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Bioenergy Potential of Europe's Perennial and Biennial Wildflowers: A Combustion Performance Benchmark

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The European Commission prioritizes addressing environmental issues like agrobiodiversity loss within a thriving bioeconomy's defossilization. This study investigates eight native European herbaceous flowering wild plant species (WPS) like common tansy (*Tanacetum vulgare* L.) and wild teasel (*Dipsacus fullonum* L.) as co-substrates for pellet combustion, aiming for more biodiversity-friendly bioenergy cropping systems. A long-term field trial in southwest Germany examined dry matter (DM) yield and biochemical composition's influence on combustion properties for these WPS and two common bioenergy crops, *Miscanthus* (*Miscanthus x giganteus* Greef et Deuter) and *Sida* (*Sida hermaphrodita* L. var. Rusby), over two growing seasons. All eight WPS showed suitable combustion properties, comparable to *Sida*, with significantly higher ash melting temperatures than *Miscanthus*. This is largely attributed to elevated calcium (5.6–15.3 mg g^{-1} DM) and magnesium (0.6–2.4 mg g^{-1} DM) contents. A consistent WPS biomass composition is suggested by no significant year effect. Additionally, lower SO_2 and HCl fugacity indicated more environmentally friendly combustion than *Miscanthus*. However, only a few WPS matched *Miscanthus's* high DM yield (6.0–12.3 Mg ha^{-1}). This underscores the need for broader WPS investigation to find effective combined solutions for bioenergy and rural environmental protection.

1. Introduction

Biofuel is considered to be one of the seven "Rainbow Energies" available for electricity generation.[1] Therefore, it can be a key energy source in fossil free European energy systems.[2–4] Perennial bioenergy crops (PBCs) such as poplar (*Populus* spp.),[5, 6] *Miscanthus* (*Miscanthus* ANDERSSON),[7–9] and common tansy (*Tanacetum vulgare* L.)[10] play a vital role in making this transition more social-ecologically sustainable by providing additional ecosystem services, e.g., decarbonization, erosion mitigation and habitat networking.[11] For instance, the production of pellets from *Miscanthus* has been shown to have a significantly reduced environmental impact in comparison to conventional substrates, such as sawmill dust.[12, 13] PBCs can be grown on marginal agricultural land[6, 14–17] with low risk indirect land use change effects on food crop cultivation[18] and beneficial effects on both soil carbon sequestration[19] and climate regulation.[20] With regard to climate change adaptation, the extensive range of PBCs offers the potential for the development of resilient perennial bioenergy cropping systems. This is because both PBCs that require warmth, such as giant reed (*Arundo donax* L.), and those that are adapted to cooler regions, such as reed canary grass (*Phalaris arundinacea* L.), can be included in future-proof

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Figure 1. Strip cultivation of perennial wild plant species (here mainly common tansy (*Tanacetum vulgare* L.) and mugwort (*Artemisia vulgaris* L.)) on a site near Hohenheim (March 2024) to improve landscape heterogeneity and support biodiversity.

perennial bioenergy cropping systems. In cooler regions, such as those where reed canary grass is native, recent projections indicate that this species may become more suitable for cultivation even under the 8.5 RCP climate change scenario in Europe.[21] However, there is a growing need for more diverse bioenergy cropping systems in order to meet the increasing demand for biodiversity-friendly cropping systems.[22–24] In this context, perennial flower-rich wild plant species (WPS) were proposed to enrich agrobiodiversity at both spatial and temporal scales.[25–28] Wild flower strips (**Figure 1**) are known to help improving biocontrol agents living conditions and thus reducing the need for chemical pesticide applications.[29–31]

The findings indicate that an increase in landscape heterogeneity has a more pronounced positive impact on agrobiodiversity than a transition from conventional to organic farming practices alone.[32, 33] This makes WPS relevant across all farming systems, and thus, not only for organic but also for conventionally managed farms or those farms following an intermediate approach like mineral-ecological farming.[34] Moreover, previous studies have shown that the biomass from several European WPS such as common tansy (*Tanacetum vulgare* L.), mugwort (*Artemisia vulgaris* L.), and common knapweed (*Centaurea jacea* L.) could meet the high quality standards as fuel for residential use[35, 36] and could thus be used as sustainable co-substrate for pellet production when harvested in winter each year.[37] Hence, if biomass for thermochemical conversion is required in a region, WPS might become a key co-substrate for providing both, the biomass and other ecosystem services.[11, 38] This could enable the establishment of bioenergy generation practices that are both socially and ecologically sustainable.

However, the spectrum of native WPS strongly differs between regions[27] and therefore one or two WPS are insufficient for upscaling. This study therefore examines the combustion quality of the biomasses of a range of WPS native to Central Europe and compares them with common perennial bioenergy crops used for combustion such as *Miscanthus* × *giganteus* Greef et Deuter (hereafter referred to as *Miscanthus*)[8] and *Sida hermaphrodita* L. var. Rusby (hereafter referred to as *Sida*).[39] The main research question guiding this study is whether the WPS available for selection include any that are comparable to or better than *Miscanthus* or *Sida* in terms of their combustion properties.

2. Experimental Section

Since 2014, a long-term field trial has been conducted on arable land near the University of Hohenheim (southwest Germany, 48°42′56.8″N 9°12′53.1″E) to evaluate the performance of common and novel perennial biomass crops and cropping systems. A comprehensive description of the site characteristics and the establishment methods employed in the field trial has been provided in a previous study, undertaken in the context of other research questions.[40] Accordingly, only the most important details are elucidated herein, with all other information sourced from the latter publication. A more detailed description of the experiment conducted from 2019 is provided (e.g., the selection of the WPS, the weather conditions, and additional analyses), as this information has not yet been published.

2.1. Site Description

The plants were cultivated in a humid-temperate climate at an altitude of 400 m above sea level (48.71504 latitude and 9.2113 longitude).[28] The climatic site conditions were characterized by an average annual temperature of 10.7 °C, and by an annual mean precipitation of 685 mm (**Table 1**). However, there were negative climatic water balances observed each year except in years 2017, 2019, and 2024 (**Figure 2**, Table S1, Supporting Information).

The soil type of the site is Luvisol with an average pH of 6.55 (as of February 2022). The proceeding crops were winter wheat (harvested August 2013) followed by a cover crop mix of black oat and beet during winter 2013–2014. The soil was prepared by ploughing (20–25 cm depth) on 4th February 2014 followed by two rotary harrow applications (8–10 cm depth) on 28th February. The soil texture can be described as clay loam.[28] According to elemental analysis in the same year, 100 g of soil contained an average of 16.0 mg potassium oxide and 10.8 mg phosphorus pentoxide.

The main chemical soil properties are presented in **Table 2**. In addition, the apparent soil electrical conductivity (EC_a) was measured using an EM38 (Geonics, Canada) in vertical mode[41] in accordance with Von Cossel et al., 2019.[42] No heterogeneity of EC_a was found. The average absolute EC_a ranged between 21 and 23 mS m^{-1} which refers to sandy loam.[43]

Table 1. Ten-year mean annual climatic conditions at the field trial during the whole cultivation period so far (2014–2024).

