

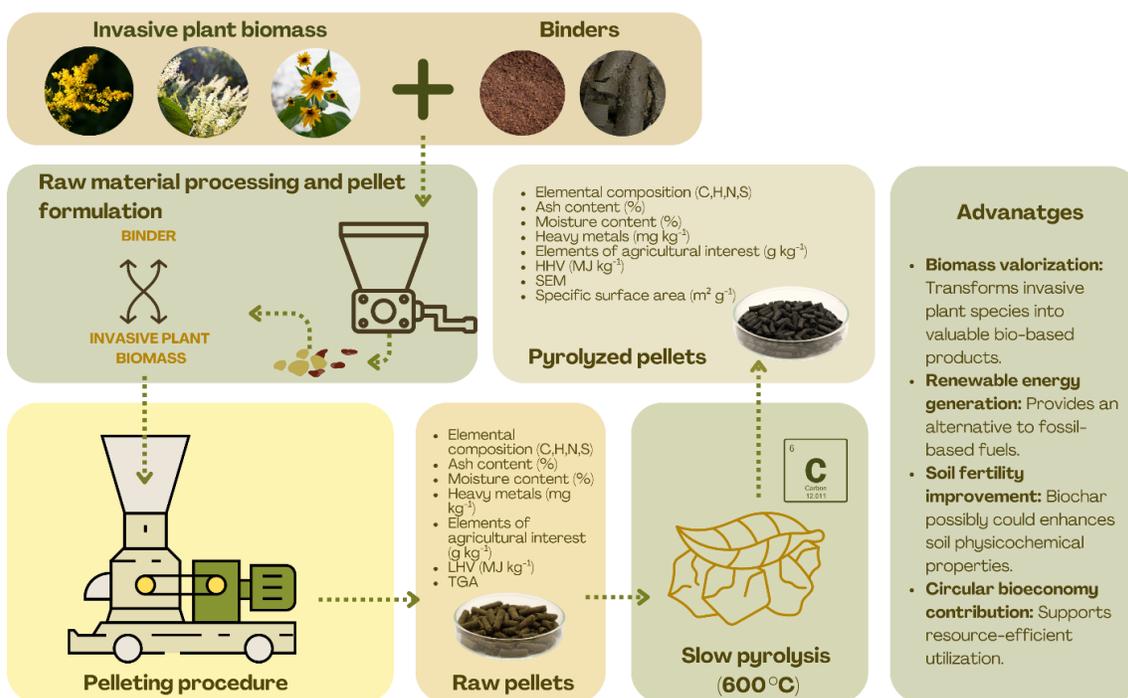
Development of Invasive Plants Control Approach through Pelletization of their Biomass to Produce Energy and Biochar

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GRAPHICAL ABSTRACT



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The aim of this study was to demonstrate the utilization of invasive plant materials a resource for energy production, applying pelletization and pellet pyrolysis, thus integrating plant eradication efforts with renewable energy solutions and valorization of plant biomass. The approach was demonstrated for three invasive plants – Japanese knotweed [*Reynoutria japonica* (Houtt.)], Jerusalem artichoke [*Helianthus tuberosus* (L.)], and Canadian goldenrod [*Solidago canadensis* (L.)] which are abundant in Northern Europe and elsewhere. As binder materials for pellet formation, sawdust and peat extraction residues were selected for their sustainability potential, as both represent organic waste materials that, similarly to invasive plant biomass, face a high likelihood of being disposed of without added value if not valorized. The calorific value of biomass plant pellets is comparable to values common for wood pellets and other plant materials, thus supporting their use for energy production. Pyrolysis provides possibilities to obtain biochar with increased specific surface area and higher caloric content, as well as application potential in agriculture. The studied invasive plant pellets do not contain elevated concentrations of heavy metals or other pollutants, thus supporting their application for the production of bioenergy or as a soil amendment.

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Keywords: Biochar; Biomass waste; *Helianthus tuberosus*; Pellets; *Reynoutria japonica*; *Solidago canadensis*

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INTRODUCTION

Invasive plants are a major environmental challenge covering large areas (Rai and Singh 2020; Macêdo *et al.* 2024). Invasive plants pose a significant threat to biodiversity and endanger native species. They also impact human and animal health and deplete local natural resources in sectors such as forestry, agriculture, aquaculture, and recreation (Senator and Rozenberg 2017). Plant invasions are driven by factors such as globalization of trade, intentional introductions, climate change, and others (Bellard *et al.* 2016). The economic losses caused by invasive plant spread are estimated in the billions of US dollars annually, and the areas occupied by invasive species are comparable to those used for key human activities (Holmes *et al.* 2009; Senator and Rozenberg 2017; Macêdo *et al.* 2024).

Given the severe risks and impacts associated with invasive plants, there is an urgent need for decisive action to control their spread and eradicate existing populations. This necessity is reflected in several legislative frameworks, including regulations in the European Union, the United States, Australia, and other regions (Beaury *et al.* 2021; Cardoso *et al.* 2021; European Commission 2023). In response to increasing evidence of the threats posed by invasive species, more stringent regulations are emerging alongside efforts to raise awareness among society and policymakers, placing the issue of invasive species high on the agenda (Sokolova and Tulina 2020).

Legislation in many countries requires measures to limit the spread and eradicate invasive plants, with additional economic and legal instruments, such as fines, being suggested. Various methods have been proposed to achieve control and eradication, including the use of herbicides, biological control methods, mechanical removal, and others (Kettenring and Adams 2011; Guido and Pillar 2017; Munné-Bosch 2024). Despite considerable efforts, invasive plant management has often achieved only limited success (Weidlich *et al.* 2020; Gioria *et al.* 2023; Marchante, *et al.* 2023), and also the costs of eradication activities are high.

The failures in controlling invasive plants are attributed to factors such as high survival potential, intensive reproduction (including vegetative), active production of allelochemicals, and other mechanisms underlying their invasiveness (Gioria *et al.* 2023; Marchante, *et al.* 2023; Weidlich *et al.* 2020). Invasive plants often can be found in areas with limited accessibility, for example, in wet areas, brownfields, protected areas (with restrictions preventing harvesting), or in sensitive areas, where harvesting equipment would cause damage. Additionally, the lack of strategies for utilizing invasive plant biomass after removal may hamper eradication efforts by increasing costs and complicating disposal.

One promising approach for managing invasive plants is to convert this waste biomass into useful products through its utilization for energy production (Gramauskas *et al.* 2023). However, this option has received surprisingly little attention (Vaverková *et al.* 2022; Liang *et al.* 2023; Klavins, *et al.* 2024; Kaushik and Arora 2024). Incineration of invasive plant biomass presents a safe method of utilization, as it eliminates the risk of further seed dispersal or vegetative propagation, at the same time producing energy. Nevertheless, limited experience with incineration and thermochemical processing largely reflects the irregular supply of invasive biomass and related logistical challenges, even though it represents a significant and valuable waste stream.

Pelletization and pyrolysis of invasive plant biomass could offer practical solutions (Anukam *et al.* 2021; Duca *et al.* 2022; Sarker *et al.* 2023). Pelletization involves pre-treatment steps (such as removal of contaminants, milling, drying, mixing, and optimizing the biomass-to-binder ratio), pelletizing, and post-treatment operations (cooling, screening, and additional drying could be applied) (Garcia-Maraver and Carpio 2015; Mortadha *et al.* 2025). This relatively straightforward process makes pelletization a feasible option for processing invasive plant biomass. Pyrolysis, in turn, converts plant biomass into stable, carbon-rich material (biochar), completely excluding and effectively preventing further seed spreading or vegetative propagation.

Pyrolyzed pellets have recently been highlighted as sustainable materials with wide applications not only in energy production (Feng *et al.* 2021) but also in agriculture and environmental management (Mong *et al.* 2022). For example, the carbon and nutrients stored in biomass can be returned to soils as biochar, thereby improving soil quality and contributing to carbon sequestration (Liao *et al.* 2013; Yang *et al.* 2022). Thus, utilizing

invasive plant biomass for energy and biochar production can provide a safe and efficient pathway to manage the large volumes of biomass generated through eradication activities, contributing to environmental sustainability.

The aim of the study was to demonstrate invasive plant utilization possibilities, using it as a resource for energy production, applying pelletization and pellet pyrolysis, thus integrating plant eradication efforts with renewable energy solutions and valorization of plant biomass. Raw pellets were analyzed for elemental composition (C, H, N, S), ash and moisture content, calorific value (LHV), heavy metal concentration, and agriculturally important elements, as well as thermal stability using thermogravimetric analysis (TGA). Pyrolyzed pellets underwent further characterization to determine their carbon content, ash and moisture levels, higher heating value (HHV), surface morphology (SEM), and specific surface area (BET), providing insights into their potential as biochar. The key parameters obtained for both the raw pellets and their pyrolyzed counterparts were evaluated in relation to relevant international standards, including the European Biochar Certificate (EBC), which provides quality guidelines for biochar use in agriculture, and EN ISO 17225 (2014), a standard for solid biofuels that defines fuel classes and specifications for non-woody pellets – regarding elemental composition, moisture, ash content, and energy value (Lin *et al.* 2025).

EXPERIMENTAL

Sampling of Invasive Plants and Applied Binders

Three species of invasive plants were chosen considering their abundance in Northern Europe and elsewhere, biomass of plants, and topicality of their eradication (included in European Commission regulation 2022/1203 as invasive alien species) (European Commission 2023). Composite samples comprising leaves, stems, and flowers were collected from *S. canadensis*, *H. tuberosus*, and *R. japonica*. In the case of *S. canadensis*, root material was also included. For each species, approximately 200 L of plant material was obtained. Biomass of all three invasive plant species was sampled from roadsides and abandoned fields located within approximately 5 km of a central reference point in the suburban area of Riga, Latvia (56°59'36.9"N, 24°12'55.3"E). Wet plant biomass was cut into uniformly sized pieces (5 to 10 cm) and used for pelleting. For analytical characterization, subsamples were dried at 105 °C.

As binders for pelleting of homogenized invasive biomass, production residues (waste materials) with the ability to act as binders were used: alkaline residues of humic substance extraction from high bog peat (Jarukas *et al.* 2021; Nieweś *et al.* 2022) and lake sediments obtained after lake dredging (sapropel) (Klavins *et al.* 2019; Vincevica-Gaile *et al.* 2019).

The elemental composition of the studied invasive plants and the used binders is provided in Table 1.

Pelletization of Invasive Plant Biomass

The preparation procedure for pellet formation consisted of the following steps: 1) proportioning of plant biomass and binder – 95:5% for biomass-sapropel and 90:10% for biomass-peat pellets; 2) separate weighing and grinding of both materials (biomass and binder) for each type of pellet (to achieve optimal particle size of 0.5 to 1.2 mm); 3) mixing of the two components with complete homogenization, and moisture adjustment

(approximately 10 to 12%). Pelleting was repeated 3 times. As a result, five different biomass mixtures were obtained: three types of pellet mixtures (from *R. japonica*, *S. canadensis*, and *H. tuberosus*) with added 5% of sawdust as a binder, and two types of mixtures (from *R. japonica* and *H. tuberosus*) with added 10% of peat processing residues as a binder.

The pelletizing process was carried out using a flat die pelletizer (Anyang Best Complete Machinery Engineering Co Ltd, China), also known as a pellet mill machine. The flat die pelletizer operates by feeding raw materials such as sawdust or biomass from a hopper onto a horizontally positioned flat die equipped with multiple holes. The device is powered by an electric motor. Either the die rotates beneath stationary rollers or the rollers rotate above a stationary die, compressing the material and forcing it through the die holes under high pressure and friction, which generates heat to soften and bind the material into dense cylindrical pellets (Fig. 1).

As the pellets are extruded, an adjustable slicer cuts them to the desired length, and the finished pellets are then discharged from the machine for collection, completing a continuous and efficient pelletizing process resulting in cylindrical granules with a diameter of 5 mm and from 8 to 12 mm in length (Fig. 1). In the final stage of the granulation process, the granules were air-dried in a Plus II drying oven (Labassco, USA) at 105 °C for 24 h to ensure moisture removal before further analysis.

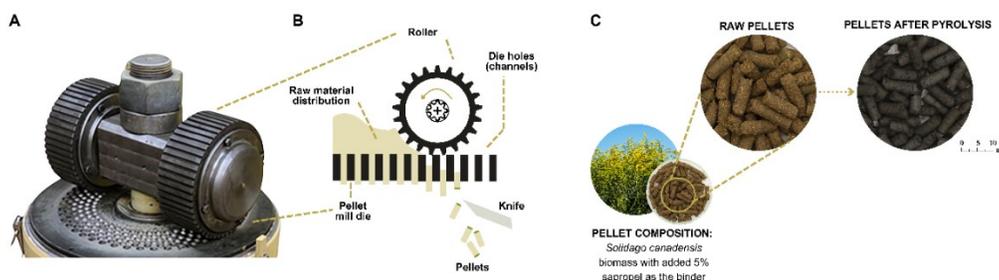


Fig. 1. Overview of pellet production and thermal conversion. (A) Flat die pelletizer roller-die couple. (B) Schematic representation of pellet formation. (C) Pellets made from *Solidago canadensis* biomass with 5% sawdust binder, shown before (raw pellets) and after pyrolysis (biochar pellets). Scale bar: 0 to 10 mm

Pyrolysis of Invasive Plant Pellets

The pyrolytic decomposition of biomass pellets was conducted using a custom-fabricated metallic pyrolysis reactor, which was constructed from corrosion-resistant stainless steel with a wall thickness of 3 mm. The internal dimensions of the reactor chamber were 210 mm × 155 mm × 125 mm, providing a controlled environment for thermal treatment. The experimental setup was designed to operate under inert atmospheric conditions, achieved by a continuous supply of nitrogen gas. This inert medium was critical for the displacement of ambient air and the efficient removal of volatile degradation products generated during the thermal conversion process. The reactor, preloaded with homogenized biomass granules, was carefully positioned within a muffle furnace model LE 05111 (LAC, Czech Republic).

