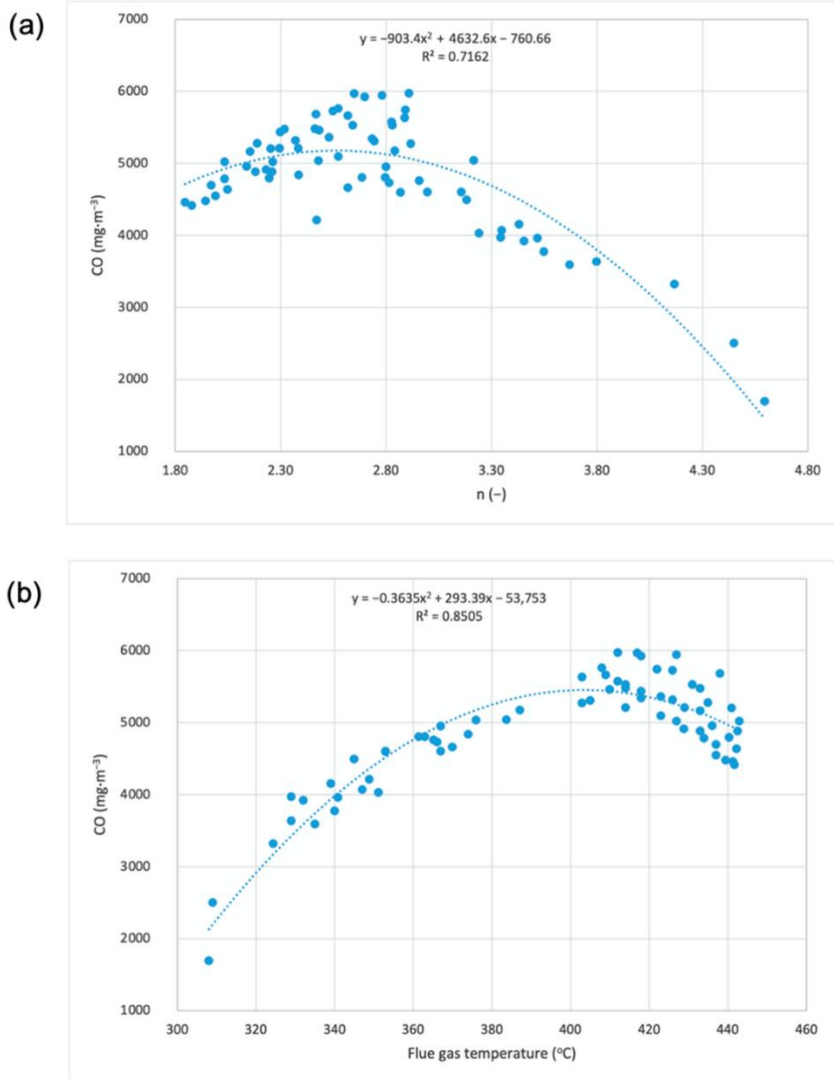


Figure 29 CO emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (summer-harvested biomass).