Parameter	Value	Unit
Mean annual temperature	10.7	°C
Mean annual climatic water balance	−72	mm
Mean annual global radiation	1234	Wh m^{-2}
Mean annual precipitation sum	685	mm
Mean annual sunshine duration	2051	h

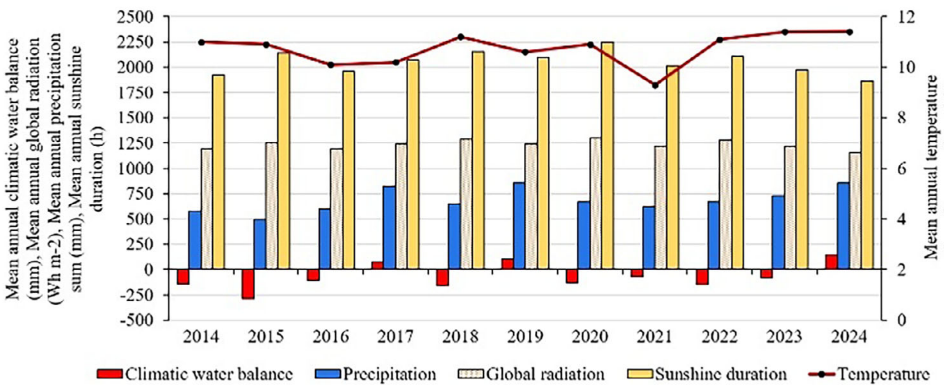

Figure 2. Climatic conditions at the field trial site from the year of establishment until 2024.

2.2. Plant Species

Data from eight different perennial WPS native to Europe were analyzed (**Table 3**). Samples of the bioenergy crops *Sida* and *Miscanthus* were also examined as comparative species.

2.3. Layout and Management of Field Trial

For the wild plant mixtures (WPM), five replicates were integrated, because a high variance was expected. In contrast, the number of replicates for *Miscanthus* and *Sida* was set to three. The plots with WPM and *Sida*, as well as the plots with subsequently established *Miscanthus* were distributed over a total of six rows with nine plots each, together with other crops such as maize and winter triticale. The square areas of the individual plots were 36 m^2 each.

Two distinct WPM (S1 and S2) were sown in three different establishment variants, across 24 of the 54 total plots.[40] The seed mixtures employed in this study were "S1"—"Wildacker-Wildaesung-Wilddeckung" from Rieger-Hofmann GmbH and "S2"—"BG70" from Saaten Zeller GmbH.[28] Both seed mixtures were sourced from 2016 and were applied with a seed density of 10 kg ha^{-1} at a row spacing of 15 cm.[51] The establishment variants for the respective samples are as follows:

- Establishment variant "E1": WPM sown solely,
- Establishment variant "E2": WPM sown under maize,
- Establishment variant "E3": WPM sown after barley.[40]

The three distinct methodologies utilized to generate these establishment variants are elucidated in the publication by Vollrath et al., 2012[27] which provides a comprehensive account of these techniques.

All crops received 100 kg nitrogen (N) ha^{-1} via mineral fertilizer, in addition to the mineral N resulting from mineralization of organic matter in the soil. Two exceptions were made with regard to fertilization: firstly, in 2014, no fertilization was carried out due to the high contents of soil mineral N (see Table 1), and secondly, in 2019 and 2020, the crops were not fertilized due to technical reasons.

Table 2. Soil properties at the beginning of the field trial in March 2014.

Parameter	Value	Soil depth [cm]
Soil mineral nitrogen (kg ha^{-1})	65.9 ± 20.8	0–30
	24.1 ± 5.6	30–60
	19.7 ± 8.6	60–90
	109.7 ± 30.8	0–90
pH	6.3 ± 0.1	0–30
P_2O_5 (mg 100 g^{-1})[a)]	9.2 ± 1.5	0–30
K_2O (mg 100 g^{-1})[a)]	15.8 ± 2.5	0–30
Mg (mg 100 g^{-1})[b)]	13.9 ± 0.7	0–30
C_{org} (% of dry soil)	1.33	0–30

[a)] CAL-Extract VDLUFA; [b)] $CaCl_2$-Extract VDLUFA.

2.4. Biomass Harvesting and Sample Collection

At harvest, the following parameters were considered: sampling area, total fresh matter, number of stems and number of plants of the total sample, and plant height.

Miscanthus and *Sida* were harvested manually (2 m^2 per plot) each year in March, beginning in 2015. The remaining aboveground biomass of each plot was removed immediately afterward. Since 2014, the WPS were harvested manually (2 m^2 per plot) each year in late summer until 2020. The remaining aboveground biomass of each plot was removed immediately afterward, except for the harvest in 2020. In that year, the remaining aboveground biomass was left on the field until March 2021. For this study, the WPS samples were harvested manually on 24th and 25th March in 2021, and 29th March in 2022, respectively, whereby the soil coverage per plant was estimated individually. For each WPS, the same plots were selected for sampling on an annual basis. The number of replicates per crop (n = 2) was constrained by the number of representative plots available.

Miscanthus samples were taken from nine plots in 2021. Of these, four were taken from a plot with a *Miscanthus* monoculture (*Miscanthus* REF), three from a plot with an establishment of *Miscanthus* under maize (*Miscanthus* MUM) and two from a plot with an establishment of *Miscanthus* intercropped with yellow melilot or woad (*Isatis tinctoria* L.). In 2022, *Miscanthus* samples were only taken from four plots. In that year, two samples

Table 3. Investigated species of wild plants and comparative species *Sida* and *Miscanthus* with scientific and common names.

Scientific name	Common name	Family	Life cycle	Refs.
Tanacetum vulgare L.	Common tansy	Asteraceae	Perennial	[44]
Centaurea nigra L.	Common knapweed	Asteraceae	Perennial	[27, 45]
Dipsacus fullonum L.	Wild teasel	Caprifoliaceae	Biennial	[44]
Artemisia vulgaris L.	Mugwort	Asteraceae	Perennial	[27, 46]
Origanum vulgare L.	Oregano/dost	Lamiaceae	Perennial	[44]
Melilotus officinalis L.	Yellow melilot	Fabaceae	Biennial	[44]
Oenothera biennis L.	Common evening primrose	Onagraceae	Biennial	[47]
Arctium lappa L.	Greater burdock	Asteraceae	Biennial	[48]
Miscanthus × giganteus (Greef et Deuter)	*Miscanthus*/Chinese reed	Poaceae	Perennial	[49]
Sida hermaphrodita L. var. Rusby	*Sida*/Virginia mallow/Virginia fanpetals	Malvaceae	Perennial	[50]

were collected from *Miscanthus*-REF plots and from *Miscanthus* MUM plots.

An attempt was made to take samples of the respective species from the same plot in both years to ensure comparability. This was achieved for all but one of the samples: yellow melilot was taken from plot 51 in 2021 and from plot 15 in 2022. This was due to the absence of any individual of the plant species in the corresponding plot from the previous year. In addition, data on alfalfa could only be collected in the 2021 harvest year, as no example of this species could be found in 2022.