The thermal treatment involved a gradual temperature rise to a final setpoint of 600 °C, employing a uniform heating rate of 5 °C min⁻¹ to ensure slow pyrolysis conditions. During this phase, a consistent nitrogen gas flow of 20 mL min⁻¹ was maintained to preserve an oxygen-free environment and facilitate the expulsion of volatile organic

compounds. Upon reaching the target temperature, the system was subjected to an isothermal hold for a duration of 60 min. This extended residence time was essential to promote thorough pyrolytic transformation of the biomass feedstock, allowing complete evolution of volatile components and stabilization of the solid biochar residue. Such process parameters are characteristic of slow pyrolysis, aiming to maximize biochar yield while minimizing the formation of secondary condensable and non-condensable products (Igalavithana *et al.* 2017). The yield of the pyrolyzed pellets was determined by Eq. 1,

$$\text{Yield}[\%] = m_2 / m_1 \times 100 \quad (1)$$

where m_1 is the mass of raw material (g) and m_2 is the the mass of biochar (g).

Characterization of Studied Materials

Elemental analysis

The elemental composition (C, H, N, and S) was determined using an Elemental Analyzer (Model EA-1108, Carlo Erba Instruments, Germany). The obtained values were normalized based on ash content. The ash content was quantified by subjecting 50 mg of each sample to thermal treatment at 750 °C for 8 hours. The oxygen (O) content used for HHV calculations was determined by difference, assuming that the total elemental composition (CHNSO) equals 100%.

Trace and major element analysis

To determine the concentration of major and trace elements in the samples – including all three invasive plant biomasses, the two binders (sapropel and peat processing residues), and pyrolyzed pellets, air-dried (for plant biomass and binders, pyrolyzed pellets were used as produced) materials were finely ground to obtain a homogeneous sample.

A 1.00 g portion of the ground sample was weighed into a Teflon vessel, followed by the addition of 8 mL of 65% HNO₃ (Sigma-Aldrich, USA) and 2 mL of 30% H₂O₂ (Enola, Latvia). The samples were sealed and digested under high pressure at 200 °C for 30 min using an Ethos Easy microwave digestion system (Milestone Systems, Denmark). Each sample was digested in triplicate. The concentrations of key macro- and microelements relevant to pellet quality and combustion properties – including Al, B, Ba, Ca, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S, Si, Sr, Ti, Zn, As, Be, Cd, Co, Li, Pb, Sb, Se, Tl and V – were determined using inductively coupled plasma optical emission spectrometry (ICP-OES) with an iCAP 7000 Series spectrometer (Thermo Scientific, USA).

Multi-element standard solution (100 mg L⁻¹) containing (21 elements in diluted nitric acid): Sb, As, Be, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Mo, Ni, Se, Sr, Tl, Ti, V, Zn (ICP multi-element standard solution XVI, Merck) and standard (iCAP 6000 Multi Element Test Solution, Thermo Scientific) for Na, K, Ba, Al, P, B, S, and Si were used for quantification. Detection limits were 1 to 10 ppb for Al, Ca, and Fe, 0.1 to 1.0 ppb for Mg, K, and Na, and 0.1 ppb for other elements. The results were expressed on a dry weight basis.

Determination of calorific value

The lower heating values (LHV) at constant volume for invasive plant pellets were determined according to the standard methodology (ASTM 2007). The higher heating values (HHV) for pyrolyzed pellets were calculated according to the empirical correlation based on ultimate analysis proposed by Qian *et al.* (2020) (Eq. 2),

$$\text{HHV (MJ kg}^{-1}\text{)} = 32.9 C + 162.7 H - 16.2 O - 954.4 S + 1.408 \quad (2)$$

where C is the carbon content (% by weight), H is the hydrogen content (% by weight), O is the oxygen content (% by weight), and S is the sulfur content (% by weight).

Thermogravimetric analysis (TGA)

TGA of pellet samples was conducted using an SDT-Q600 thermogravimeter (TA Instruments, USA). Air-dried samples were ground into a fine powder with an agate mortar and pestle, and approximately 10 mg was weighed into a ceramic crucible. The analysis was performed under a nitrogen (N_2) atmosphere, heating from room temperature to 105 °C at 10 °C min^{-1} , followed by a 5-min isothermal hold. After that, the heating continued to 900 °C at the same rate. Upon reaching 900 °C, the atmosphere was switched to oxygen (O_2), and the sample was held isothermally for 7 min to assess fixed carbon in the sample and to calculate the ash content.

Nitrogen adsorption porosimetry by Brunauer-Emmett-Teller (BET) surface analysis

Degassing was conducted to remove moisture and other impurities adsorbed from the air onto the sample surfaces. An Autosorb Degasser Model AD-9 (Quantachrome, USA) was used for this process, with 9 mm round sample cells. Sample weights ranged from approximately 0.35 to 2 g, and degassing was performed either for 24 hours at 23 °C or for 3 hours at 200 °C under a vacuum of approximately -0.5 torr, following IUPAC recommendations to minimize moisture content and sample loss. After degassing, the samples were reweighed.

The specific surface area and pore structure of the samples were analyzed using a Quadrasorb EVO (Quantachrome, USA) gas sorption system *via* low-temperature nitrogen adsorption-desorption isotherms at 77 K (-196 °C). The specific surface area was determined using the Brunauer-Emmett-Teller (BET) method. The desorption curve was recorded at 43 points. The BET or Langmuir method was employed to calculate the specific surface area.

Scanning electron microscope (SEM) analysis

A scanning electron microscope, Tescan VEGA\LMS (Tescan, Brno, Czech Republic), was used to visualize the surface morphology of the pellets and fracture surface morphology. Secondary electrons created at an acceleration voltage of 5 kV were used for the sample image generation. For microscopy, the samples were fixed on standard aluminum pin stubs with electrically conductive double-sided adhesive carbon tape.

Statistical analysis

Statistical analysis was performed using R (version 4.5.0) within the RStudio environment (Posit team 2025). For each pyrolyzed pellet heavy metal concentration, a one-way analysis of variance (ANOVA) was done using the `aov()` from base R (stats package) function to determine any statistically significant differences in concentrations between sample groups ($n = 3$). In cases where ANOVA revealed significant differences ($p < 0.05$), a Tukey's Honest Significant Difference (HSD) post-hoc test was performed using the `HSD.test` function from the `agricolae` R package (de Mendiburu 2023). The Tukey HSD results were expressed as grouping letters (a, b, c, ...), where groups sharing the same letter were not significantly different from each other. The letter groupings were later used for statistical annotation in data visualizations. Descriptive statistics (means and standard

deviations) were calculated for each group, and the results were visualized as grouped bar plots with error bars using the ggplot2 package (Wickham 2016).

RESULTS AND DISCUSSION

Elemental Composition of the Biomass and Binders Used for Pellet Preparation

Understanding the elemental composition of biomass to use it for energy production – particularly the content of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) – is essential, as it directly influences the energy potential of the material. For example, a higher C and H content typically indicates a greater energy value, thereby making the biomass a more efficient fuel source (Parikh *et al.* 2007; Ghugare *et al.* 2017). The lowest C content was observed in *H. tuberosus* (HT) at slightly less than 40.0%, while both *S. canadensis* (SC) and *R. japonica* (RJ) exceeded the 40% threshold. The highest H content among the invasive plant species was recorded in *S. canadensis*, reaching 6.31% (Table 1). C (42.2 to 58.4%) and H (3.2 to 9.2%) contents reported in the literature for herbaceous biomass (Vassilev *et al.* 2010) align with the values observed in this study, supporting the high energy potential of the investigated materials.

In contrast, N and S are important for evaluating potential pollutant emissions during thermal processing (Kamga *et al.* 2024). Elevated N content can contribute to the formation of nitrogen oxides (NO_x), while higher S levels may lead to sulfur oxide (SO_x) emissions, which are harmful to the environment (Miranda *et al.* 2015). Compared to N values (0.1 to 3.4%) reported in the literature for herbaceous biomass (Vassilev *et al.* 2010), invasive plant biomass indicates values within a moderate range, while S was detected only in sapropel (0.51%) (Table 1).

Ash content in the studied samples ranged from 2.8 to 3.5% in invasive plant biomass and from 10.2% (peat processing residues) to 14.0% (sapropel) in binders. It has been shown that woody biomass typically contains significantly lower ash content compared to herbaceous biomass, which can influence its classification in biomass quality standards (Puri *et al.* 2024). The relatively low ash content observed in the invasive plant species supports their suitability for pellet production, whereas the higher ash levels in peat and sapropel reflect their mineral-rich composition and should be carefully considered when designing biomass formulations (Table 1).

To ensure safe application, especially in environmental or agricultural contexts, as well as in incineration planning, thorough evaluation of the pellet composition remains essential (Jagustyn *et al.* 2017; Orecchio *et al.* 2016). The concentrations of selected heavy metals (Cu, Cr, Ni, Pb, V, Co, and Cd) in the binders and invasive plant biomass are provided in Table 1. Several elements were found to be below detection limits, including As, Be, Cd, Co, Li, Pb, Sb, Se, Tl, and V in the invasive plant biomass, and As, B, Li, Mo, Sb, Se, and Tl in the binder materials.

Among the binders, sapropel exhibited the highest concentrations across all metals, with Cu (195.24 mg kg⁻¹), Cr (174.38 mg kg⁻¹), Ni (168.76 mg kg⁻¹), Pb (80.42 mg kg⁻¹), V (203.85 mg kg⁻¹), and Co (62.84 mg/kg), while peat processing residues also contained elevated levels of Cu (182.55 mg kg⁻¹) and Cd (81.16 mg kg⁻¹). These results indicate that binders are likely to be a major source of heavy metal input in pellet mixtures, especially sapropel, which may be influenced by sedimentary and anthropogenic background (Ignatavičius *et al.* 2021).

Invasive plant biomass showed considerably lower levels of contamination. Cu concentrations ranged from 5.40 mg kg⁻¹ in *H. tuberosus* to 10.30 mg kg⁻¹ in *R. japonica*. Ni was only detected in *S. canadensis* at 0.70 mg kg⁻¹, while Cr, Pb, V, Co, and Cd were below detection limits in all plant samples (Table 1).

Table 1. Proximate Elemental Composition (C, H, N, S; %), Ash Content (%), and Macro- and Trace-Element Concentrations of Binders and Invasive Plant Biomasses used for Pellet Preparation

Parameter	Biomass				
	Binders		Invasive plants		
	P	S	SC	RJ	HT
C (%)	45.77 ±0.05	39.41 ±0.24	46.54 ±0.19	44.68 ±1.01	39.69 ±0.21
H (%)	5.32 ±0.29	4.85 ±0.16	6.31 ±0.06	5.55 ±0.29	5.46 ±0.03
N (%)	0.66 ± 0.002	3.07 ±0.03	2.12 ±0.06	1.81 ±0.58	2.14 ±0.05
S (%)	<LOD	0.51 ±0.04	<LOD	<LOD	<LOD
Ash (%)	10.2	14	3.2	2.8	3.5
Cu (mg kg ⁻¹)	195.24 ±4.63	182.55 ±16.72	5.70 ±1.03	10.30 ±0.14	5.40 ±0.26
Cr (mg kg ⁻¹)	174.38 ±3.04	36.02±6.65	<LOD	<LOD	<LOD
Ni (mg kg ⁻¹)	168.76 ±3.59	29.61 ±5.88	0.70 ±0.09	<LOD	<LOD
Pb (mg kg ⁻¹)	80.42 ±15.14	53.64 ±4.45	<LOD	<LOD	<LOD
V (mg kg ⁻¹)	203.85 ±5.96	9.44 ±0.54	<LOD	<LOD	<LOD
Co (mg kg ⁻¹)	62.84 ±2.71	<LOD	<LOD	<LOD	<LOD
Cd (mg kg ⁻¹)	<LOD	81.16 ±18.85	<LOD	<LOD	<LOD
Ca (g kg ⁻¹)	130.16 ±2.09	15.66 ±2.13	10.05 ±0.45	3.19 ±0.13	20.35 ±0.27
K (g kg ⁻¹)	30.01 ±1.31	677.56 ±27.24	18.18 ±0.77	12.86 ±0.80	14.99 ±0.36
Mg (g kg ⁻¹)	28.11 ±0.53	3.47 ±0.33	2.43 ±0.09	0.36 ±0.02	5.66 ±0.10
P (g kg ⁻¹)	6.52 ±0.13	0.47 ±0.03	2.15 ±0.04	0.79 ±0.07	2.23 ±0.05
S (g kg ⁻¹)	46.72 ±0.75	4.83 ±0.24	1.05 ±0.03	0.37 ±0.03	1.67 ±0.04
Fe (g kg ⁻¹)	70.04 ±1.28	4.09 ±0.27	0.09 ±0.01	0.06 ±0.003	0.07 ±0.002
Mn (g kg ⁻¹)	1.77 ±0.06	0.05 ±0.003	0.01 ±0.0004	0.002 ±0.00	0.01 ±0.0005
Zn (g kg ⁻¹)	1.50 ±0.04	0.25 ±0.03	0.02 ±0.003	0.008 ±0.002	0.05 ±0.002
B (g kg ⁻¹)	<LOD	<LOD	0.03 ±0.003	<LOD	0.04 ±0.003

C, H, N, S values are presented as mean ± standard deviation ($n = 3$), where the standard deviation reflects the variation among replicate measurements for each sample. <LOD – below the limit of detection (< 0.4%). Measured concentrations of Cu, Cr, Ni, Pb, V, Co, Cd, Ca, K, Mg, P, S, Fe, Mn, Zn, and B are expressed on a dry weight basis and presented as mean ± standard deviation ($n = 3$), where the standard deviation reflects the variation among replicate measurements for each sample. <LOD – below the limit of detection. Samples: S – sapropel; P – peat processing residues; SC – *Solidago canadensis*; HT – *Helianthus tuberosus*; RJ – *Reynoutria japonica*.