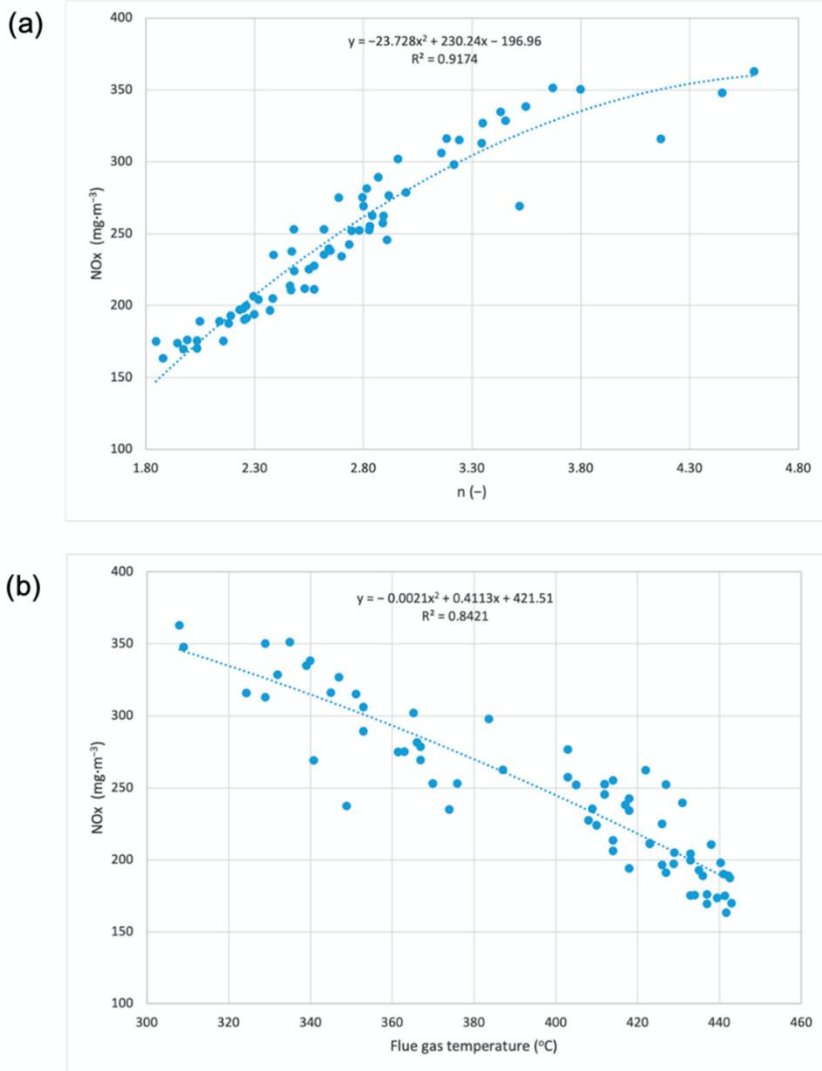


Figure 30 NO_x emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (summer-harvested biomass).

The 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 optimisation 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 Fig. 30a,b). The requirement for average emission concentrations of NO_x, where the limit value is 500 mg/m³ (Commission Regulation (EU) 2015/1185 of 24 April 2015 Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Solid Fuel Local Space Heaters. European Union., 2015) under the same conditions, was met.

The concentration is lower than that of the commonly used energy crop miscanthus, with a mean value of 473.51 mg/m³ (Malat'ák et al., 2022), and corresponds to the results obtained for briquettes made from switch grass (Roy & Corscadden, 2012).

Testing of the autumn-harvested sample resulted in an increasing trend in carbon monoxide concentration in the flue gas, depending on n, with decreasing flue gas temperature (Figure 31a,b). This trend and the average values of CO concentrations are similar to those obtained by Malat'ák et al. (2022) for briquettes made from the typical energy crop miscanthus. According to Roy & Corscadden (2012) the average value is similar to hardwood (maple) and non-woody material (hay).

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 (Fig. 32a,b). This suggests that other factors likely influence the emission levels beyond those included in the analysis (Win et al., 2012).