2.5. Sample Processing and Preparation

The methodology employed in the 2022 harvest is delineated below. The harvesting and preparation process in the 2021 harvest year is identical to that of 2022 in terms of the general process steps. However, it was not recorded in such detail, which is why slight deviations in details such as the storage time are possible.

After the plants were cut 2-5 cm above the ground, the number of stems in the sample was counted in the field and their weight was determined using a field scale (Sf-550, G&G GmbH, Kaarst, Germany). Representative subsamples were then taken from each of the harvested samples.

These samples were divided into coarse pieces and then packed in perforated, labelled plastic bags and weighed using a scale (F61S-*D2, Sartorius Werkzeuge GmbH & Co. KG Ratingen, Germany). The dry weight of the entire samples was then determined after drying (VTU 125/200, formerly: Vötsch Industrietechnik/today: Weiss Technik GmbH, Reiskirchen, Germany) at 60 °C for ≈24 h. Immediately after removal, the dry mass of the samples was determined in order to calculate both the dry matter content and the dry matter yield for each sample.

Subsequently, the entire plant samples including inflorescence, leaves and stems were ground in a cutting mill (SM200 stainless, Retsch GmbH, Haan, Germany) at a sieve diameter of 1 mm. The ground sample was mixed in the collecting container to ensure homogeneity of the sample. The samples were checked for fineness and further used for the laboratory tests.

2.6. Procedures for Dry Matter and Elemental Analysis

First, the finely ground and homogenized samples were transferred to small, sealable plastic containers for more convenient handling and subsequent analysis in the laboratory. Then the dry substance determination was carried out in accordance with Chapter 3.1 in VDLUFA Method Book III. For this purpose, a second drying was conducted at 105 °C for a duration of 4 h in porcelain crucibles within the drying oven (FD53, Binder, Tuttlingen, Germany), whereby the samples were weighed before and after drying.

The mineral analysis was conducted in accordance with the methodology delineated in Chapter 10.8.1 of the VDLUFA Method Book III. In this method, the elements to be analyzed are initially dissolved, after which they can be measured using atomic absorption spectrometry (AAS), plasma emission spectrometry (ICP-OES), plasma mass spectrometry (ICP-MS) or other appropriate methods.[52]

Of each dried sample, a homogenized subsample of 0.5 g was digested by adding 1 mL of water (H_2O), 8 mL of concentrated nitric acid (HNO_3) and 5 mL of 30% hydrogen peroxide (H_2O_2) for ≈58 min in a microwave digestion system (ETHOS.lab with MAXI-44 rotor, MLS Mikrowellen-Labor-Systeme GmbH, Leutkirch, Germany).

The solutions were then used to quantify the elements silicon (Si), phosphorus (P), potassium (K), calcium (Ca) and

Table 4. Results of the type 3 fixed effects tests for the dry matter content (DMC), the ash content (Ash) and the dry matter yield (DMY).

Parameter[a)]	Effect	Num DF	Den DF	*F*-value	Pr > *F*
DMC	Year	1	30	2.98	0.0946
	Crop	10	30	13.01	**<.0001**
	Year × Crop	10	30	2.38	**0.0323**
Ash	Year	1	30	0.38	0.5398
	Crop	10	30	13.58	**<.0001**
	Year × Crop	10	30	0.8	0.6297
DMY	Year	1	30	24.43	**<.0001**
	Crop	10	30	5.43	**0.0001**
	Year × Crop	10	30	2.17	**0.0498**

a) Significant effects shown in bold.

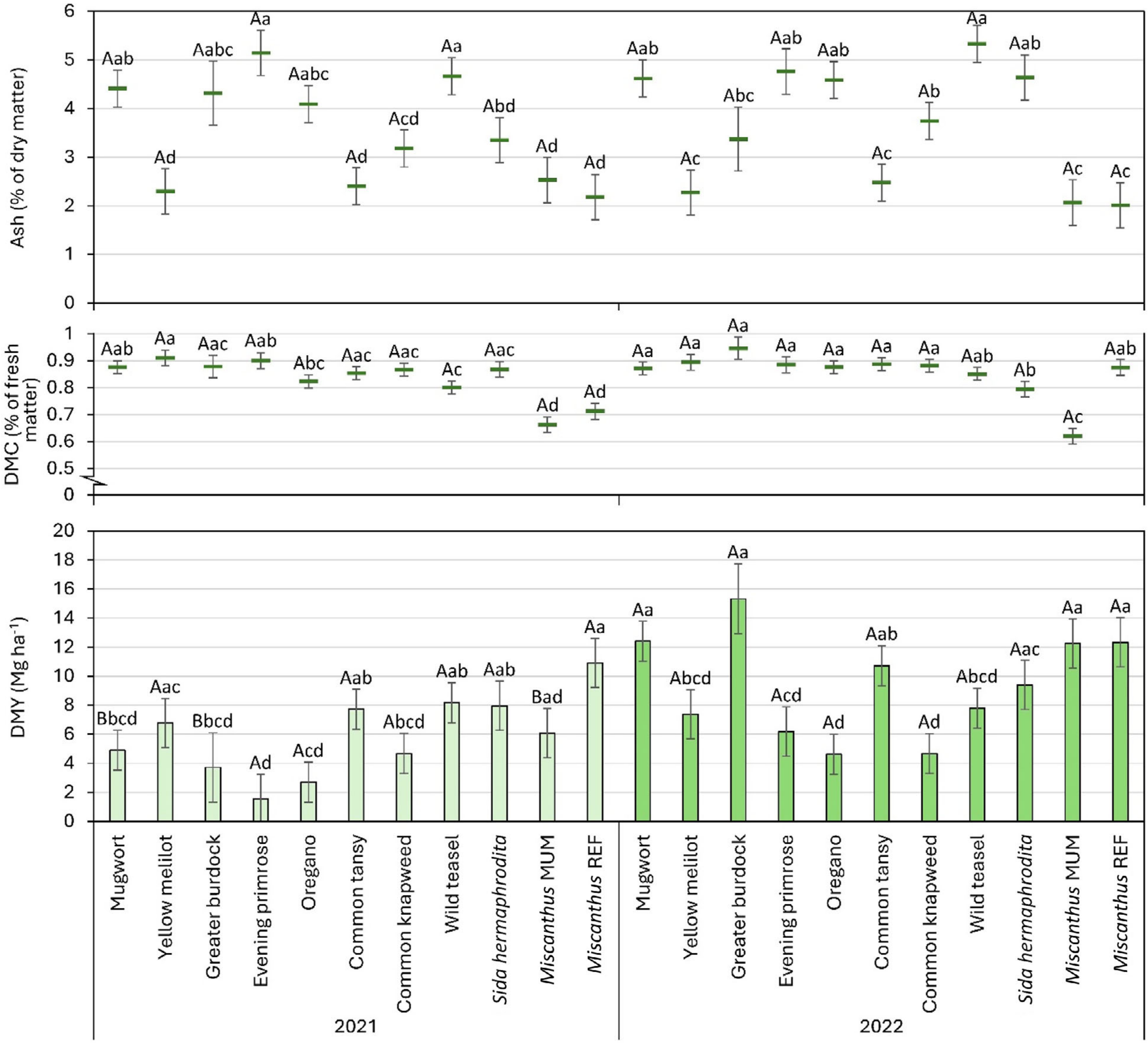

Figure 3. Estimated mean values of ash content (Ash), dry matter content (DMC) and dry matter yield (DMY) from the 2021 and 2022 harvest years with standard errors. Different capital and small letters denote significant ($p < 0.05$) differences between years within crops and between crops within years, respectively.

magnesium (Mg) via optical emission spectrometry with inductively coupled plasma analysis (ICP-OES, Agilent 5110, Agilent Technologies, Inc., Santa Clara, USA), in accordance with the specifications outlined in Chapter 8.10 of the VDLUFA Method Book Volume II, 2017. The quantitative determination was carried out using a linear calibration with the respective standard solutions.