According to the EN ISO 17225 (2014) standard, the heavy metal thresholds for non-woody biomass pellets (class A) are: Cu ≤ 20 mg kg⁻¹; Cr ≤ 50 mg kg⁻¹; Ni ≤ 10 mg kg⁻¹; Pb ≤ 10 mg kg⁻¹; Cd ≤ 0.05 mg kg⁻¹ (EN ISO 17225-6; Rupasinghe *et al.* 2023). Results showed that all invasive plant biomasses described in this study fell well below these regulatory limits, confirming their compliance with fuel quality standards. Although the concentrations of heavy metals found in the binders, particularly in sapropel, substantially exceeded the limits set by the standard, the proportion added to the final product (*i.e.*, the pellets) was relatively small (5% for sapropel and 10% for peat processing residues). This is further supported by the results obtained for the pyrolyzed pellets (Fig. 3), where the average values did not show significant increases.

Despite the fact that the presence of heavy metals may influence biomass quality,

their impact on bioenergy recovery was relatively minor. Furthermore, during pyrolysis, a significant proportion of heavy metals such as Cd and Cu are retained in the solid residues, suggesting the possibility of further recovery (Han *et al.* 2018).

It should also be noted that the sampling location is a determining factor for the concentration of various environmentally hazardous heavy metals in plant biomass (Jagustyn *et al.* 2017). Low concentrations obtained in the experiment confirm that the invasive plants themselves have not accumulated hazardous levels of heavy metals, and any elevated values in pellets result primarily from binder addition. However, when selecting invasive plant biomass for the production of pellets or other products, special attention must be paid, as invasive plant species have been observed to exhibit hyperaccumulation capacity (Khan *et al.* 2023).

The concentrations of agriculturally important elements (Ca, K, Mg, P, S, Fe, Mn, Zn, and B) in binders and invasive plant biomass are summarized in Table 1. Among the binders, spropel showed the highest overall nutrient content, particularly rich in Ca (130 g kg⁻¹), S (46.7 g kg⁻¹), Fe (70.0 g kg⁻¹), and Mg (28.1 g kg⁻¹). In contrast, peat processing residues were distinguished by a very high concentration of K (678 g kg⁻¹) because of peat processing with a high concentration of KOH, while other elements such as Ca, P, and Fe were present at lower levels.

Invasive plant biomasses displayed species-specific profiles. *H. tuberosus* contained the highest Ca (20.4 g kg⁻¹) and Mg (5.66 g kg⁻¹), while *S. canadensis* and *R. japonica* showed lower values for most elements. Micronutrients such as Fe, Mn and Zn were present at low levels across all plant samples.

Evaluating the micro- and macroelemental composition of raw biomass is essential for understanding the multifunctional potential of the resulting pellets. In addition to their suitability as a renewable energy source, the presence of plant-essential elements enhances their potential for agricultural use, including soil amendment (Jones and Jacobsen 2005). Moreover, determining the concentrations of not only trace elements but also soluble salts in biomass is crucial, as excessive levels of elements can increase soil salinity and pose toxicity risks to plants, thereby limiting the direct application of biomass ash to soil or other applications (Ondrašek *et al.* 2021; Antonkiewicz *et al.* 2022).

Invasive Plant Pellets

Although raw biomass such as agricultural residues, garden waste, or even invasive plant biomass can be used for direct combustion, its high moisture content, irregular form, and low energy density make it inefficient and unsuitable for modern energy systems (Garcia-Maraver and Carpio 2015). For both industrial and fully automated household burners, a stable and uniform form of fuel is essential to ensure consistent combustion efficiency and operational reliability. Pelletizing the biomass addresses these issues by producing standardized, high-density fuel with low moisture content, making biomass pellets a highly suitable solution for scalable and efficient energy production (Stelte *et al.* 2012).

The use of binders is essential in pellet production to improve mechanical strength, density, and durability – particularly when working with herbaceous biomass, which often exhibits weak self-binding properties (Pradhan *et al.* 2018; Vershinina *et al.* 2024). Pelletization trials were done using only invasive plant biomass without binder. The resulting pellets exhibited lower, but still acceptable mechanical strength. Pellets obtained without binder were brittle, but could be used for energy production. However, during the subsequent pyrolysis process, they disintegrated. Thus, further experiments were done

using pellets obtained with binder. A variety of natural and inorganic binders have been explored for this purpose, including starch, lignin, peat, microalgae, and even sewage sludge (Muazu and Stegemann 2017; Vincevica-Gaile *et al.* 2019; Zhao *et al.* 2022).

In this study, two organic binders were selected: homogenized peat processing residues and sapropel. Peat residues, rich in partially decomposed organic matter such as lignin and cellulose, are known to enhance pellet durability, porosity, and combustion properties (Borowski *et al.* 2021). Sapropel, a sediment rich in organic material sourced from Latvian freshwater lakes, was chosen for its natural adhesive properties and ability to improve pellet structure and cohesion (Vincevica-Gaile *et al.* 2019). Beyond their technical performance, the use of such binders contributes to circular economy principles by recycling organic by-products and reducing overall pellet production costs. Binder composition (Table 1) further supports their use in improving pellet structure, energy potential, and agricultural benefits, as discussed in this section.

As a result of the incorporation of invasive plant biomass and two different binders, five different pellet types were produced through the pelletization – SC(S): *S. canadensis* with sapropel (5%), RJ(S): *R. japonica* with sapropel (5%), RJ(P): *R. japonica* with peat processing residues (10%), HT(S): *H. tuberosus* with sapropel (5%) and HT(P): *H. tuberosus* with peat processing residues (10%). The resulting raw pellets were evaluated for their elemental composition, ash and moisture content, and thermogravimetric properties.

The elemental and physical composition of the produced biomass pellets varied depending on the type of binder and biomass used. Because the S concentration in the raw biomass was very low or below the detection limit, it was not further analyzed in the pellet samples. C content ranged from 44.3% in HT(S) pellets to 50.1% in SC(S) pellets, falling well within the typical range reported for herbaceous biomass (Jagustyn *et al.* 2017; Vassilev *et al.* 2017) (Table 2).

Table 2. Characteristics of Invasive Plant Biomass Pellets Prepared with Sapropel and Peat-Based Binders

Pellets	Binder	Added binder (%)	N (%)	C (%)	Moisture content (%)	Ash content (%)	Lower heating value (MJ kg ⁻¹)
SC(S)	sapropel	5	2.35 ±0.04	50.07 ±0.39	2.41	7.75	17.15
RJ(S)	sapropel	5	2.04 ±0.03	48.23 ±0.38	3.31	7.90	17.8
RJ(P)	peat processing residues	10	1.81 ±0.03	47.74 ±0.37	1.83	6.18	18.03
HT(S)	sapropel	5	2.44 ± 0.04	44.28 ±0.35	6.73	10.40	16.43
HT(P)	peat processing residues	10	2.19 ±0.04	44.30 ±0.35	2.17	9.04	16.7

Pellet samples: SC(S) – *Solidago canadensis* with sapropel (5%); RJ(S) – *Reynoutria japonica* with sapropel (5%); RJ(P) – *Reynoutria japonica* with peat processing residues (10%); HT(S) – *Helianthus tuberosus* with sapropel (5%); HT(P) – *Helianthus tuberosus* with peat processing residues (10%). Standard deviations for carbon (C) and nitrogen (N) represent the overall relative measurement error for each element, applied to the calculated mean values.

When compared to various wood-based pellets, for example, vine shoot biomass (from vineyards in the northern Spain) with a C content of 46.9% or Pyrenean pine biomass with 51.8% – invasive plant biomass reinforces its suitability as a competitive alternative

for bioenergy production (Miranda *et al.* 2015). The N content in all samples was relatively high compared to woody biomass, which may be related to the different structural characteristics of the plants and the formation of green biomass (Table 2). It has been reported that N content in various woody materials can range from 0.34% (olive branches) to 1.8% (pyrene oak) (Miranda *et al.* 2015). According to the EN ISO 17225-6 (2014) standard, N content for industrial-grade non-woody pellets must not exceed 1.5% for Class A and 2.0% for Class B fuels. The N content in SC(S), RJ(S), HT(S), and HT(P) exceeded the specified limits for both classes. Therefore, only the RJ(P) sample qualified for the Class B standard (Rupasinghe *et al.* 2023). A clear trend was observed for both C and N, with their concentrations increasing in the final pellets compared to the original biomass.

The moisture content measured in the pellets was significantly below the typical threshold for non-woody high-quality pellets ($\leq 12\%$ for Class A and $\leq 15\%$ for Class B) according to EN ISO 17225-6 (2014), ranging from 1.83% to 6.73%, further supporting their suitability as a solid biofuel (Table 2). However, it should be noted that pellet moisture content may be influenced by storage conditions (Vershina *et al.* 2024).

Assessing ash content in pellets is important for several reasons. Higher ash content reduces the effective calorific value, as ash consists of inorganic matter that does not contribute to heat generation, thereby lowering the energy output per unit mass (Vassilev *et al.* 2017). Excessive ash can also cause operational problems in combustion systems, increasing maintenance needs and potentially shortening equipment lifespan (Monedero *et al.* 2024). Additionally, the chemical composition of ash can influence combustion efficiency and emissions, with certain elements contributing to corrosion or air pollution (da Silva *et al.* 2020; Sippula *et al.* 2017). Ash content also serves as an indicator of pellet quality according to standards such as ISO 17225-6 (2014) and may reflect the cleanliness of the raw biomass material.

The ash content of the produced pellets ranged from 6.18% in RJ(P) pellets to 10.40% in HT(S) pellets (Table 2). According to the EN ISO 17225-6 (2014) standard for graded non-woody pellets, Class A pellets should have an ash content of $\leq 6\%$, while Class B pellets allow up to $\leq 10\%$. Based on these limits, none of the produced pellets fully meet Class A requirements, but all samples comply with the Class B criteria.

The lower heating value (LHV) is a key parameter for evaluating the energy efficiency of solid biofuels, as it reflects the amount of usable heat released during combustion after accounting for moisture and volatile losses (Gravalos *et al.* 2010). In the present study, the LHV of the produced pellets ranged from 16.4 MJ kg⁻¹ for HT(S) to 18.0 MJ kg⁻¹ for RJ(P), demonstrating favorable energy potential across all samples (Table 2). The highest LHV was observed in sample RJ(P) (18.0 MJ kg⁻¹), which may correspond to a higher lignin content in *R. japonica*, which, compared to cellulose and hemicellulose, can contribute to a higher calorific value (Hennequin *et al.* 2021).

The LHV of herbaceous biomass pellets can vary depending on the specific type of biomass and applicable quality standards, but it is generally above 14.5 MJ kg⁻¹ and can reach approximately 17 MJ kg⁻¹ or even higher depending on the conditions, indicating the comparability – and in some cases, even relatively higher calorific values – of the selected invasive plant-based pellets (Gravalos *et al.* 2010; Miranda *et al.* 2015; Kamperidou 2022; Rupasinghe *et al.* 2023). Invasive plant biomass pellets meet the LHV requirements specified in the EN ISO 17225-6 (2014) standard for non-woody pellets and, based on this parameter, are suitable for residential and industrial applications.