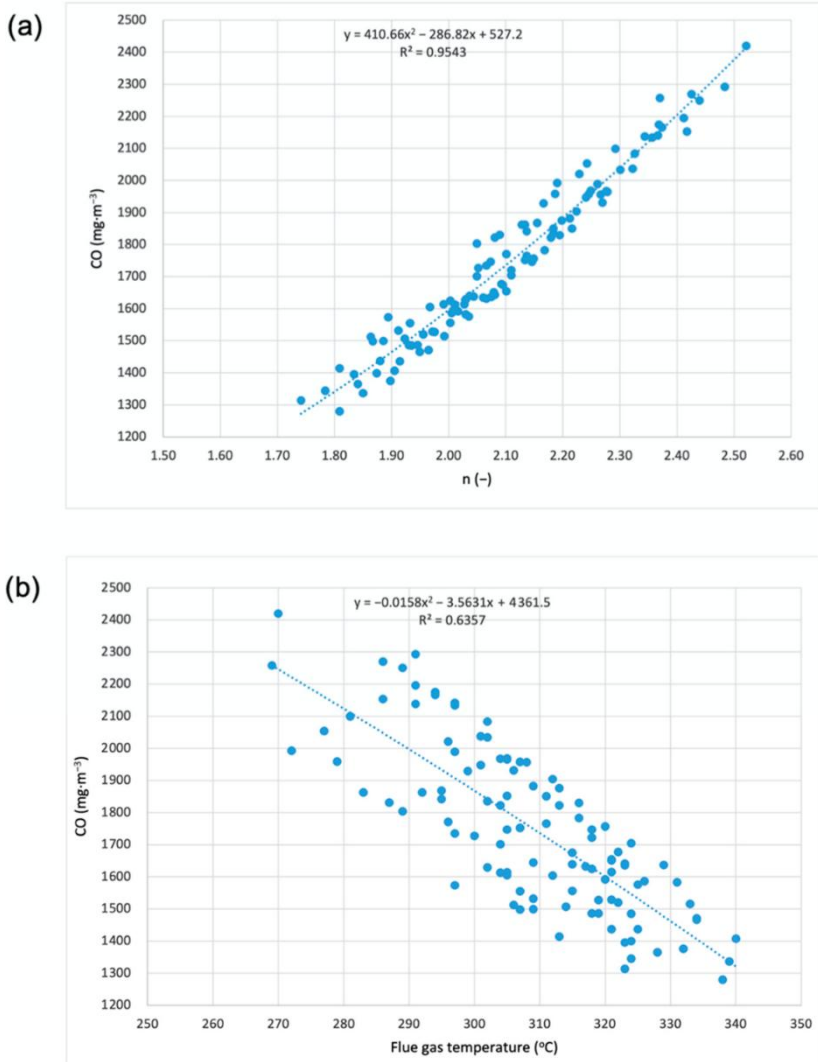
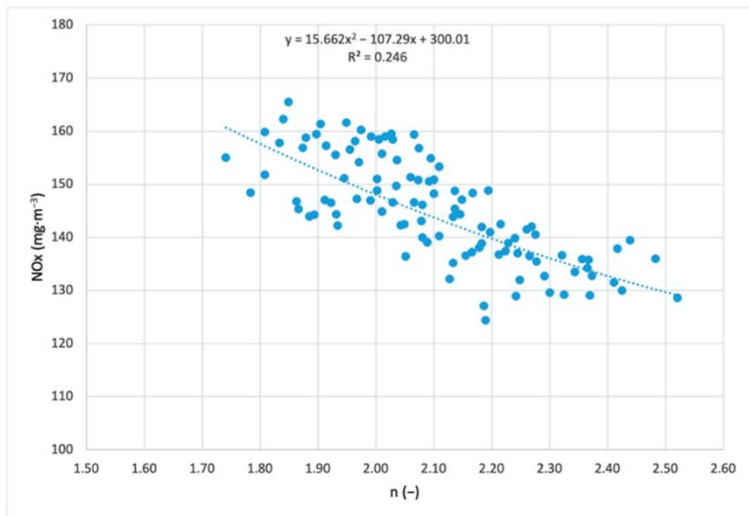


Figure 31 CO emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (autumn-harvested biomass).

(a)



(b)