2.7. Ash Melting Process and Scoring

The ash determination and ash melting behavior of the samples was carried out in alignment with Chapter 8.1 of VDLUFA Method Book III[52] as outlined below.

The ash melting behavior was assessed using the method of Tonn et al., 2012.[53] At first, ash was prepared at 550 °C for ≈9 h in an electric muffle furnace (KLS 45/11 (T_{max} 1100 °C) Thermconcept Dr. Fischer GmbH & Co KG, Bremen, Germany) by using biomass samples and the size of sample was varied from 20 to 25 g depending on ash content. With an ash content of >2.5%, ≈20 g were weighed and with an ash content of 2%, at least 25 g were weighed. To monitor ash melting behavior 100 mg of ash per sample was transferred to four ceramic combustion boats (Lab Logistics group GmbH, Meckenheim, Germany), each treated at 800, 900, 1000, or 1100 °C, for 2 h in a muffle furnace (KLS 45/11 and KLS 45/12 (T_{max} 1200 °C) Thermconcept Dr. Fischer GmbH & Co KG, Bremen, Germany), heated at an average rate of 10 °C min^{-1} until the desired heating temperature was reached, followed by a 2-h cooling period in a

Table 5. Results of the type 3 fixed effects tests for the ash mineral contents of potassium, phosphorus, magnesium, calcium, and the sum of these.

Parameter[a)]	Effect	*F*-value	Pr > *F*
Potassium (K)	Year	2.51	0.3582
	Crop	13.75	**<.0001**
	Year × Crop	3.76	**0.0029**
Phosphorus (P)	Year	1.33	0.2572
	Crop	5.25	**0.0002**
	Year × Crop	1.73	0.1201
Magnesium (Mg)	Year	0.06	0.8078
	Crop	38.17	**<.0001**
	Year × Crop	1.83	0.0973
Calcium (Ca)	Year	2.49	0.125
	Crop	20.79	**<.0001**
	Year × Crop	1.18	0.3418
Sum[a]	Year	2.49	0.125
	Crop	20.79	**<.0001**
	Year × Crop	1.18	0.3418

[a)] Significant effects shown in bold.

desiccator.

The samples were individually removed from the desiccator for examination and initially assessed mechanically using a spatula. The next step of the examination involved the utilization of a stereomicroscope (Stemi DV4, Carl Zeiss AG, Oberkochen, Germany), for the observation of the ash structure and the glass phase. The evaluation was conducted in accordance with the classification system for ash fusion classes proposed by Tonn et al., 2012.[53] The three observations were recorded in the form of scoring levels with values ranging from one to five, and values were recorded in the single-digit comma range. The values obtained from the partial assessments of the three properties were aggregated to derive an overall score for the sample. The entire scoring was repeated once by a second person.

Hot stage microscopy (HSM) was used for the determination of the melting behavior of the ashes. Both ash characterization methods complemented each other. The primary method facilitated the determination of ash properties after annealing at a desired temperature, while the secondary method provided insight into the ash behavior during uninterrupted heating to a maximum temperature. Therefore, about 120 mg of ash was pressed into a cylindrical pellet with a diameter of 5 mm (strength ≈1.5 kN). Due to varying density of the sample material, the sample height varied between 4 and 7 mm. The pellets were placed centrally within a temperature-calibrated tube furnace (ERO 4/30, Prüfer Industrieofenbau, Neuss, Germany), heated from room temperature up to 1370 °C at 5 K min^{-1}. A CCD camera was placed behind the furnace outlet, and photos were taken at every degree Celsius, starting from 500 °C. A corresponding in-house software evaluated the change of the sample shape depending on the temperature change. Depending on this information, conclusions can be drawn from the ash melting behavior.[54] The evaluation was based on the ratio of current sample height/original sample height (coefficient h_x/h_0) according to Pang et al.[54] The samples were weighed before and after the measurement to determine mass changes, e.g., caused by vaporization of ash constituents.

2.8. Thermodynamic Modeling

Thermodynamic equilibrium calculations were conducted to predict the formation of inorganic phases in ash constituents under gasification-like conditions, utilizing the FactSage 8.2 computational package.[55] The SGPS commercial database was employed for pure gaseous compounds and certain solid stoichiometric compounds. Furthermore, the GTOX database, developed collaboratively by Forschungszentrum Jülich and GTT-Technologies, was also referenced in this study.[56] The chemical composition of the relevant biomass ashes was incorporated into the thermodynamic equilibrium calculations. These calculations were performed under combustion conditions, specifically using an air-fuel ratio (lambda value) of 1.3.

2.9. Literature Research

The literature search was aimed at gathering background information and classifying the topic, as well as determining comparative values for the data collected. Relevant publications were identified using the search tools Scopus (Elsevier B.V., Amsterdam, NL) and Google Scholar (Google LLC, Mountain View, USA). The search included German and English-language literature, which is why the keywords were (partially) used in both languages for the search. Further publications were found through references of the selected publications and with the help of suggestions generated by Scopus. The Zotero software (Center for History and New Media, George Mason University, USA) was used to manage literature sources.

2.10. Calculations and Statistical Analysis

The evaluation was conducted using a reduced data set comprising only those species that were harvested in both years.

To calculate the plant density, the total number of plants was divided by the estimated area of the sample. The dry matter content (DMC) was calculated by dividing the dry matter of the sample by the fresh matter of the sample. In order to calculate the dry matter yield (DMY), the values for the dry matter content were extrapolated to an area of one hectare.

Both Microsoft Excel and the statistical program SAS 9.4 (SAS Institute Inc., Cary, USA/SAS Institute GmbH, Heidelberg, Germany) were used for the statistical analysis of the results. The data was analyzed using the "PROC MIXED" procedure, whereby the model can be described by the following equation (1):

$$y_{ij} = \mu + \alpha_j + \tau_i + e_{ij} + (\alpha\tau)_{ij} \quad (1)$$

μ = intercept; α_j = fixed effect of the *j*th year; τ_i = fixed effect for the *i*th plant species; e_{ij} = random deviation; $(\alpha\tau)_{ij}$ = interaction between year and plant species. For a letter-wise description of the pairwise comparisons, a SAS-macro[57] was used. Firstly, the interaction between the effects of year and plant species was analyzed using a Kenward–Roger analysis of variance.[58] A significance level of 0.05 was assumed. The mean values were then estimated using the least squares method, whereby the mean values for the individual years were calculated for the factors with a significant interaction effect between year and plant species and averaged over both harvest years for the remaining factors. In addition, the standard errors of the values were calculated in each case. Furthermore, letter plots were created using Microsoft Excel for the factors with non-significant year-plant species interactions.