Thermogravimetric Analysis

TGA analysis was performed to evaluate the thermal stability and decomposition behavior of pellets produced from *H. tuberosus*, *R. japonica*, and *S. canadensis* with sawpellet or peat processing residues as binders (Fig. 2). In all samples, an initial minor mass loss was observed around 100 to 150 °C, corresponding to the evaporation of physically bound water and low-boiling volatiles (El-Sayed and Mostafa 2014; Kanga *et al.* 2024). A sharp weight loss was recorded between approximately 250 and 400 °C in all formulations, which was attributed to the thermal degradation of hemicellulose and cellulose. This phase marks the main decomposition stage of organic components (Zhou *et al.* 2015).

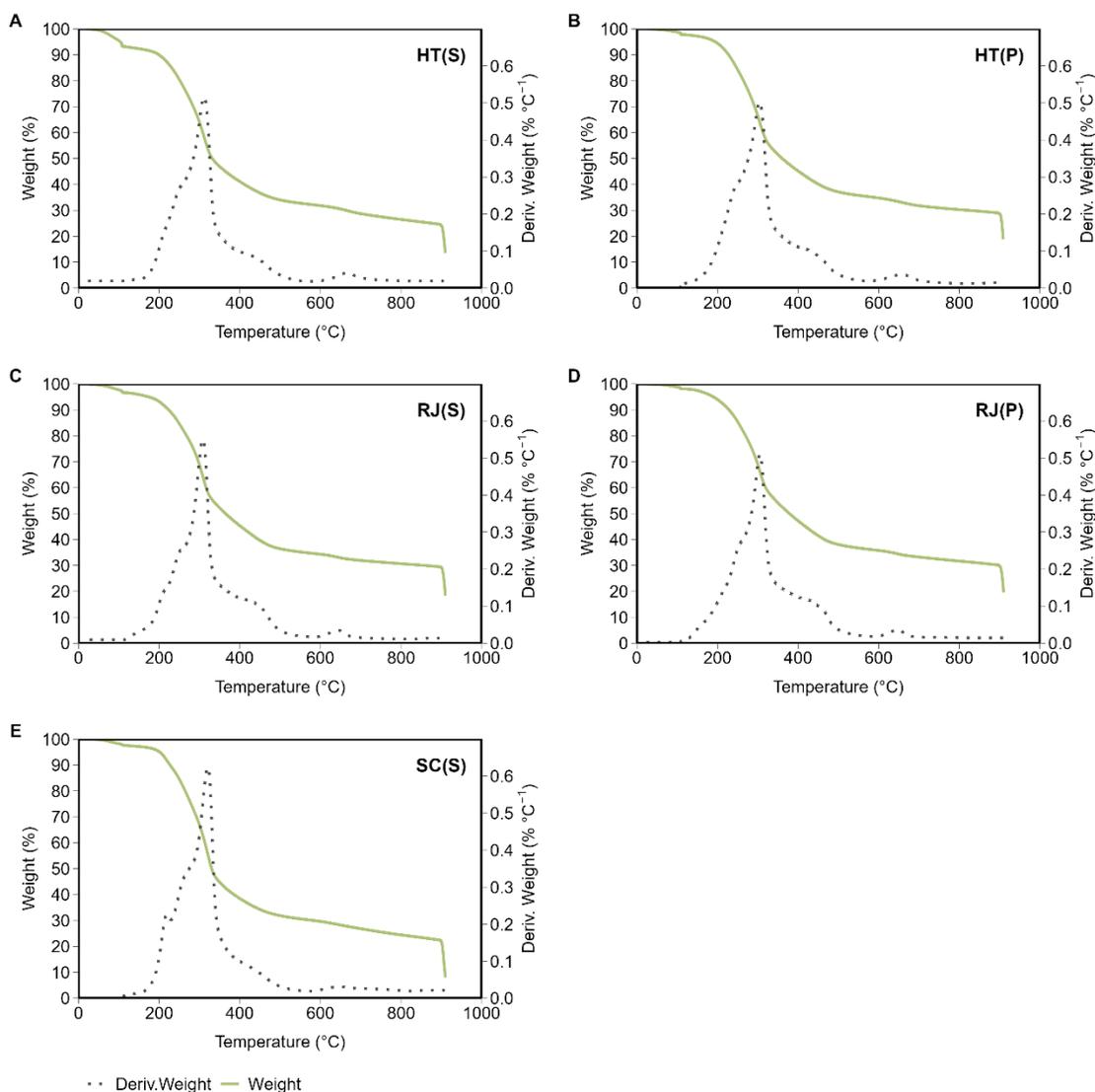


Fig. 2. Weight loss (%) of pellets derived from invasive plant biomass with either sawpellet (S) (shown in graphs A, C, E) or peat residues (P) (shown in graphs B, D) as binders was recorded under increasing temperature up to 900 °C. The results reflect the thermal degradation behavior of each pellet formulation. Pellet samples: SC(S) – *Solidago canadensis* with sawpellet (5%); RJ(S) – *Reynoutria japonica* with sawpellet (5%); RJ(P) – *Reynoutria japonica* with peat processing residues (10%); HT(S) – *Helianthus tuberosus* with sawpellet (5%); HT(P) – *Helianthus tuberosus* with peat processing residues (10%)

A slower and more gradual mass loss phase followed, continuing up to 600 to 700 °C, for analyzed samples, associated with the breakdown of lignin and more thermally stable components (Li *et al.* 2013). The final residue above 700 °C, particularly in spropel-containing samples, indicates higher inorganic content, consistent with their known ash levels.

The decomposition patterns varied depending on both the biomass type and binder. RJ(P) and HT(P) showed the highest thermal stability, retaining more mass at elevated temperatures, which was potentially due to higher lignin content. Meanwhile, HT(S) showed the lowest residual mass, indicating a higher proportion of volatile organics (Fig. 2). These thermogravimetric profiles are essential for understanding the suitability of each pellet type for pyrolysis or combustion-based applications.

Pyrolyzed Invasive Plant Pellets

Raw biomass pellets were used for slow pyrolysis in order to convert them into biochar and evaluate their potential for carbon-rich solid fuel production or use as soil amendments. Pelletization before pyrolysis offers several advantages, including improved feedstock handling, uniform size and density, and enhanced thermal conversion efficiency due to better heat transfer during the process (Kallis *et al.* 2013; Hu *et al.* 2018; Yildiz *et al.* 2025).

All samples were pyrolyzed at 600 °C, using a heating rate of 5 °C min⁻¹ and a 4-hour residence time. The biochar yield ranged from 32.1% (SC(S) C-C) to 34.2% (RJ(S) C-C) (Table 3). Slightly higher yields were observed in spropel-bound pellets, although the differences between formulations were insignificant. Reported biochar yields from lignocellulosic biomass in the literature vary widely, primarily depending on the feedstock characteristics and pyrolysis parameters, with values ranging from as low as 20% to as high as 95% (Abdullah *et al.* 2022; Batista and Gomes 2021).

The C content of the pyrolyzed invasive plant biomass pellets ranged from 78.1% to 85.3%, with the highest value observed in the sample SC(S) C-C (Table 3), which exceeded the minimum requirements set by the European Biochar Certificate (EBC) for both basic and premium biochar grades. EBC defines quality requirements for biochar based on various criteria, including elemental composition. According to the EBC standard, biochar must contain at least 50% total C to be classified as biochar (Lin *et al.* 2025). Obtained C content values indicated a high degree of C enrichment typical for herbaceous biochar, which generally contains 70 to 85% C when produced *via* slow pyrolysis, as reported in the literature (Chatterjee *et al.* 2020; Šáner *et al.* 2025). High C content is crucial for biochar's effectiveness in applications such as carbon sequestration and soil amendment.

N content after pyrolysis remained relatively elevated compared to pellets before pyrolysis, ranging between 1.25% and 2.82%, with RJ(S) C-C showing the highest N concentration (Table 3). The elevated N levels reflect the contribution of nitrogen-rich binder and plant material. Compared to N contents reported for herbaceous biomass after slow pyrolysis in other studies – ranging between 0.28% and 3.3%, the values obtained in this study fell within a similar range (Chatterjee *et al.* 2020; Šáner *et al.* 2025). According to the EBC, total N content is not restricted by fixed thresholds, but it is an important parameter to monitor due to its potential agronomic impact (Lin *et al.* 2025).

Similar to pellets before pyrolysis, measuring and maintaining optimal moisture content in the resulting biochar pellets is essential for preserving their physical integrity, facilitating efficient storage and handling, thereby ensuring effective application as soil

amendments and supporting energy-efficient production and use (Sadeq *et al.* 2023). Moisture content across all biochar samples remained low, ranging from 3.73% (SC(S) C-C) to 6.54% (RJ(S) C-C) (Table 3). While the EBC standard does not impose a strict moisture limit and only requires it to be measured and reported, the CNAIS (Carbon Negative Artificial Inorganic Soil standard) framework sets a maximum allowable moisture content of 30% for biochar intended for soil applications (Lin *et al.* 2025), which in this case is not exceeded.

Ash content ranged from 16.8% to 28.5%, with the lowest value in the sample RJ(P) C-C and the highest in the sample HT(S) C-C (Table 3). These results reflect the original mineral content of the biomass and binders (Table 1), especially the influence of sapropel, which is known to be rich in inorganic material (Klavins *et al.* 2019; Vincevica-Gaile *et al.* 2019). According to the literature, the ash content of biochar derived from rice straw ranged from 21.8% to 32.7%, which is pretty similar to the obtained values from pyrolyzed invasive plant pellets (Tu *et al.* 2022). Herbaceous biochar generally has higher ash content compared to woody origin biochar (Chaturvedi *et al.* 2021). While higher ash content can be a drawback for combustion for energy uses due to slagging risks, it may enhance the value of biochar as a soil amendment by contributing essential minerals and regulating soil acidity.

Table 3. Characteristics of Pyrolyzed Invasive Plant Biomass Pellets Prepared with Sapropel and Peat-Based Binders

Pellets	Binder	Added binder (%)	N (%)	C (%)	Moisture content (%)
SC (S) C-C	sapropel	5	1.25 ±0.03	85.26 ±0.62	3.73
RJ (S) C-C	sapropel	5	2.82 ±0.03	78.07 ±0.13	6.54
RJ (P) C-C	peat processing residues	10	2.57 ±0.03	78.57 ±0.49	5.9
HT (S) C-C	sapropel	5	1.92 ± 0.01	81.67 ±0.80	4.62
HT (P) C-C	peat processing residues	10	2.08 ±0.04	78.84 ±0.97	5.37

Pellets	Binder	Added binder (%)	Ash content (%)	Biochar yield (%)	Higher heating value (MJ kg ⁻¹)*
SC (S) C-C	sapropel	5	23.50	32.08	30.97
RJ (S) C-C	sapropel	5	19.19	34.23	26.97
RJ (P) C-C	peat processing residues	10	16.78	33.38	27.13
HT (S) C-C	sapropel	5	28.54	33.41	28.90
HT (P) C-C	peat processing residues	10	26.08	33.04	27.49

*HHV of the biochar samples were calculated using the empirical correlation based on ultimate analysis proposed by Qian *et al.* (2020): $HHV (MJ kg^{-1}) = 32.9C + 162.7H - 16.2O - 954.4S + 1.408$.

Pellet samples: SC(S) C-C – pyrolyzed *Solidago canadensis* with sapropel (5%); RJ(S) C-C – pyrolyzed *Reynoutria japonica* with sapropel (5%); RJ(P) C-C – pyrolyzed *Reynoutria japonica* with peat processing residues (10%); HT(S) C-C – pyrolyzed *Helianthus tuberosus* with sapropel (5%); HT(P) C-C – pyrolyzed *Helianthus tuberosus* with peat processing residues (10%).

Standard deviations for carbon (C) and nitrogen (N) represent the overall relative measurement error for each element, applied to the calculated mean values.

Parameter	Pyrolyzed pellets				
	SC (S) C-C	RJ (S) C-C	RJ (P) C-C	HT (S) C-C	HT (P) C-C
Binder	sapropel	sapropel	peat processing residues	sapropel	peat processing residues
Added binder (%)	5	5	10	5	10
N (%)	1.25 ±0.03	2.82 ±0.03	2.57 ±0.03	1.92 ± 0.01	2.08 ±0.04
C (%)	85.26 ±0.62	78.07 ±0.13	78.57 ±0.49	81.67 ±0.80	78.84 ±0.97
Moisture content (%)	3.73	6.54	5.9	4.62	5.37
Ash content (%)	23.50	19.19	16.78	28.54	26.08
Biochar yield (%)	32.08	34.23	33.38	33.41	33.04
Higher heating value (MJ kg ⁻¹)*	30.97	26.97	27.13	28.90	27.49

*HHV of the biochar samples were calculated using the empirical correlation based on ultimate analysis proposed by Qian et al. (2020): $HHV (MJ kg^{-1}) = 32.9C + 162.7H - 16.2O - 954.4S + 1.408$.