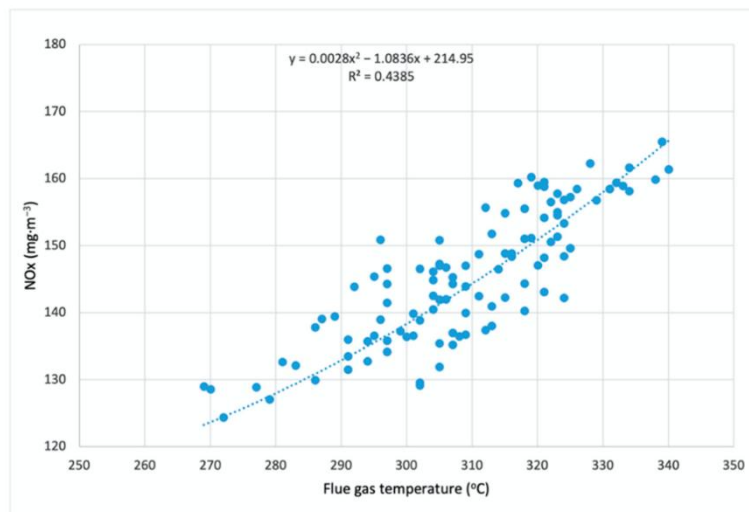


Figure 32 NOx emission concentrations plotted as a function of the excess air coefficient (a) and flue gas temperature (b) recorded during the combustion of the briquettes (autumn-harvested biomass).

All the values of measured NO_x emission concentrations are below the established level (Chandrasekaran et al., 2013). The average value is similar to the value measured for sawdust briquettes in the study performed by Roy & Corscadden (2012).

In general, low CO emissions demonstrate improved combustion efficiency, and the overall performance of combustion units (Ciupek et al., 2019; Hrdlička et al., 2016; Siegmund et al., 2024) of the autumn-harvested biomass is preferable to use for combustion.

5.5.3. 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 (Chen & Kuo, 2010; Krutul et al., 2024).

The dehydration stage, reflected by the initial mass loss, was nearly identical in both samples and occurred up to 150 °C (see Figure 33), as is commonly observed (Oladokun et al., 2016). The next stages of decomposition under an oxidative environment, according to López-González et al. (2015), are described as follows: at low temperatures (160–400 °C), the devolatilisation 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.

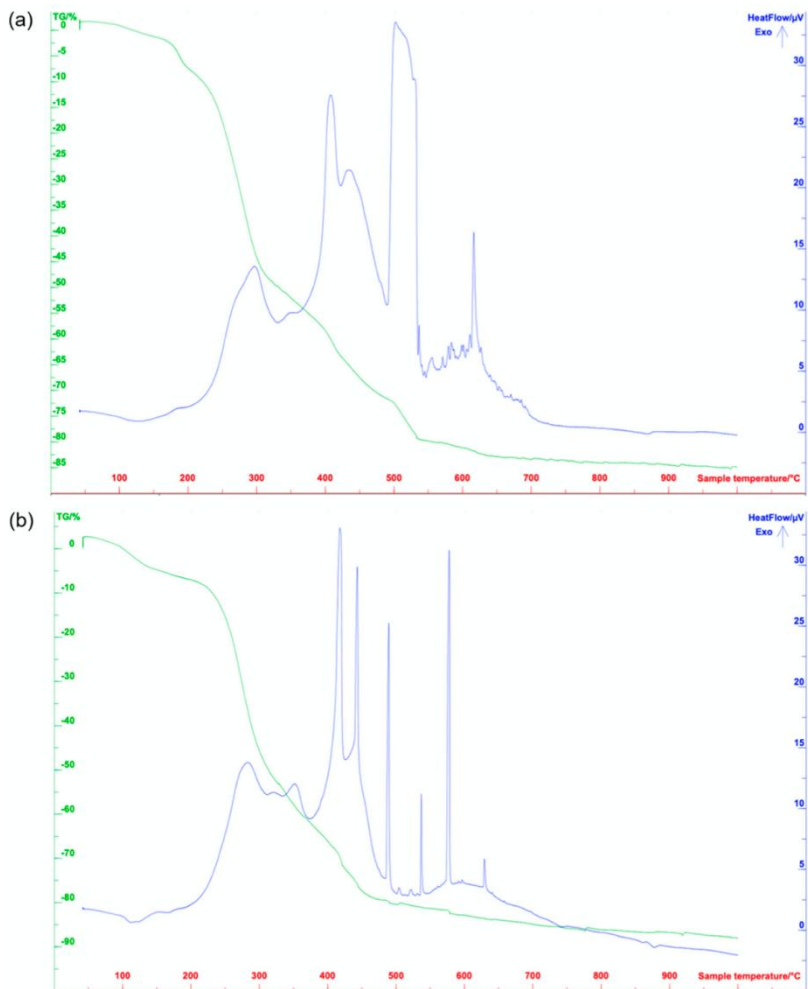


Figure 33 TGA-DSC graphs of the studied biomass: summer-harvested (a) and autumn-harvested biomass (b).