3. Results

3.1. Harvest Data

The detailed results of the harvest measurements are comprised in Table S2 (Supporting Information). Plant height across both harvest years ranged from 61 to 261 cm (Table S2, Supporting Information), with *Miscanthus* and *Sida* achieving the maximum values. Within WPS, height varied from 61 (oregano, 2021) to 221 cm (mugwort, 2022).

Plant density ranged from a low of 1 plant m^{-2} (*Miscanthus*, common tansy, mugwort in 2021) to a high of 77 plants m^{-2} (common evening primrose, 2022). This maximum plant density for common evening primrose was significantly higher than its other recorded values of 8 to 21 plants m^{-2} (Table S2, Supporting Information). Only wild teasel approached this maximum with 56 plants m^{-2} (2021), while its other values spanned 11 to 32 plants m^{-2}. *Miscanthus* consistently exhibited the lowest densities, ranging from 1 to 2 plants m^{-2}.

3.2. Interaction between the Effects of Year and Plant Species

A preliminary analysis assessed the interaction between year and plant species to determine if data could be averaged across the two harvest years. The null hypothesis, assuming no significant interaction, was accepted for four parameters: P, Mg, Ca, and ash content (Table 4,5). Conversely, a significant year–species interaction ($p < 0.05$) was found for K, DMC, DMY (Table 4,5) and ash melting scores (see section 3.5.1), necessitating year-specific analysis for these factors.

3.3. DMC, Ash Content, and DMY

There was a significant effect of the crop for both DMC and ash content of the plant biomass (**Table 4**). For the DMY, a significant effect of the interaction of year × crop was found (Table 4).

3.3.1. Dry Matter Content (DMC)

In 2021, the estimated mean DMC of the WPS ranged from 80.1 ± 2.4% (wild teasel) to 91.5 ± 2.9% (yellow melilot). *Miscanthus* reached a DMC of 66.3 ± 2.9% (*Miscanthus* MUM) to 71.3 ± 2.9% (*Miscanthus* REF) (**Figure 3**), and *Sida* achieved a mean DMC of 86.8 ± 2.9%. In 2022, greater burdock achieved the highest value of 94.6 ± 4.2%, while wild teasel had the lowest value (85.1 ± 2.4%), as observed in the previous year. In contrast, the values for *Miscanthus* ranged from 62.0 ± 2.9% to 87.5 ± 2.9%, while the mean value for *Sida* was 79.4 ± 2.9% (Figure 3). While the year effect was not significant, significant differences between the crops were found (Figure 3).

3.3.2. Ash Content

The ash content is frequently employed as an indicator of combustion quality and provides valuable insights into the inorganic content present in the biomass.[59] The figure is expressed as a percentage of the dry mass. As no significant interaction between year and plant species was observed for the “ash content” parameter, the data can be averaged over the two harvest years. The estimated mean values of the ash contents of the examined plant species are illustrated in Figure 3. The highest value in terms of ash content was observed in wild teasel at 5.0 ± 0.3%, closely followed by common evening primrose (4.9 ± 0.3%). The *Miscanthus* samples achieved the lowest values with average values of 2.1 ± 0.3% (*Miscanthus* MUM) and 2.3 ± 0.32% (*Miscanthus* REF), respectively. Among the WPS, yellow melilot exhibited the lowest values at 2.3 ± 0.3%. Conversely, *Sida* exhibited an ash content of 4.0 ± 0.3%, which exceeded the mean value of *Miscanthus*, but remained lower than that of some WPS.

3.3.3. Dry Matter Yield (DMY)

The highest DMY of 10.9 t ha^{-1} ± 1.7 was recorded for *Miscanthus*. Among the WPS, the DMY amounted to values between 1.6 t ha^{-1} ± 1.7 (common evening primrose) and 8.2 t ha^{-1} ± 1.4 (wild teasel), whereby the values of oregano and common evening primrose were notably lower in comparison to the other species. *Sida* reached a value of 8.0 t ha^{-1} ± 1.7.

The DMYs were found to be higher in the second year for almost all species. The exceptions to this trend were wild teasel and common knapweed (see Figure 3). The latter had the second lowest value in crop year 2022 with a yield of 4.7 t ha^{-1} ± 1.4. The lowest DMY was observed for oregano (4.6 t ha^{-1} ± 1.4). In contrast, the highest DMY was calculated for greater burdock, with a yield of 15.3 t ha^{-1} ± 2.4. However, it is noteworthy that the same species only achieved a DMY of 3.7 t ha^{-1} ± 2.4 in the preceding year.

3.4. Mineral Content

A significant effect of the crop on the contents of P, K, Mg, and Ca was found (**Table 5**) with a significant interaction year × crop for K (Table 5).

Overall, *Miscanthus* showed a significantly lower sum of P, K, Mg, and Ca contents compared with all other crops (**Figure 4**).

3.4.1. Potassium (K)

Given the significant interaction between year and plant species, individual harvest years were analyzed separately (Figure 4). In