Pellet samples: SC(S) C-C – pyrolyzed *Solidago canadensis* with sapropel (5%); RJ(S) C-C – pyrolyzed *Reynoutria japonica* with sapropel (5%); RJ(P) C-C – pyrolyzed *Reynoutria japonica* with peat processing residues (10%); HT(S) C-C – pyrolyzed *Helianthus tuberosus* with sapropel (5%); HT(P) C-C – pyrolyzed *Helianthus tuberosus* with peat processing residues (10%).

Standard deviations for carbon (C) and nitrogen (N) represent the overall relative measurement error for each element, applied to the calculated mean values.

Higher heating value (HHV) serves primarily as an indicator of the biochar's energy potential, especially when considered for energy recovery or combustion applications (Qian *et al.* 2020). It represents the total energy released during complete combustion of a dry sample, including the latent heat of water vaporization, and is therefore higher than the net calorific value. However, both values are strongly influenced by the elemental composition of the biomass, as well as its ash and moisture content (Gravalos *et al.* 2016). The conditions under which biochar is produced, such as temperature and time, significantly affect the final calorific value (Selvarajoo *et al.* 2022).

The HHV values based on elemental composition ranged from 27.0 MJ kg⁻¹ (RJ(S) C-C) to 31.0 MJ kg⁻¹ (SC(S) C-C). The obtained biochar HHV values were higher than the LHV values of the original pelletized biomass, as the pyrolysis process removed volatile compounds, thereby concentrating C in the biochar and increasing its calorific value (Table 2; Table 3). Compared to other herbaceous biomass types reported in the literature, where measured HHV values after pyrolysis at 600 °C range from 23.8 to 30.1 MJ kg⁻¹, the results obtained in this study were comparable (Reza *et al.* 2020). Although the calculation method provides a high level of confidence in the estimated HHV values, a more precise assessment would require direct analytical determination.

The final pyrolyzed pellets showed markedly lower metal concentrations compared to raw binders. Cu levels in pyrolyzed pellets ranged from 7.7 to 11.0 mg kg⁻¹, and Cr from 1.19 to 2.99 mg kg⁻¹. Statistical analysis (one-way ANOVA followed by Tukey's HSD test, $p < 0.05$) revealed significant differences among pellet types for both elements. Ni and Pb were present at low levels, with concentrations ranging from 0.89 to 1.57 mg kg⁻¹ and 1.20 to 1.51 mg kg⁻¹, respectively. However, no statistically significant differences were

observed among pellet types for Ni and Pb ($p > 0.05$). As, Be, Cd, Co, Li, Mo, Sb, Se, Tl and V were not detected in pyrolyzed pellets (Fig. 3).

The significantly lower metal concentrations in pyrolyzed pellets compared to raw materials can be attributed primarily to dilution effects during mixing, where the invasive plant biomass constitutes the majority of the pellet mass. Variations in the concentrations of certain heavy metals may also be attributed to the pyrolysis process itself, which can alter metal distribution through volatilization, redistribution within the char matrix, or transformation into more stable mineral forms (Kujawska *et al.* 2024; Sørmo *et al.* 2024).

The concentrations of heavy metals in the obtained biochar samples were evaluated against the threshold values established by EBC for Premium grade. All analyzed samples met the limits for Cu ($<100 \text{ mg kg}^{-1}$), Cr ($<80 \text{ mg kg}^{-1}$), Ni ($<30 \text{ mg kg}^{-1}$), and Pb ($<120 \text{ mg kg}^{-1}$), and they also remained below the maximum allowable concentration (Lin *et al.* 2025). These results confirm that the produced biochar complies with EBC basic and premium biochar grades requirements and is suitable for use in agricultural or environmental applications.

The final pyrolyzed pellets retained nutrients in varying amounts depending on the biomass and binder used. HT-based pyrolyzed pellets contained elevated levels of Ca (up to 21.2 g kg^{-1}), Mg (up to 5.90 g kg^{-1}), and K (up to 25.1 g kg^{-1}). Statistically significant differences in nutrient concentrations were observed among the different pellet types for most elements (Ca, K, Mg, Mn, Zn, Fe, and S) (Tukey's HSD, $p < 0.05$) (Fig. 3).

Pellets made from RJ and SC showed lower but still measurable concentrations of key elements. B was detected only in SC and HT-based pellet types (up to 0.05 g kg^{-1}), depending on the biomass-binder combination. For example, K is one of the essential macronutrients used as fertilizer for increasing crop yield in agriculture, as it remains critical for osmoregulation, cell extension, stomatal movement, sucrose loading, and other important functions in plants (Jones and Jacobsen 2005; University of Minnesota 2018). Ca (7.12 to 7.51 g/kg), Mg (5.25 to 5.34 g/kg), K (2.70 to 21.4 g/kg), and P (1.89 to 2.0 g/kg) concentrations found in corn stover and switchgrass biochar were comparable to or in some cases even lower than the values found in invasive plant biochar (Chintala *et al.* 2014).

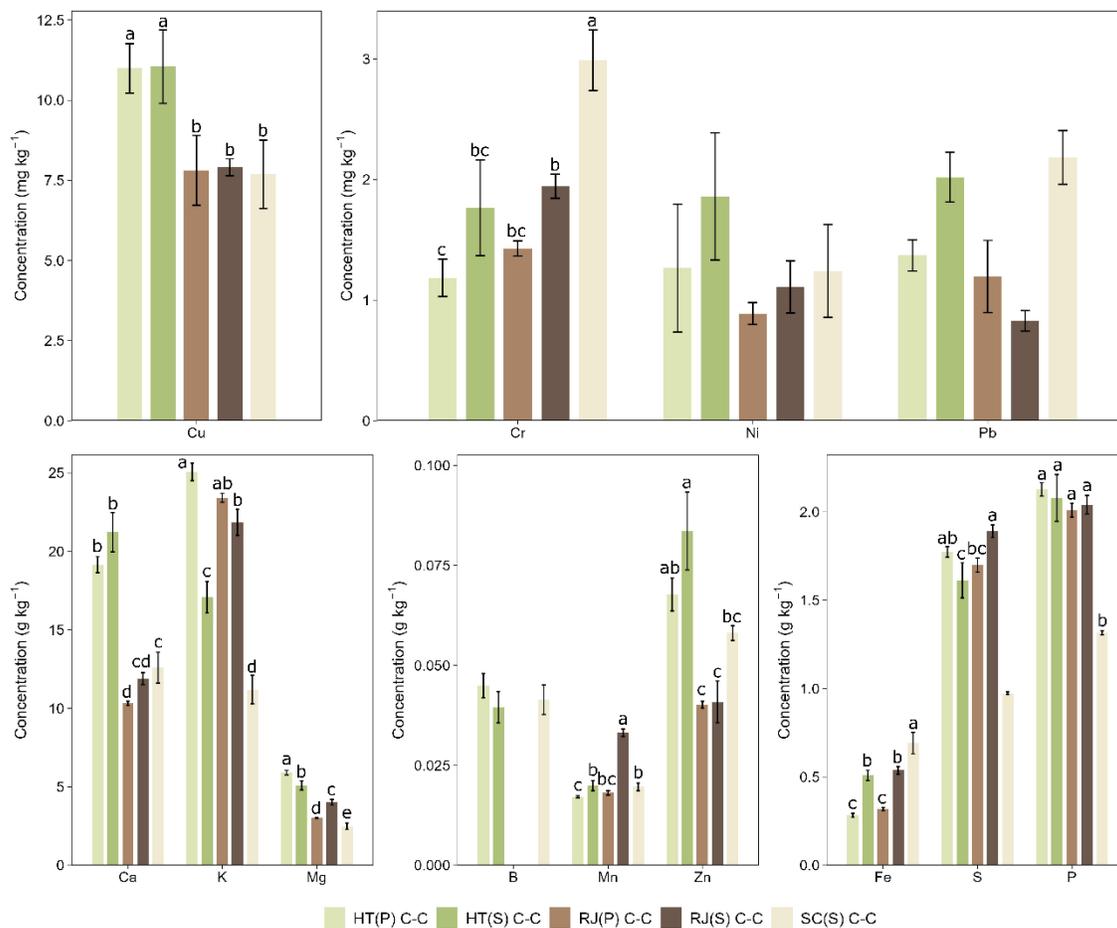


Fig. 3. Measured concentrations of Cu, Cr, Ni, Pb and Ca, K, Mg, B, Mn, Zn, Fe, S, P in pyrolyzed invasive plant pellets. Pellet samples: SC(S) C-C – *Solidago canadensis* with sapropel (5%); RJ(S) C-C – *Reynoutria japonica* with sapropel (5%); RJ(P) C-C – *Reynoutria japonica* with peat processing residues (10%); HT(S) C-C – *Helianthus tuberosus* with sapropel (5%); HT(P) C-C – *Helianthus tuberosus* with peat processing residues (10%). All concentrations are expressed on a dry weight basis. Error bars for Cu, Cr, Ni, and Pb show the element-specific relative analytical uncertainty applied to the mean concentration, whereas error bars for Ca, K, Mg, B, Mn, Zn, Fe, and S represent the standard deviation of triplicate measurements ($n = 3$), reflecting variability among replicates. Statistical differences among samples within each element group ($n = 3$) were assessed using one-way ANOVA followed by Tukey's HSD test ($p < 0.05$). Lowercase letters above bars are shown only for element groups where significant differences were detected.

Surface Area and Morphological Characterization of Pyrolyzed Pellets

As surface area strongly influences the functional performance of porous materials, it is a critical parameter when evaluating their suitability for various applications. Increased pore volume can improve the adsorption potential of biochar for contaminants such as heavy metals (Wu *et al.* 2022; Hu *et al.* 2023). Such adsorption can also be useful in wastewater treatment, for example, by adsorbing phosphorus or various anionic and cationic dyes from aqueous media (Zubair *et al.* 2020; Januševičius *et al.* 2024).

The specific surface area of pyrolyzed pellets of invasive plants ranges from 56.71 to 1.27 m² g⁻¹ (Table 4). According to IUPAC classification, materials with pore diameters between 2 and 50 nm are considered mesoporous, while those below 2 nm are microporous (Thommes *et al.* 2015). Based on average pore diameter, samples HT(P) C-C, and RJ(P) C-C fall into the mesoporous range, whereas RJ(S) C-C and HT(S) C-C are closer to the

microporous category with a small surface area from 1.27 to 1.28 m²g⁻¹. Samples SC(S) C-C and RJ(P) C-C have a large surface area relative to samples HT(P) C-C, HT(S) C-C, and RJ(S) C-C. These surface area differences may occur due to variations in feedstock composition and pyrolysis conditions. The intrinsic properties of the biomass – such as lignin, cellulose, and hemicellulose content – can significantly influence pore structure development, while higher pyrolysis temperatures promote the formation of micropores and mesopores, resulting in increased surface area (Chafik *et al.* 2024; Cho *et al.* 2024; Song *et al.* 2024).

Notably, SC(S) C-C and RJ(P) C-C exhibited specific surface areas (56.7 and 7.31 m²/g, respectively) that exceeded those reported for pyrolyzed corn cobs at 200 to 600 °C (Nguyen *et al.* 2022). Similarly, the total pore volume of all tested samples surpassed that of walnut shell-derived biochar (Xu *et al.* 2022).

Table 4. Multi-point BET, Total Pore Volume, and Average Diameter of Pyrolyzed Pellets

Pellets	Multi-point BET (m ² g ⁻¹)	Total pore volume (cc g ⁻¹)	Average pore diameter (nm)
SC(S) C-C	56.71	5.45 · 10 ⁻²	3.85
HT (P) C-C	1.43	4.77 · 10 ⁻³	13.31
HT (S) C-C	1.27	4.16 · 10 ⁻³	13.08
RJ (P) C-C	7.31	7.79 · 10 ⁻³	4.27
RJ (S) C-C	1.28	2.94 · 10 ⁻³	9.18

Pellet samples: SC(S) C-C – pyrolyzed *Solidago canadensis* with sapropel (5%); RJ(S) C-C – pyrolyzed *Reynoutria japonica* with sapropel (5%); RJ(P) C-C – pyrolyzed *Reynoutria japonica* with peat processing residues (10%); HT(S) C-C – pyrolyzed *Helianthus tuberosus* with sapropel (5%); HT(P) C-C – pyrolyzed *Helianthus tuberosus* with peat processing residues (10%).

Scanning electron microscopy (SEM) provides detailed visual information on biochar surface morphology, porosity, and structural features, which are critical for assessing its suitability for applications like adsorption and soil amendment (Amin *et al.* 2016). SEM images reveal how pyrolysis conditions, such as temperature and duration, influence pore development and surface texture (Amin *et al.* 2016; Reza *et al.* 2020). Variations in raw materials and thermal processing can significantly affect SEM results, making it a valuable tool for optimizing biochar production and functionality (Amin *et al.* 2016; Igalavithana *et al.* 2017).