The weight loss curve indicates that between 150 °C and 300 °C, the weight loss of both samples was similar, with similar amounts of hemi-cellulose 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 (Kok & Özgür, 2013), the profile exhibited a series of narrow peaks, as can be seen on the heat flow curve of both tested samples. There are different behaviours 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 (Kučerová et al., 2016). 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.

5.6. Pellets

The experimental production of solid biofuels from *H. mantegazzianum* biomass also involved pressing the biomass into pellets. The pelletisation was undertaken to evaluate the suitability of biomass processing into densified biofuel for combustion units equipped with automated feeding. While biofuels in the form of briquettes more often remain a practical solution for manual heating systems serving as a substitute for firewood or coal, the pellets nowadays are preferred to be used for both domestic and industrial purposes as it ensures a uniform fuel quality and high energy density. To the best of our knowledge, production of pellets from *H. mantegazzianum* and their characterisation have not been previously reported. The produced experimental standardised pellets, made from summer-harvested biomass as a feedstock characterised by a moisture content of 8.63 %, are shown in Figure 34.



Figure 34 Pellets produced from summer-harvested biomass

A good structural integrity and smooth surface of the produced pellets indicated that the natural lignin content in biomass was sufficient to act as a binder during the process without the need for additives.

Determination of the mechanical durability of the produced pellets revealed a value of 95.67 % (mean value, the difference between the two replicates was 0.20 %, which is well within the 0.30 % (absolute) limit permitted by the applied ISO standard for solid biofuels). Our results indicate that the pellets meet the established criteria for Class B non-woody pellets under ISO 17225-6. The selected parameters for densification of the studied biomass were effective in achieving production of good-quality pellets. Considering the use of a small-scale granulator, it can be anticipated that utilising industrial-scale equipment would lead to the production of pellets with higher mechanical durability. In comparison, the value for energy crop miscanthus is less than 85%, and blending with corn stover and switchgrass has been proposed to enhance physical properties to achieve results similar to ours (Hossain et al. 2024). Bulk density determination yielded a value of 644 kg/m³. The result meets the ISO 17225-2 standard requirements for woody pellets of being above 600 kg/m³. This indicates that pellets derived from summer-harvested biomass achieved sufficient density for efficient storage and transport.

The compression resistance (the maximum critical loads) of pellets made from *H.sosnowskyi* was determined in a study done by Gramauskas et al. (2023) applying not standardised method for mechanical durability determination. The authors concluded that pellets will not be destroyed during the transportation and utilisation processes, but in comparison to giant knotweed pellets, pellets made from *H.sosnowskyi* reached a lower maximum crushing force.

Pelletisation of raw *H. mantegazzianum* biomass facilitates the conversion into a standardised form of biofuel, which is compatible with modern combustion systems. Nevertheless, the high ash concentration

characteristic of the studied biomass presents a critical challenge for automated systems that necessitates further optimisation, for example, the use of additives to improve the thermal behaviour.

6. Conclusion

Historically, the studied species were unintentionally spread. Due to attempts to cultivate hogweed as a forage crop and insufficient research in the 20th century, this plant has inflicted harm on subsequent generations. Presently, it is officially recognised as a problematic invasive species, causing concern due to its uncontrolled spread and negative impacts.

Large quantities of non-woody lignocellulosic biomass are generated in invaded areas and often remain disposed and underutilised. This biomass can be used as a feedstock for value-added applications, among which solid biofuel production represents a viable option.

With the advancement of technology in analysing herbal biomass properties, valuable bioresources are being studied and extracted. It has been identified that this biomass holds promise for applications in medicine, bioenergy, and other industries. However, despite various studies, practical development remains in the early stages, primarily limited to laboratory-scale experiments. While medical applications might require more time for extensive research, there is potential for their utilisation in various industries. Potential use of invasive hogweeds biomass for solid biofuels production was highlighted.