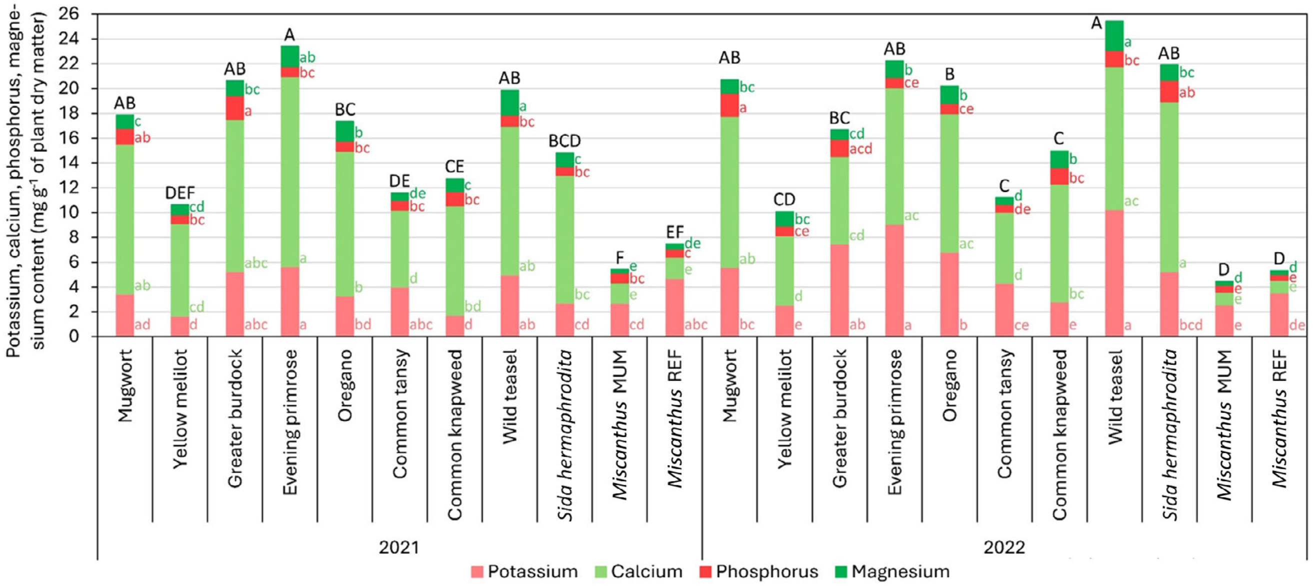

Figure 4. Overview of estimates for the mineral contents of the plant dry matter. Different capital and small letters denote significant ($p < 0.05$) differences between total mineral contents per crop within years and single mineral contents per crop within years, respectively. Estimate values and standard errors are provided in the annex (Table S4). The abbreviations "MUM" and "REF" denote different approaches of *Miscanthus* establishment back in 2016: establishment under maize (MUM) and sole establishment (REF).

2021, WPS K content ranged from 1.7 mg g^{-1} ± 1.3 (yellow melilot) to 5.7 mg g^{-1} ± 1.3 (common evening primrose). *Miscanthus* values spanned 2.7 mg g^{-1} ± 0.9 (*Miscanthus* MUM) to 4.7 mg g^{-1} ± 1.0 (*Miscanthus* REF), while *Sida's* average was 2.7 mg g^{-1} ± 1.0. Strikingly high K contents were observed in 2022 for wild teasel (10.2 mg g^{-1} ± 0.8) and common evening primrose (9.1 mg g^{-1} ± 1.4). In contrast, *Miscanthus* values in 2022 ranged narrowly from 2.5 mg g^{-1} ± 0.9 to 3.5 mg g^{-1} ± 1.0.

3.4.2. Phosphorus (P)

Given the absence of significant interaction between the effects of year and crop, it was reasonable to average the values for P over the years (Figure 4). On average over the two harvest years, the P content ranged between 0.6 mg g^{-1} ± 0.2 (*Miscanthus* REF) and 1.6 mg g^{-1} ± 0.3 (greater burdock). Among the WPS, the lowest content was found in common tansy with 0.7 mg g^{-1} ± 0.2. Overall, *Miscanthus* scored lower here, while *Sida* had an average value of 1.2 mg g^{-1} ± 0.2.

3.4.3. Magnesium (Mg) and Calcium (Ca)

Mg and Ca contents, like P, were averaged across years due to the lack of a significant year × species interaction (Figure 4). Mg contents in the WPS ranged between 0.6 mg g^{-1} ± 0.1 (common tansy) and 2.2 mg g^{-1} ± 0.1 (wild teasel). *Miscanthus* Mg levels were consistently lower, spanning 0.3 mg g^{-1} ± 0.1 to 0.4 mg g^{-1} ± 0.1. The average *Sida* Mg content of 1.2 mg g^{-1} ± 0.1 was comparable to the values observed in the WPS.

Differences in Ca content between *Miscanthus* and the WPS were more pronounced (Figure 4). Ca levels in the WPS ranged from 5.9 mg g^{-1} ± 0.8 (tansy) to 13.1 mg g^{-1} ± 1.0 (common evening primrose). In sharp contrast, *Miscanthus* samples showed very low Ca content, ranging only from 1.3 mg g^{-1} ± 1.0 to 1.4 mg g^{-1} ± 1.0, with comparable ranges found for both the *Miscanthus* MUM and *Miscanthus* REF plots. With a mean value of 12.0 mg g^{-1} ± 1.0, *Sida* exhibited Ca levels similar to the higher values seen in wild teasel and mugwort.

3.5. Ash Melting Behavior

The objective of this study was to examine the ash melting behavior of the different plant species in the form of bonitures of the treated ash samples, which were subjected to varying temperatures. The differences in the melting behavior of the samples are apparent, as evidenced by the different coloring patterns. To obtain even more precise results, the samples were also evaluated mechanically and under a stereomicroscope, as presented in the following section.

In addition, the melting behavior was observed by hot stage microscopy (HSM) (Table S3). Three typical curves for the coefficient h_x/h_0 over temperature were observed for the different samples as illustrated in **Figure 5**.

Type A is characterized by a slight, continuous increase of the coefficient h_x/h_0 over several 100 degrees, type B by a slight increase over a few 10 degrees, both starting at $T >> 500$ °C. All ashes of these types were sintered after the measurement. Type C is characterized by shrinking the sample to a local minimum of h_x/h_0, followed by a continuous growth up to the maximum of h_x/h_0, and a final decrease of h_x/h_0 to the minimum. It shall be noted, that for some samples h_{max} was larger than the image section taken.

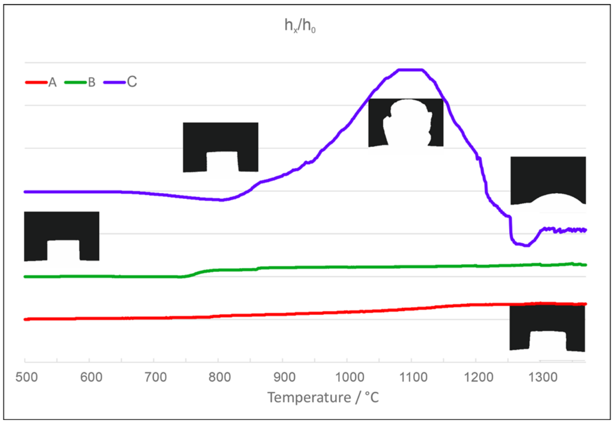

Figure 5. Different types of height profile of ashes investigated by HSM in dependence of increasing temperature and typical examples for photos recorded during ash fusion test. A) Evening primrose 2021, B) Yellow melilot 2021, and C) *Miscanthus* 2022.

The first decrease in coefficient indicates the start of melt formation causing closure of pores while the increase thereafter is likely caused by formation of gases, e.g., CO_2 from decomposition of carbonates, which cannot escape. The second, steep decrease in coefficient indicates the increase of melt fraction with lower viscosity allowing encapsulated gas to escape. All ashes of this type were completely molten after the measurement.

3.5.1. Ash Melting Behavior in Biomass Samples of 2021

As a significant interaction between the effects of year and plant species was found in the results of the ash melting assessment for each temperature (800, 900, 1000, and 1100 °C), the values for the two harvest years were considered separately.

Miscanthus exhibited inferior performance in all temperature treatments relative to the WPS (**Figure 6**). The mean values for *Miscanthus* demonstrated a considerable range, from 5.2 ± 0.3 for a temperature treatment of 800 °C to 14.9 ± 0.4 for a temperature treatment of 1100 °C. In comparison, the values for the WPS exhibited a relatively narrower range, from 2.7 ± 0.5 at 800 °C (greater burdock) to 5.7 ± 0.3 at 1100 °C (mugwort).