SEM images of the pyrolyzed invasive plant biomass pellets reveal micro- and mesoporous structural features typical for herbaceous biomass pyrolyzed at moderate temperatures (Reza *et al.* 2020) (Fig. 4). All samples display a heterogeneous and porous surface, with visible fissures, layered textures, and partially collapsed structures, suggesting structural degradation due to volatile release during pyrolysis (Chen *et al.* 2022). As the research results show, invasive plant biomass palletization approach can achieve the effective use of biomass that would otherwise go to waste, transforming it into a valuable energy source while mitigating ecological threats posed by invasive plant species. It effectively integrates invasive species control, renewable energy production, waste valorization, and soil enhancement into one coherent framework, thereby contributing to broader environmental and climate goals outlined by the European Green Deal and strategies promoting the bioeconomy and circular economy (European Commission 2020a,b). These approaches aim to reduce dependence on fossil resources by substituting them with renewable biological materials, in line with the EU's vision for a

sustainable bioeconomy. Moreover, the results suggest that invasive plant biomass, when combined with nutrient-rich binders, produces pellets and biochar that not only serve as a bioenergy source but also retain considerable nutrient value. This further supports pellet potential role in agricultural applications such as soil amendments, especially when applied as biochar or ash resulting from thermal treatment. SEM and BET results suggest that the pyrolysis of invasive plant-based pellets can yield biochar with diverse and tunable surface characteristics, making them potentially suitable for various applications.

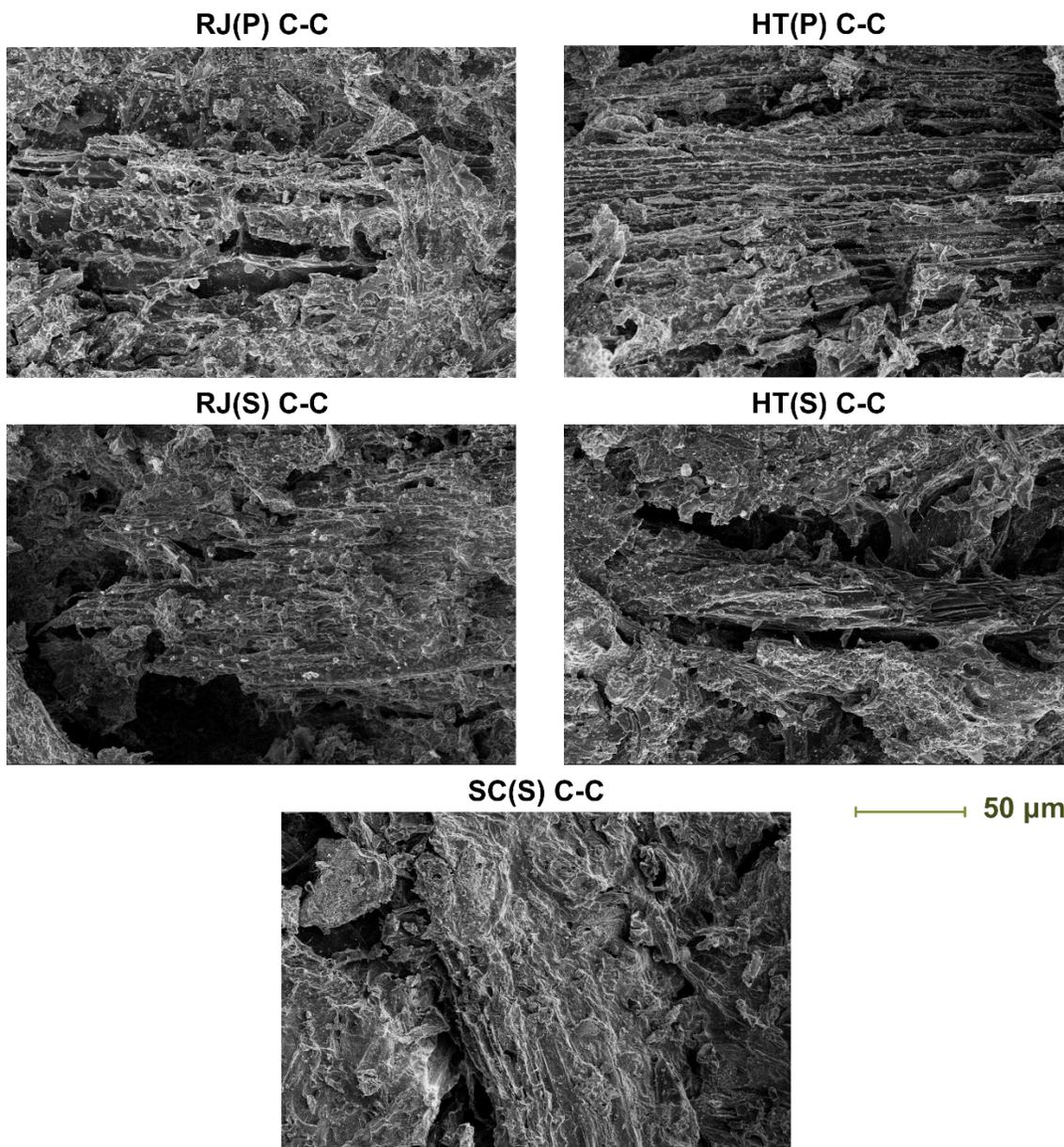


Fig. 4. Surface morphology of the pyrolyzed pellet observed by scanning electron microscopy (SEM) at 500× magnification. Pellet samples: SC(S) C-C – pyrolyzed *Solidago canadensis* with sapropel (5%); RJ(S) C-C – pyrolyzed *Reynoutria japonica* with sapropel (5%); RJ(P) C-C – pyrolyzed *Reynoutria japonica* with peat processing residues (10%); HT(S) C-C – pyrolyzed *Helianthus tuberosus* with sapropel (5%); HT(P) C-C – pyrolyzed *Helianthus tuberosus* with peat processing residues (10%)

CONCLUSIONS

1. The pelletization of invasive plant biomass for energy production presents a multifaceted, sustainable approach that not only supports invasive species eradication but also promotes renewable energy and resource efficiency.
2. The benefits of pelletization include possibilities for biomass processing on-site directly after the eradication, the dry or wet biomass waste can be homogenized and mixed with binders that provide possibilities to obtain pellets with high mechanical stability.
3. The energy value of invasive plant pellets, with a lower heating value ranging from 16.4 to 18.0 MJ kg⁻¹, meets international standards for non-woody biomass fuels and is comparable to conventional wood pellets.
4. Chemical analyses indicate that invasive plant pellets can be environmentally safe, with low levels of heavy metals and the absence of hazardous elements, for example, As, Cd and Co, making them suitable for energy safe biochar usage in agriculture as soil amendments.

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Authorship Contribution Statement

Evelina Niedrite: Conceptualization, Writing - Original Draft, Visualization. **Linda Ansone-Bertina:** Methodology, Formal analysis. **Lauris Arbidans:** Methodology. **Andrei Shiskin:** Planning of experiments. **Oskars Purmalis:** Writing - Review & Editing. **Marina Zhylina:** Experiments. **Linards Klavins:** Writing - Review & Editing. **Maris Klavins:** Supervision, Writing - Review & Editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of Generative AI

AI tools have not been used at the preparation of the article.

REFERENCES CITED

- Abdullah, I., Ahmad, N., Hussain, M., Ahmed, A., Ahmed, U., and Park, Y. K. (2022). "Conversion of biomass blends (walnut shell and pearl millet) for the production of solid biofuel via torrefaction under different conditions," *Chemosphere* 295, article 133894. <https://doi.org/10.1016/j.chemosphere.2022.133894>
- Amin, F. R., Huang, Y., He, Y., Zhang, R., Liu, G., and Chen, C. (2016). "Biochar applications and modern techniques for characterization," *Clean Technologies and Environmental Policy* 18, 1457-1473. <https://doi.org/10.1007/s10098-016-1218-8>
- Antonkiewicz, J., Kowalewska, A., Mikołajczak, S., Kołodziej, B., Bryk, M., Sychaj Fabisiak, E., Koliopoulos, T., and Babula, J. (2022). "Phytoextraction of heavy metals after application of bottom ash and municipal sewage sludge considering the risk of environmental pollution," *Journal of Environmental Management* 306, article 114517. <https://doi.org/10.1016/j.jenvman.2022.114517>
- Anukam, A., Berghel, J., Henrikson, G., Frodeson, S., and Ståhl, M. (2021). "A review of the mechanism of bonding in densified biomass pellets," *Renewable and Sustainable Energy Reviews* 148, article 111249. <https://doi.org/10.1016/j.rser.2021.111249>
- Batista, R. R., and Gomes, M. M. (2021). "Effects of chemical composition and pyrolysis process variables on biochar yields: Correlation and principal component analysis," *Floresta e Ambiente* 28, article e20210007. <https://doi.org/10.1590/2179-8087-FLORAM-2021-0007>
- Beaury, E. M., Fusco, E. J., Allen, J. M., and Bradley, B. A. (2021). "Plant regulatory lists in the United States are reactive and inconsistent," *Journal of Applied Ecology* 58(9), 1957-1966. <https://doi.org/10.1111/1365-2664.13934>
- Bellard, C., Leroy, B., Thuiller, W., Rysman, J. F., and Courchamp, F. (2016). "Major drivers of invasion risks throughout the world," *Ecosphere* 7(3), article e01241. <https://doi.org/10.1002/ecs2.1241>
- Borowski, G. (2021). "Using of adhesives and binders for waste agglomeration," in: *Proceedings of the 18th International Symposium on Waste Management and Sustainable Landfilling*, CISA Publisher, Cagliari, Italy, pp. 11-15.
- Buneviciene, K., Drapanauskaite, D., Mazeika, R., Tilvikiene, V., and Baltrusaitis, J. (2021). "Granulated biofuel ash as a sustainable source of plant nutrients," *Waste Management and Research* 39(6), 806-817. <https://doi.org/10.1177/0734242X20948952>
- Cardoso, A. C., Tsiamis, K., Deriu, I., D'Amico, F., and Gervasini, E. (2021). *EU Regulation 1143/2014: Assessment of Invasive Alien Species of Union Concern Distribution, Member States Reports vs JRC Baselines*, Publications Office of the European Union Report 173, Luxembourg.
- Chafik, Y., Hassan, S. H., Lebrun, M., Sena-Velez, M., Cagnon, B., Carpin, S., Boukroute, A., Bourgerie, S., and Morabito, D. (2024). "Biochar characteristics and Pb²⁺/Zn²⁺ sorption capacities: The role of feedstock variation," *International Journal of Environmental Science and Technology* 21(16), 9829-9842. <https://doi.org/10.1007/s13762-024-05646-0>
- Chatterjee, R., Sajjadi, B., Chen, W. Y., Mattern, D. L., Hammer, N., Raman, V., and Dorris, A. (2020). "Effect of pyrolysis temperature on physicochemical properties and acoustic-based amination of biochar for efficient CO₂ adsorption," *Frontiers in Energy Research* 8, article 85. <https://doi.org/10.3389/fenrg.2020.00085>
- Chaturvedi, S., Singh, S. V., Dhyani, V. C., Govindaraju, K., Vinu, R., and Mandal, S.

- (2021). "Characterization, bioenergy value, and thermal stability of biochars derived from diverse agriculture and forestry lignocellulosic wastes," *Biomass Conversion and Biorefinery* 13, 879-892. <https://doi.org/10.1007/s13399-020-01239-2>
- Chen, D., Cen, K., Zhuang, X., Gan, Z., Zhou, J., Zhang, Y., and Zhang, H. (2022). "Insight into biomass pyrolysis mechanism based on cellulose, hemicellulose, and lignin: Evolution of volatiles and kinetics, elucidation of reaction pathways, and characterization of gas, biochar, and bio-oil," *Combustion and Flame* 242, article 112142. <https://doi.org/10.1016/j.combustflame.2022.112142>
- Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D., and Julson, J. L. (2014). "Effect of biochar on chemical properties of acidic soil," *Archives of Agronomy and Soil Science* 60(3), 393-404. <https://doi.org/10.1080/03650340.2013.789870>
- Cho, E. J., Lee, C. G., and Park, S. J. (2024). "Adsorption of phenol on kenaf derived biochar: Studies on physicochemical and adsorption characteristics and mechanism," *Biomass Conversion and Biorefinery* 14(8), 9621-9638. <https://doi.org/10.1007/s13399-022-03262-x>
- Duca, D., Maceratesi, V., Fabrizi, S., and Toscano, G. (2022). "Valorising agricultural residues through pelletisation," *Processes* 10(2), article 232. <https://doi.org/10.3390/pr10020232>
- El-Sayed, S. A., and Mostafa, M. E. (2014). "Pyrolysis characteristics and kinetic parameters determination of biomass fuel powders by differential thermal gravimetric analysis (TGA/DTG)," *Energy Conversion and Management* 85, 165-172. <https://doi.org/10.1016/j.enconman.2014.05.068>
- EN ISO 17225-6 (2014). "Solid biofuels - Fuel specifications and classes - Part 6: Graded non-woody pellets," European Committee for Standardization (CEN), Brussels, Belgium.
- European Commission. (2020a). *The European Green Deal*, Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions, COM/2019/640 final. (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52019DC0640>), accessed 16 June 2025.
- European Commission. (2020b). *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*, Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions, COM/2020/98 final. (<https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN>), accessed 16 June 2025.
- European Commission. (2023). "Commission Implementing Regulation (EU) 2022/1203 of 12 July 2022 amending Implementing Regulation (EU) 2016/1141 to update the list of invasive alien species of Union concern," *Official Journal of the European Union*. (http://data.europa.eu/eli/reg_impl/2022/1203/oj), accessed 20 May 2025.
- Feng, Q., Wang, B., Chen, M., Wu, P., Lee, X., and Xing, Y. (2021). "Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: A review," *Resources, Conservation and Recycling* 164, article 105204. <https://doi.org/10.1016/j.resconrec.2020.105204>
- Garcia-Maraver, A., and Carpio, M. (2015). "Biomass pelletization process," in: *Biomass Pelletization: Standards and Production*, P. Basu (ed.), CRC Press, London, UK, pp. 53-66.