This research presents results obtained by thoroughly analysing the properties of *H.mantegazzianum* biomass and comparing with respect to the relevant standards in particular Fuel specification and classes for non-woody briquettes and pellets prescribed by the International Organisation for Standardisation (ISO). The evaluated properties of biomass were found to be largely compliant with the requirements of ISO standards, indicating the applicability in solid biofuels production with adequate performance characteristics. However, ash content and its composition may pose challenges for combustion efficiency.

The comparative analysis highlights that when the harvesting is timed to correspond with the period of flowering (no seed dispersal), limiting the risk of contributing to reproduction and spread, the biomass largely complies with standard requirements related to safe use. However, the calorific value of biomass is slightly lower than required. The ash content of summer-harvested biomass represents a major limiting factor in the utilisation of both non-torrefied and torrefied biomass. Even an uncertainty of biomass supply from invaded areas may limit commercial viability, but this approach contributes to mitigating invasion consequences. This bioenergy approach appears promising, as it provides added value to biomass and facilitates improved management.

This approach enabled a comparative evaluation of biomass quality and harvesting feasibility in relation to both processing efficiency and ecological considerations. During the summer, plants typically reach their maximum vegetative growth, providing the highest biomass yield. Seeds development has not yet occurred at this stage, which minimises the risk of seeds dispersal. Biomass collected during the late autumn period tends to have more favorable properties for energy use. Nonetheless, by this stage, seeds have already been released into the environment, which compromises the potential for using the harvest as a control measure against the spread of the species.

Given the phototoxic and potentially hazardous nature of furanocoumarins, their concentration profiles were examined to evaluate the exposure risk associated with biomass harvesting, handling, and processing depending on harvesting time. It is of utmost importance to comprehend the risks associated with furanocoumarins during handling when they can be processed into useful components and products.

The variation in furanocoumarin concentrations in biomass was found to be notably higher during the peak growth period in August, and leaves were identified as the primary organ of concern regarding

toxicity. Understanding this temporal and organ-specific distribution is essential to mitigate potential health hazards associated with the handling and processing of the fresh biomass.

Biomass of giant hogweed was obtained from the invaded site and processed into briquettes using a hydraulic briquetting press. Combustion trials conducted for briquettes in a conventional combustion unit for residential heating revealed that emissions fell well below established regulatory thresholds. It was observed that biomass of the same plant species, when harvested at different growth stages, exhibits variations in emission characteristics. These differences may be attributed to changes in fuel properties and chemical composition, which naturally vary during plant development. As a result, CO emissions may increase even under high excess air conditions if the combustion of a particular sample becomes less efficient.

There is no doubt that the cultivation of plants for a sustainable feedstock supply is not achievable due to restrictions. Amounts of landscape management residues cannot be estimated because the density of the plant population may vary considerably. Anyway, in some heavily affected regions, biomass can be utilised when safety precautions are followed carefully.

While hogweed biomass is unlikely to represent a significant share of the bioenergy feedstock supply, it may serve as an available non-woody resource within localised energy systems.

Targeted harvesting and utilisation of the biomass of invasive *Heracleum* spp, rather than leaving it on-site after mowing, represents a promising practical strategy for enhancing the effectiveness of invasive species management.

There is a need to find an approach that takes into account its ecological and biological characteristics, and it is limited till the plant will be eradicated.

Additionally, various economic aspects must be examined as well.

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8. Appendices

Author's CV

Ing. Kseniia Paramonova

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EDUCATION

PhD, Sustainable Rural Development, Department of Sustainable Technologies, Faculty of Tropical AgriSciences

Czech University of Life Sciences Prague. 2026.

Thesis: Viability assessment of invasive hogweeds' (*Heracleum spp.*) utilisation for energy purposes.

Master of Science (Ing.), Sustainable Rural Development, Faculty of Tropical AgriSciences

Czech University of Life Sciences Prague. 2020.

Thesis: The fate of abandoned small-scale biogas plants – case of Vietnam.

Bachelor, Trvale udržitelný rozvoj tropů a subtropů, Faculty of Tropical AgriSciences

Czech University of Life Sciences Prague. 2018.