Furthermore, it was found for the 800 and 900 °C temperature treatments, that greater burdock (2.7 ± 0.5/3 ± 0.5), common evening primrose (3.2 ± 0.4/3.1 ± 0.4) and *Sida* (3.2 ± 0.3/3 ± 0.3) have particularly low values. At 1000 °C, common tansy (3.6 ± 0.4) has the lowest values, followed by common evening primrose (3.6 ± 0.6) and greater burdock (3.7 ± 0.7). At the highest temperature treatment of 1100 °C, greater burdock (4.7 ± 0.6) again has slightly lower scoring values than common tansy (4.8 ± 0.3), with the values of common evening primrose (4.9 ± 0.4) being similar to those of common tansy.

A corresponding behavior was also observed in the HSM measurements. While all WPS and *Sida* (except for one *Sida* sample) were categorized as types A or B with a maximum h_x/h_0 of 1.15 ± 0.05, the *Miscanthus* samples were categorized as type C with a maximum h_x/h_0 of 2.35 ± 0.28. The increase of the coefficient started in case of *Miscanthus* at 807 ± 25 °C and the maximum was reached at 1108 ± 72 °C. While the ash samples of the WPS had a mass loss of 37.8 ± 3.4%, the ashes of *Miscanthus* had only a mass loss of 14.0 ± 1.4%.

3.5.2. Ash Melting Behavior in Biomass Samples of 2022

The results of 2022 confirmed that *Miscanthus* exhibits higher scoring values at all temperature levels (see Figure 6). The values for *Miscanthus* MUM ranged from 8.0 ± 0.3 at 800 °C to 13.6 ± 0.4 at 1100 °C. For *Miscanthus* REF, the values were even higher, ranging from 9.6 ± 0.3 at 800 °C to 15 ± 0.4 at 1100 °C. Among WPS, greater burdock exhibited highest values in every temperature treatment, except 1100 °C, where the values for yellow melilot (6 ± 0.4) and common evening primrose (5.9 ± 0.4) were higher. In contrast, the lowest values were recorded at 800 °C for oregano (2.9 ± 0.3), at 900 and 1000 °C for *Sida* (3.4 ± 0.3 and 3.8 ± 0.5, respectively) and at 1100 °C for wild teasel (4.7 ± 0.3).

A corresponding behavior was revealed in the HSM measurements. The WPS, all categorized as types A or B, had a maximum h_x/h_0 of 1.14 ± 0.04. The *Miscanthus* samples, categorized as type C, had a maximum h_x/h_0 of 2.3 ± 0.1, the increase started at 779 ± 38 °C and the maximum was reached at 1035 ± 54 °C. The ash samples of the WPS had a mass loss of 39.8 ± 5.1%, while the *Miscanthus* ashes displayed a significantly lower mass loss of 12.8 ± 0.9%.

3.6. Modeling Corrosion Risks Induced by Inorganic Species

Thermodynamic predictions for the gas phase at temperatures of interest (800, 900, 1000, and 1100 °C) were conducted, with a particular focus on hydrochloric acid (HCl) and sulfur dioxide (SO_2). HCl and partially SO_2 play a significant role in the corrosion of steel under deposits.[60] The presence of HCl in the atmosphere or as a deposit accelerates the oxidation of iron and steel. This process results in the formation of $FeCl_2$ at the oxide/metal interface, leading to a porous oxide layer that promotes active oxidation. Additionally, HCl converts sulfates within the deposits into chlorides, which then interact with the oxide layer to release chlorine, further enhancing the process of active oxidation.

Figure 7 displays the predicted fugacity of HCl and SO_2 for WPS harvested in 2021 and 2022, compared to *Miscanthus* and *Sida*. It is noteworthy that the fugacity of the sample series for HCl show little variation, regardless of the harvest year. On average, this fugacity accounts for ≈0.001 vol% or 10 ppm, and decreases as combustion temperature increases. For *Sida* and *Miscanthus*, the concentration in the gas phase tends to be higher, accounting for around 100 ppm. The interaction of HCl with fuel ash results in an overall reduction of HCl concentration in the gas phase. Alkali metals and silicates in the ash bind HCl by forming solid salts, such as alkali chlorides, which lowers the partial pressure of HCl.

As the temperature rises, both the reaction kinetics and thermodynamic effects intensify, significantly shifting the equilibrium. In addition to HCl, the partial pressure of SO_2 in the gas phase was also predicted. The results indicate that the levels in samples collected in 2021 tend to be slightly higher than those in samples collected in 2022. Specifically, the gas phase exhibits a partial pressure of just under 100 ppm for *Sida* and *Miscanthus*,

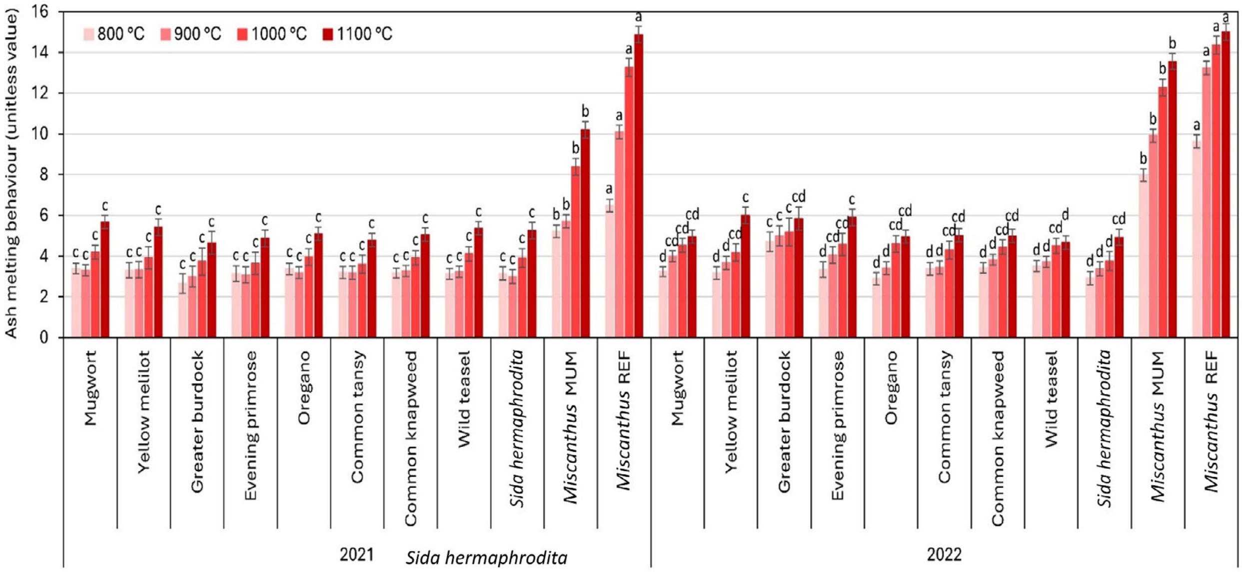

Figure 6. Overview of the results of the ash melting behavior (AMB, ranging from the lower the value the better the AMB) assessment for each temperature (800, 900, 1000, and 1100 °C). Estimates and standard errors are shown. Different letters denote significant differences between crops within temperature and year of harvest.

which is significantly higher compared to the other plant species, where the average ranges between 1 and 10 ppm. Furthermore, the fugacity of SO_2 increases considerably with rising temperatures. The formation of SO_2 is both thermodynamically and kinetically favored at elevated temperatures due to oxidation, which also results in a higher saturation vapor pressure of SO_2 in the gas phase. Additionally, the interaction between ash components and SO_2 is less pronounced than that with HCl.