- Ghugare, S. B., Tiwary, S., and Tambe, S. S. (2017). “Computational intelligence based models for prediction of elemental composition of solid biomass fuels from proximate analysis,” *International Journal of System Assurance Engineering and Management* 8, 2083-2096. <https://doi.org/10.1007/s13198-014-0324-4>
- Gioria, M., Hulme, P. E., Richardson, D. M., and Pyšek, P. (2023). “Why are invasive plants successful?” *Annual Review of Plant Biology* 74(1), 635-670. <https://doi.org/10.1146/annurev-arplant-070522-071021>
- Gramauskas, G., Jasinskas, A., Kleiza, V., Mioldažys, R., Blažauskas, E., and Souček, J. (2023). “Evaluation of invasive herbaceous plants utilization for the production of pressed biofuel,” *Processes* 11(7), article 2097. <https://doi.org/10.3390/pr11072097>
- Gravalos, I., Kateris, D., Xyradakis, P., Gialamas, T., Loutridis, S., Augousti, A., Georgiades, A., and Tsiropoulos, Z. (2010). “A study on calorific energy values of biomass residue pellets for heating purposes,” in: *Proceedings of the 43rd International Symposium on Forest Engineering: Meeting the Needs of the Society and the Environment*, FORMEC, Padova, Italy.
- Gravalos, I., Xyradakis, P., Kateris, D., Gialamas, T., Bartzialis, D., and Giannoulis, K. (2016). “An experimental determination of gross calorific value of different agroforestry species and bio-based industry residues,” *Natural Resources* 7(1), 57-68. <https://doi.org/10.4236/nr.2016.71006>
- Guido, A., and Pillar, V. D. (2017). “Invasive plant removal: Assessing community impact and recovery from invasion,” *Journal of Applied Ecology* 54(4), 1230-1237. <https://doi.org/10.1111/1365-2664.12848>
- Han, Z., Guo, Z., Zhang, Y., Xiao, X., and Peng, C. (2018). “Potential of pyrolysis for the recovery of heavy metals and bioenergy from contaminated *Broussonetia papyrifera* biomass,” *BioResources* 13(2), 2932-2944. <https://doi.org/10.15376/biores.13.2.2932-2944>
- He, H., Wang, Y., Sun, W., Sun, Y., and Wu, K. (2024). “Effects of different biomass feedstocks on the pelleting process and pellet qualities,” *Sustainable Energy Technologies and Assessments* 69, article 103912. <https://doi.org/10.1016/j.seta.2024.103912>
- Hennequin, L. M., Polizzi, K., Fennell, P. S., and Hallett, J. P. (2021). “Rhododendron and Japanese knotweed: Invasive species as innovative crops for second generation biofuels for the ionoSolv process,” *RSC Advances* 11(30), 18395-18403. <https://doi.org/10.1039/D1RA01943K>
- Holmes, T. P., Aukema, J. E., Von Holle, B., Liebhold, A., and Sills, E. (2009). “Economic impacts of invasive species in forests: Past, present, and future,” *Annals of the New York Academy of Sciences* 1162(1), 18-38. <https://doi.org/10.1111/j.1749-6632.2009.04446.x>
- Hu, J., Shen, Y., and Zhu, N. (2023). “Optimizing adsorption performance of sludge-derived biochar via inherent moisture-regulated physicochemical properties,” *Waste Management* 169, 70-81. <https://doi.org/10.1016/j.wasman.2023.06.033>
- Hu, Q., Yang, H., Xu, H., Wu, Z., Lim, C. J., Bi, X. T., and Chen, H. (2018). “Thermal behavior and reaction kinetics analysis of pyrolysis and subsequent *in-situ* gasification of torrefied biomass pellets,” *Energy Conversion and Management* 161, 205-214. <https://doi.org/10.1016/j.enconman.2018.02.003>
- Igalavithana, A. D., Mandal, S., Niazi, N. K., Vithanage, M., Parikh, S. J., Mukome, F. N. D., Rizwan, M., Oleszczuk, P., Al-Wabel, M., Bolan, N., Tsang, D. C. W., Kim, K. H., and Ok, Y. S. (2017). “Advances and future directions of biochar

- characterization methods and applications,” *Critical Reviews in Environmental Science and Technology* 47(23), 2275-2330.
<https://doi.org/10.1080/10643389.2017.1421844>
- Ignatavičius, G., Satkūnas, J., Grigienė, A., Nedveckytė, I., Hassan, H. R., and Valskys, V. (2021). “Heavy metals in sapropel of lakes in suburban territories of Vilnius (Lithuania): Reflections of paleoenvironmental conditions and anthropogenic influence,” *Minerals* 12(1), article 17. <https://doi.org/10.3390/min12010017>
- Jagustyn, B., Kmieć, M., Smędowski, Ł., and Sajdak, M. (2017). “The content and emission factors of heavy metals in biomass used for energy purposes in the context of the requirements of international standards,” *Journal of the Energy Institute* 90(5), 704-714. <https://doi.org/10.1016/j.joei.2016.07.007>
- Januševičius, T., Mažeikienė, A., Stepova, K., Danila, V., and Paliulis, D. (2024). “The removal of phosphorus from wastewater using a sewage sludge biochar: A column study,” *Water* 16(8), article 1104. <https://doi.org/10.3390/w16081104>
- Jarukas, L., Ivanauskas, L., Kasparaviciene, G., Baranauskaite, J., Marksa, M., and Bernatoniene, J. (2021). “Determination of organic compounds, fulvic acid, humic acid, and humin in peat and sapropel alkaline extracts,” *Molecules* 26(10), article 2995. <https://doi.org/10.3390/molecules26102995>
- Jones, C., and Jacobsen, J. (2005). *Plant Nutrition and Soil Fertility*, Montana State University Extension, Nutrient Management Module 2(11), 1-11.
- Kallis, K. X., Susini, G. A. P., and Oakey, J. E. (2013). “A comparison between *Miscanthus* and bioethanol waste pellets and their performance in a downdraft gasifier,” *Applied Energy* 101, 333-340.
<https://doi.org/10.1016/j.apenergy.2012.01.037>
- Kamga, P. L. W., Vitoussia, T., Bissoue, A. N., Nguimbous, E. N., Dieudjio, D. N., Bot, B. V., and Njeugna, E. (2024). “Physical and energetic characteristics of pellets produced from movingui sawdust, corn spathes, and coconut shells,” *Energy Reports* 11, 1291-1301. <https://doi.org/10.1016/j.egy.2024.01.006>
- Kamperidou, V. (2022). “Quality analysis of commercially available wood pellets and correlations between pellets characteristics,” *Energies* 15(8), article 2865.
<https://doi.org/10.3390/en15082865>
- Kaushik, Y., and Arora, P. (2024). “Investigating the sustainable energy generation potential of an invasive weed: *Lantana camara*,” *Environmental Science and Pollution Research* 31, 62493-62509. <https://doi.org/10.1007/s11356-024-35322-2>
- Kettenring, K. M., and Adams, C. R. (2011). “Lessons learned from invasive plant control experiments: A systematic review and meta-analysis,” *Journal of Applied Ecology* 48(4), 970-979. <https://doi.org/10.1111/j.1365-2664.2011.01979.x>
- Khan, I., Qi, S., Gul, F., Manan, S., Rono, J., Naz, M., Shi, X., Zhang, H., Dai, Z., and Du, D. (2023). “A green approach used for heavy metals ‘phytoremediation’ via invasive plant species to mitigate environmental pollution: A review,” *Plants* 12(4), article 725. <https://doi.org/10.3390/plants12040725>
- Klavins, M., Purmalis, O., Klavina, L., Niedrite, E., and Ansonė-Bertina, L. (2024). “Biomass of invasive plants as a resource for the development of the bioeconomy,” *BioResources* 19(4), article 9788. <https://doi.org/10.15376/biores.19.4.Klavins>
- Kujawska, J., Wojtaś, E., and Charmas, B. (2024). “Biochar derived from sewage sludge: The impact of pyrolysis temperature on chemical properties and agronomic potential,” *Sustainability* 16(18), article 8225. <https://doi.org/10.3390/su16188225>
- Li, Y., Cui, D., Tong, Y., and Xu, L. (2013). “Study on structure and thermal stability

- properties of lignin during thermostabilization and carbonization,” *International Journal of Biological Macromolecules* 62, 663-669.
<https://doi.org/10.1016/j.ijbiomac.2013.09.040>
- Liang, J., Wang, L., Shi, Y., Lin, S., Evrendilek, F., Huang, W., Chen, Z., Zhong, S., Yang, Z., and Liu, J. (2023). “Air and oxy-fuel incineration disposal of invasive biomass water lettuce (*Pistia stratiotes* L.): Performance, kinetics, flue gas emissions, mechanisms, and ash characteristics,” *Biomass Conversion and Biorefinery* 15(2), 2243-2262. <https://doi.org/10.1007/s13399-023-04853-y>
- Liao, R., Gao, B., and Fang, J. (2013). “Invasive plants as feedstock for biochar and bioenergy production,” *Bioresource Technology* 140, 439-442.
<https://doi.org/10.1016/j.biortech.2013.04.117>
- Lin, G., Wang, Y., Wu, X., Meng, J., Ok, Y. S., and Wang, C. H. (2025). “Enhancing agricultural productivity with biochar: Evaluating feedstock and quality standards,” *Bioresource Technology Reports* 29, article 102059.
<https://doi.org/10.1016/j.biteb.2025.102059>
- Lorenzo, P., and Morais, M. C. (2023). “Strategies for the management of aggressive invasive plant species,” *Plants* 12(13), article 2482.
<https://doi.org/10.3390/plants12132482>
- Macêdo, R. L., Haubrock, P. J., Klippel, G., Fernandez, R. D., Leroy, B., Angulo, E., Carniero, L., Musseau, C. L., Rocha, O., and Cuthbert, R. N. (2024). “The economic costs of invasive aquatic plants: A global perspective on ecology and management gaps,” *Science of the Total Environment* 908, article 168217.
<https://doi.org/10.1016/j.scitotenv.2023.168217>
- Marchante, H., Marchante, E., Verbrugge, L., Lommen, S., and Shaw, R. (2023). “Knowledge and perceptions of invasive plant biocontrol in Europe versus the rest of the world,” *Journal of Environmental Management* 327, article 116896.
<https://doi.org/10.1016/j.jenvman.2022.116896>
- de Mendiburu, F. (2023). *agricolae: Statistical Procedures for Agricultural Research*, R package version 1.3-7. <https://doi.org/10.32614/CRAN.package.agricolae>
- Miranda, T., Montero, I., Sepúlveda, F. J., Arranz, J. I., Rojas, C. V., and Nogales, S. (2015). “A review of pellets from different sources,” *Materials* 8(4), 1413-1427.
<https://doi.org/10.3390/ma8041413>
- Monedero, E., Pazo, A., Collado, R., Dura, O. J., and Hernández, J. J. (2024). “Analysis of fouling in domestic boilers fueled with non-woody biomass,” *Renewable Energy* 226, article 120459. <https://doi.org/10.1016/j.renene.2024.120459>
- Mong, G. R., Chong, C. T., Chong, W. W. F., Ng, J. H., Ong, H. C., Ashokkumar, V., Tran, M. V., Karmakar, S., Goh, B. H. H., and Mohd Yasin, M. F. M. (2022). “Progress and challenges in sustainable pyrolysis technology: Reactors, feedstocks and products,” *Fuel* 324, article 124777. <https://doi.org/10.1016/j.fuel.2022.124777>
- Mortadha, H., Kerrouchi, H. B., Al-Othman, A., and Tawalbeh, M. (2025). “A comprehensive review of biomass pellets and their role in sustainable energy: Production, properties, environment, economics, and logistics,” *Waste and Biomass Valorization*, 1-33. <https://doi.org/10.1007/s12649-024-02873-x>
- Muazu, R. I., and Stegemann, J. A. (2017). “Biosolids and microalgae as alternative binders for biomass fuel briquetting,” *Fuel* 194, 339-347.
<https://doi.org/10.1016/j.fuel.2017.01.019>
- Munné-Bosch, S. (2024). “Achieving the impossible: Prevention and eradication of invasive plants in Mediterranean-type ecosystems,” *Trends in Plant Science* 29(4),