Thesis: Biochar for agriculture and energy.

EXPERIENCE

Faculty of Tropical AgriSciences, Dept. of Sustainable Technologies,
CZU Prague

10/2020 – 08/2024

Laboratory of Biofuels, headed by Associate Professor Tatiana Alexiou Ivanova
Dept. of Sustainable Technologies

- Conducted laboratory experiments and analyses (calorimetry, moisture and ash content determination, production and testing of briquettes and pellets);
- Operated and maintained laboratory equipment;
- Familiarisation with ISO Solid Biofuel standards: 17225 series, and 181xx series;
- Representation of the laboratory at official events, including Open Days and public engagement activities (Garden Fest etc.);
- Provided guidance and support to interns in the laboratory;
- Involvement in teaching activities, presenting at conferences, and publishing high-impact journal articles.

OTHER WORK EXPERIENCE

Czech Agrifood Research Center, Prague

Project support 03/2025 – 11/2025

- Evaluation of measured data and processing of data for scientific publications and TAČR project requirements.
- Support for R&D activities within the project, including assistance with field and semi-operational trials.

Project: Arba Minch Fruit Value Chain. Mendel University, Brno

Project support 08/2023 – 10/2023

- Analysis of materials derived from mango fruits, transportation, and processing of samples.

Development project: Supporting Ukrainian students-refugees through academic collaboration between universities in Moldova and

the Czech Republic, Republic of Moldova. Donor: Ministry of Foreign Affairs of the Czech Republic.

Project expert 03/2025 – 12/2025

Development project: Modernization and raising the prestige of Higher Agricultural Education in Moldova, Republic of Moldova.

Donor: Ministry of Foreign Affairs of the Czech Republic.

Project expert 03/2024 – 12/2025

ABROAD PLACEMENTS

- Technical University of Moldova (MD)
Erasmus 21-27, KA171, 7/2024 – 8/2024

Center for Development of Renewable Energy Sources
(CEDER) CIEMAT, Biomass Unit (ES)

Erasmus+ internship for training, 10/2023

Internship at a leading national research centre, internationally recognised and renowned for its excellence in renewable energy research and commitment to sustainable energy development

- University of Mostar (BA)
Erasmus+ internship for training, 6/2024 – 7/2023
 - Hue University of Agriculture and Forestry (VN)
University/Faculty mobility scholarship for data collection, 8/2019
-

RESEARCH AND DEVELOPMENT PROJECTS

Appropriate technologies in waste and water management [grant number 20233108]. 2023

Donor: Internal Grant Agency of the Faculty of Tropical

AgriSciences, CZU Prague.

Position: **PhD researcher**.

Appropriate technologies in waste and water management [grant number 20223110]. 2022

Donor: Internal Grant Agency of the Faculty of Tropical AgriSciences, CZU Prague.

Position: **PhD researcher**.

Support of teaching innovation, Research development and Inter-university cooperation of SAUM and TSU (Moldova), Republic of Moldova. 2021 – 2022 Donor: Ministry of Foreign Affairs of the Czech Republic.

Research on environmental and sustainable technologies for developing countries [grant number 20213108]. 2021

Donor: Internal Grant Agency of the Faculty of Tropical AgriSciences, CZU Prague.

Position: **PhD researcher**.

CO-SUPERVISION OF THESES AND TEACHING ACTIVITIES

- Course Environmental Engineering: Summer Semester 2021, 2022, 2023, 2024
- Course Appropriate Rural Technologies: Summer Semester 2021, 2022, 2023, 2024

Thesis Consultation/Award Date

(Principal Supervisor: Assoc. Prof. T. A. Ivanova)

- Jan Faktor. Investigation of appropriate disposal methods of seagrass biomass with the focus on *Posidonia oceanica* (MSc. Thesis; 30/05/2023).

- Tetiana Liashko. Use of biomass of the invasive plant giant hogweed via the process of anaerobic digestion (Bc. Thesis; 23/05/2023).
 - Diyanat Nazarova. Study of hogweed's composition and risks (Bc. Thesis; 29/05/2024).
 - Wuraola Adenike Adeyemi. Utilization of Mango Endocarps as Energy Source (MSc. Thesis; 06/06/2025).
-

AWARDS

- The winning project "Utilisation of mango seeds as a source of sustainable energy and valuable oils" – First Prize, category Development Cooperation, Peace, and Partnership, SDGs awards 2024 (Association of Social Responsibility) - team member
- The winning project "Novel systemic advisory tool to reduce food loss and waste in Cambodia" – 3rd place, category New Services, Youth Hackathon for Reducing Food Loss and Waste 2022 (FAO, CAAS, YPARD) - team member

List of publications

Paramonova, K., Ivanova, T.A., Muntean, A., Passian, L., Malaťák, J., Hutla, P., & Ribintev, I. (2025). Assessment of quality and combustion characteristics of briquettes derived from giant hogweed biomass. *Agronomy*, 15(9), 2213.

<https://doi.org/10.3390/agronomy15092213>

Paramonova, K., Chaloupková, V., & Ivanova, T. A. (2024). Invasive *Heracleum sosnowskyi* as a potential feedstock for biorefineries: A review. *Industrial Crops and Products*, 216, 118754.

<https://doi.org/10.1016/j.indcrop.2024.118754>

Alexiou Ivanova, T., **Paramonova, K.**, Talipov, O., Tanyrbergenov, N., Zhakupov, T., & Akayev, A. (2024). Assessment of common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) biomass suitability for solid biofuels production. *Sustainability*, 16, 7378.

<https://doi.org/10.3390/su16177378>

Paramonova, K., Mazancová, J., & Roubík, H. (2023). Dis-adoption of small-scale biogas plants in Vietnam: what is their fate? *Environmental Science and Pollution Research*, 30, 2329–2339.

<https://doi.org/10.1007/s11356-022-24047-9>

Paramonova, K., Ivanova, T., & Malik, A. (2021). Exploring the potential of invasive plant Sosnowsky's hogweed for densified biofuels production. *Știința Agricolă*, 2, 105-108. ISSN 1857-0003.

Conferences

Paramonova, K., Chubur, V., & Alexiou Ivanova, T. (May 2025). Oral presentation: Use of Giant Hogweed leaves as a substrate for anaerobic co-digestion. 24th International Workshop for Young Scientists "BioPhys Spring 2025". Czech University of Life Sciences Prague. Czech Republic.

Paramonova, K. (October 2024). Oral presentation: Invasive *Heracleum sosnowskyi* as a potential feedstock for biorefineries. Faculty of Tropical AgriSciences – Faculty Day – Student Conference. Czech University of Life Sciences Prague. Czech Republic.

Paramonova, K., Alexiou Ivanova, T., & Bappah, M. (March 2023). Oral presentation: Some aspects of *Heracleum mantegazzianum* biomass applicability for densified biofuels producing. 10th Edition International Scientific-Practical Conference "Education through research for a prosperous society". Tiraspol State University. The Republic of Moldova.

Paramonova, K., Mazancová, J., & Roubík, H. (November 2020). Poster: The Fate of Abandoned Small-Scale Biogas Plants – Case of Vietnam. The Euroleague for Life Sciences (ELLS) Scientific Student Conference "The World of Tomorrow – A Green and Sustainable Society". University of Natural Resources and Life Sciences. Austria.

Tanyrbergenov, N., **Paramonova, K.**, Talipov, O., Alexiou Ivanova, T., & Zhakupov, T. (October 2023). Oral presentation: Common reed as a prospective bioenergy feedstock. 4th International Multidisciplinary Conference for Young Researchers "Energy, Sustainability & Society". Czech University of Life Sciences Prague. Czech Republic.

Malik, A., Ivanova, T., & **Paramonova, K.** (September 2021). Oral presentation: *Lantana Camara* as a prospective feedstock for solid biofuels: a mini review. Conference "Regulation of the Use of Natural Resources: Achievements and Perspectives". State Agrarian University of Moldova. The Republic of Moldova.