- 437-446. <https://doi.org/10.1016/j.tplants.2023.11.007>
- Nguyen, C. T., Tungtakanpoung, D., Tra, V. T., and Kajitvichyanukul, P. (2022). “Kinetic, isotherm and mechanism in paraquat removal by adsorption process using corn cob biochar produced from different pyrolysis conditions,” *Case Studies in Chemical and Environmental Engineering* 6, article 100248. <https://doi.org/10.1016/j.cscee.2022.100248>
- Nieweś, D., Huculak-Mączka, M., Braun-Giwerska, M., Marecka, K., Tyc, A., Biegun, M., Hoffmann, K., and Hoffmann, J. (2022). “Ultrasound-assisted extraction of humic substances from peat: Assessment of process efficiency and products’ quality,” *Molecules* 27(11), article 3413. <https://doi.org/10.3390/molecules27113413>
- Ondrašek, G., Zovko, M., Kranjčec, F., Bubalo Kovačić, M., Husnjak, S., Čoga, L., Babić, D., Rašeta, D., Volarić, N., Fulajtar, E., Rashid, M. I., Včev, A., and Petrinec, B. (2021). “Wood biomass fly ash ameliorates acidic, low-nutrient hydromorphic soil and reduces metal accumulation in maize,” *Journal of Cleaner Production* 283, article 124650. <https://doi.org/10.1016/j.jclepro.2020.124650>
- Orecchio, S., Amorello, D., Barreca, S., and Valenti, A. (2016). “Wood pellets for home heating: Can they be considered environmentally friendly fuels? Polycyclic aromatic hydrocarbons (PAHs) in their ashes,” *Microchemical Journal* 124, 267-271. <https://doi.org/10.1016/j.microc.2015.09.003>
- Palai, S. P., Sahoo, B. P., Senapati, S., Panda, A. K., Bastia, T. K., Rath, P., and Parhi, P. K. (2024). “A review on exploring pyrolysis potential of invasive aquatic plants,” *Journal of Environmental Management* 371, article 123017. <https://doi.org/10.1016/j.jenvman.2024.123017>
- Parikh, J., Channiwal, S. A., and Ghosal, G. K. (2007). “A correlation for calculating elemental composition from proximate analysis of biomass materials,” *Fuel* 86(12-13), 1710-1719. <https://doi.org/10.1016/j.fuel.2006.12.029>
- Posit team. (2025). *RStudio: Integrated Development Environment for R*, Posit Software, PBC, Boston, MA, USA.
- Pradhan, P., Mahajani, S. M., and Arora, A. (2018). “Production and utilization of fuel pellets from biomass: A review,” *Fuel Processing Technology* 181, 215-232. <https://doi.org/10.1016/j.fuproc.2018.09.021>
- da Silva, S. B., Arantes, M. D. C., de Andrade, J. K. B., Andrade, C. R., Carneiro, A. D. C. O., and de Paula Protásio, T. (2020). “Influence of physical and chemical compositions on the properties and energy use of lignocellulosic biomass pellets in Brazil,” *Renewable Energy* 147, 1870-1879. <https://doi.org/10.1016/j.renene.2019.09.131>
- Puri, L., Hu, Y., and Naterer, G. (2024). “Critical review of the role of ash content and composition in biomass pyrolysis,” *Frontiers in Fuels* 2, article 1378361. <https://doi.org/10.3389/ffuel.2024.1378361>
- Qian, C., Li, Q., Zhang, Z., Wang, X., and Hu, J., and Cao, W. (2020). “Prediction of higher heating values of biochar from proximate and ultimate analysis,” *Fuel* 265, 116925. <https://doi.org/10.1016/j.fuel.2019.116925>
- Quirantes, M., Calvo, F., Romero, E., and Nogales, R. (2016). “Soil-nutrient availability affected by different biomass-ash applications,” *Journal of Soil Science and Plant Nutrition* 16(1), 159-163. <http://dx.doi.org/10.4067/S0718-95162016005000012>
- Rai, P. K., and Singh, J. S. (2020). “Invasive alien plant species: Their impact on environment, ecosystem services and human health,” *Ecological Indicators* 111, article 106020. <https://doi.org/10.1016/j.ecolind.2019.106020>

- Reza, M. S., Afroze, S., Bakar, M. S., Saidur, R., Aslfattahi, N., Taweekun, J., and Azad, A. K. (2020). "Biochar characterization of invasive *Pennisetum purpureum* grass: Effect of pyrolysis temperature," *Biochar* 2, 239-251. <https://doi.org/10.1007/s42773-020-00048-0>
- Rupasinghe, R. L., Perera, P., Bandara, R., Amarasekera, H., and Vlosky, R. (2023). "Insights into properties of biomass energy pellets made from mixtures of woody and non-woody biomass: A meta-analysis," *Energies* 17(1), article 54. <https://doi.org/10.3390/en17010054>
- Sadeq, A., Heinrich, D., Pietsch-Braune, S., and Heinrich, S. (2023). "Influence of oscillating water content on the structure of biomass pellets," *Powder Technology* 426, article 118631. <https://doi.org/10.1016/j.powtec.2023.118631>
- Šáner, A., Ambye-Jensen, M., Jensen, S. K., Vorkamp, K., Ceccato, M., and Smith, A. M. (2025). "Biochar produced from bio-refined herbaceous fibre residue for feed and technical purposes," *Journal of Analytical and Applied Pyrolysis* 187, article 107004. <https://doi.org/10.1016/j.jaap.2025.107004>
- Sarker, T. R., Nanda, S., Meda, V., and Dalai, A. K. (2023). "Densification of waste biomass for manufacturing solid biofuel pellets: A review," *Environmental Chemistry Letters* 21(1), 231-264. <https://doi.org/10.1007/s10311-022-01510-0>
- Selvarajoo, A., Wong, Y. L., Khoo, K. S., Chen, W. H., and Show, P. L. (2022). "Biochar production via pyrolysis of citrus peel fruit waste as a potential usage as solid biofuel," *Chemosphere* 294, article 133671. <https://doi.org/10.1016/j.chemosphere.2022.133671>
- Senator, S. A., and Rozenberg, A. G. (2017). "Assessment of economic and environmental impact of invasive plant species," *Biology Bulletin Reviews* 7, 273-278. <https://doi.org/10.1134/S2079086417040089>
- Sippula, O., Lamberg, H., Leskinen, J., Tissari, J., and Jokiniemi, J. (2017). "Emissions and ash behavior in a 500 kW pellet boiler operated with various blends of woody biomass and peat," *Fuel* 202, 144-153. <https://doi.org/10.1016/j.fuel.2017.04.009>
- Sokolova, A. K., and Tulina, E. I. (2020). "Legal aspects of invasive alien plant species regulation," *Environmental Policy and Law* 49(4-5), 300-305. <https://doi.org/10.3233/EPL-190177>
- Song, Y., Zhang, H., Zhang, Y., Li, W., Xuan, X., and Yao, J. (2024). "Influence of crystal structure of polymorphic cotton cellulose on the adsorption and photocatalysis properties of biochar TiO₂ composites," *Cellulose* 31(15), 9087-9110. <https://doi.org/10.1007/s10570-024-06156-5>
- Sørmo, E., Dublet-Adli, G., Menlah, G., Flatabø, G. Ø., Zivanovic, V., Carlsson, P., Almås, Å., and Cornelissen, G. (2024). "Heavy metals in pyrolysis of contaminated wastes: Phase distribution and leaching behaviour," *Environments* 11(6), article 130. <https://doi.org/10.3390/environments11060130>
- Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., and Henriksen, U. B. (2012). "Recent developments in biomass pelletization—A review," *BioResources* 7(3), 4451-4490. <https://doi.org/10.15376/biores.7.3.stelte>
- Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., and Sing, K. S. (2015). "Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report)," *Pure and Applied Chemistry* 87(9-10), 1051-1069. <https://doi.org/10.1515/pac-2014-1117>
- Tu, P., Zhang, G., Wei, G., Li, J., Li, Y., Deng, L., and Yuan, H. (2022). "Influence of

- pyrolysis temperature on the physicochemical properties of biochars obtained from herbaceous and woody plants,” *Bioresources and Bioprocessing* 9(1), article 131. <https://doi.org/10.1186/s40643-022-00618-z>
- University of Minnesota (2018). “Potassium for crop production,” (<https://extension.umn.edu/phosphorus-and-potassium/potassium-crop-production>), Accessed June 16, 2025.
- Vassilev, S. V., Vassileva, C. G., Song, Y. C., Li, W. Y., and Feng, J. (2017). “Ash contents and ash-forming elements of biomass and their significance for solid biofuel combustion,” *Fuel* 208, 377-409. <https://doi.org/10.1016/j.fuel.2017.07.036>
- Vaverková, M. D., Paleologos, E. K., Adamcová, D., Podlasek, A., Pasternak, G., Červenková, J., Skutník, Z., Koda, E., and Winkler, J. (2022). “Municipal solid waste landfill: Evidence of the effect of applied landfill management on vegetation composition,” *Waste Management and Research* 40(9), 1402-1411. <https://doi.org/10.1177/0734242X221079304>
- Vershinina, K. Y., Dorokhov, V. V., Nyashina, G. S., and Romanov, D. S. (2024). “Influence of binders on the properties of pellets based on wood waste,” *Coke and Chemistry* 67(2), 104-111. <https://doi.org/10.3103/S1068364X24701291>
- Vincevica Gaile, Z., Stankevica, K., Irtiseva, K., Shishkin, A., Obuka, V., Celma, S., Ozolins, J., and Klavins, M. (2019). “Granulation of fly ash and biochar with organic lake sediments - A way to sustainable utilization of waste from bioenergy production,” *Biomass and Bioenergy* 125, 23-33. <https://doi.org/10.1016/j.biombioe.2019.04.004>
- Vincevica Gaile, Z., Zhylina, M., Shishkin, A., Ansone Bērtiņa, L., Klavins, L., Arbidans, L., Dobkevica, L., Zekker, I., and Klavins, M. (2025). “Selected residual biomass valorization into pellets as a circular economy-supported end-of-waste,” *Cleaner Materials* 15, article 100295. <https://doi.org/10.1016/j.clema.2025.100295>
- Weidlich, E. W., Flórido, F. G., Sorrini, T. B., and Brancalion, P. H. (2020). “Controlling invasive plant species in ecological restoration: A global review,” *Journal of Applied Ecology* 57(9), 1806-1817. <https://doi.org/10.1111/1365-2664.13656>
- Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. R package version 3.5.2. Available at: <https://CRAN.R-project.org/package=ggplot2>. Accessed June 22, 2025.
- Wu, J., Wang, T., Shi, N., and Pan, W. P. (2022). “Insight into mass transfer mechanism and equilibrium modelling of heavy metals adsorption on hierarchically porous biochar,” *Separation and Purification Technology* 287, article 120558. <https://doi.org/10.1016/j.seppur.2022.120558>
- Xu, H., Han, Y., Wang, G., Deng, P., and Feng, L. (2022). “Walnut shell biochar based sorptive remediation of estrogens polluted simulated wastewater: Characterization, adsorption mechanism and degradation by persistent free radicals,” *Environmental Technology and Innovation* 28, article 102870. <https://doi.org/10.1016/j.eti.2022.102870>
- Yang, L., Deng, Y., Shu, Z., Chen, Q., Yang, H., and Tan, X. (2022). “Application of invasive plants as biochar precursors in the field of environment and energy storage,” *Frontiers in Environmental Science* 10, article 902915. <https://doi.org/10.3389/fenvs.2022.902915>
- Yildiz, M. J., Wurzer, C., Robinson, T., Wietecha, J., and Mašek, O. (2025). “Biochar from pellets: Influence of binders and pyrolysis temperature on physical properties of pyrolyzed pellets,” *Sustainable Materials and Technologies* 43, article e01327.

<https://doi.org/10.1016/j.susmat.2025.e01327>

Zhao, H., Zhou, F., Ma, C., Wei, Z., and Long, W. (2022). “Bonding mechanism and process characteristics of special polymers applied in pelletizing binders,” *Coatings* 12(11), article 1618. <https://doi.org/10.3390/coatings12111618>

Zhou, H., Long, Y., Meng, A., Chen, S., Li, Q., and Zhang, Y. (2015). “A novel method for kinetics analysis of pyrolysis of hemicellulose, cellulose, and lignin in TGA and macro-TGA,” *RSC Advances* 5(34), 26509-26516. <https://doi.org/10.1039/c5ra02715b>

Zihare, L., Soloha, R., and Blumberga, D. (2018). “The potential use of invasive plant species as solid biofuel by using binders,” *Agronomy Research* 16(3), 923-935. <https://doi.org/10.15159/AR.18.102>

Zubair, M., Mu’azu, N. D., Jarrah, N., Blaisi, N. I., Aziz, H. A., and Al-Harhi, M. A. (2020). “Adsorption behaviour and mechanism of methylene blue, crystal violet, eriochrome black T, and methyl orange dyes onto biochar-derived date palm fronds waste produced at different pyrolysis conditions,” *Water, Air, and Soil Pollution* 231, 1-19. <https://doi.org/10.1007/s11270-020-04595-x>

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