4. Discussion

4.1. Classification of the Values

4.1.1. Dry Matter Content (DMC)

A high moisture content affects the density, calorific value and in general the quality of the end product, such as pellets, which are produced from the biomass.[61, 62] The differences in dry matter content between years were relatively minor for all species except for *Miscanthus* which showed much lower dry matter contents when compared with earlier findings of about 93.1% reported by Panahi et al., 2017.[63] In contrast, the value of 66.9 ± 4.4% reported by Von Cossel et al.[35] is more closely aligned with the findings of this study. As with the study by Von Cossel et al.,[35] the same experimental conditions can be assumed, apart from year-specific differences such as climatic conditions. It can thus be posited that the experimental conditions exert an influence, thereby accounting for the observed difference. Furthermore, Varnero et al., 2018[64] identified notable differences in the moisture content of *Miscanthus* indicated by dry matter contents ranging from 40% to 85%.[64]

The dry matter content of *Sida* (87 ± 2.9%) in the first harvest year was comparable to that of the WPS. However, in the second year it was significantly lower at 79 ± 2.9%. Nevertheless, the values are consistent with the range of 67.8% to 93.1% derived from the data set compiled by Cumplido-Marin et al., 2020.[50]

The lowest dry matter content among the WPS was observed for wild teasel in both years (Figure 3), failing to meet the minimum value of 85% for class B, as stipulated by the German Institute for Standardization[65] for biogenic solid fuels in 2021—along with oregano. However, the majority of WPS were found to meet the required dry matter content. The highest values among the WPS were recorded for common evening primrose, yellow melilot and greater burdock in 2021 and for greater burdock, yellow melilot, common evening primrose, common tansy and *Miscanthus* (*Miscanthus* REF) in 2022. These values also meet the requirements for class A.

4.1.2. Dry Matter Yield (DMY)

The DMY was considered an important parameter, in addition to combustion quality, for evaluating crop performance. It is derived from dry matter content and is typically expressed per area (e.g., one hectare). Area measurement accuracy directly influences the DMY estimation; thus, data validity is limited. Inaccurate area estimation of the harvested sample results in inaccurate DMY.[66]

In the practical component of this study, for instance, yellow melilot's area could not be precisely quantified, potentially causing DMY over- or underestimation. An examination of harvest data shows plant density varying yearly. Calculated values ranged from 6 to 9 plants m^{-2} in 2021, but a considerably wider range of 29 to 31 plants m^{-2} in 2022. This suggests area in 2022 was systematically underestimated, leading to a significantly higher plant density and influencing the DMY. Nevertheless, the comparable melilot DMY between the two years indicates a likely high degree of accuracy. The discrepancy between the two harvest years is minimal, especially compared to other plant species.

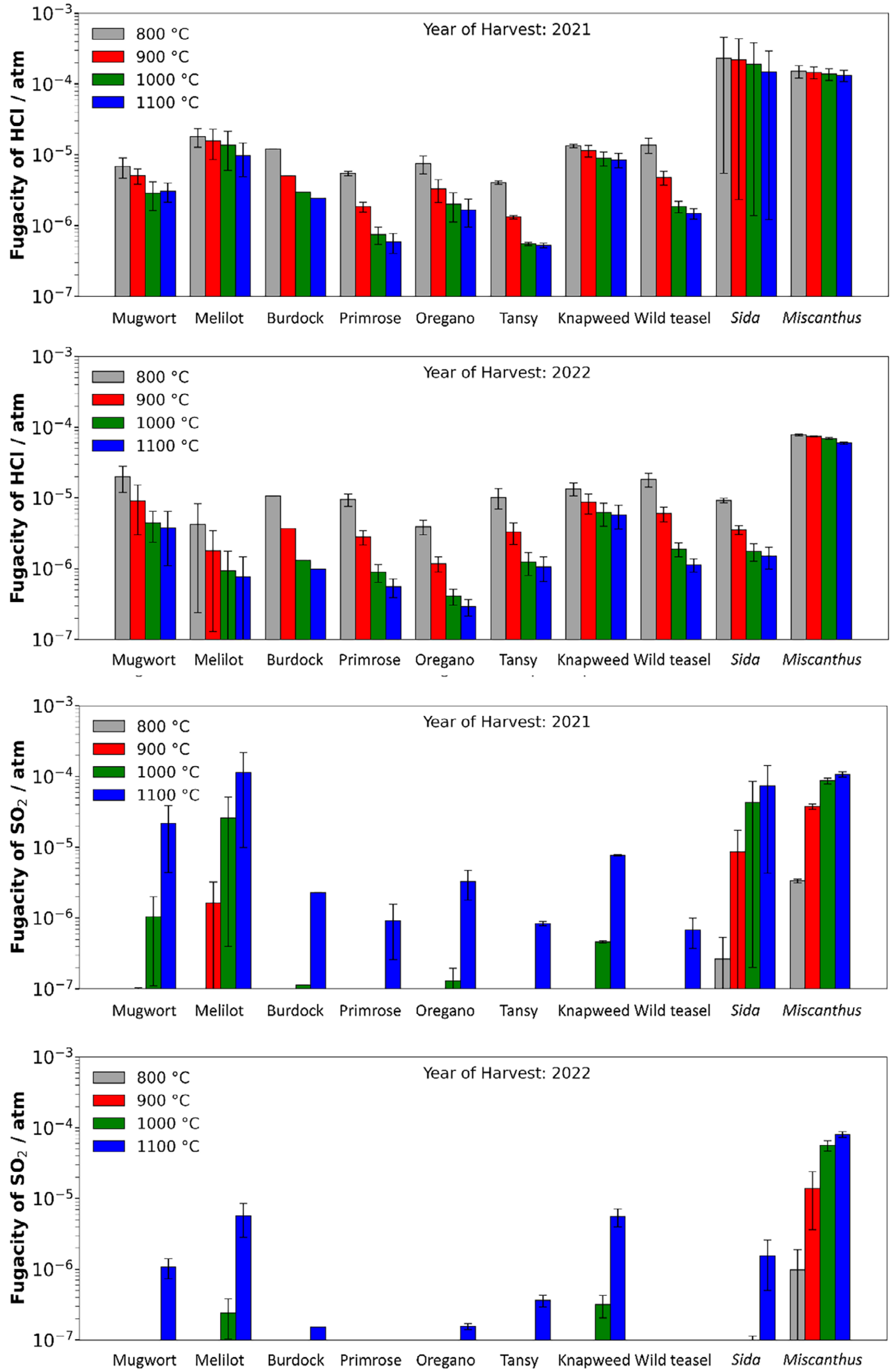

Figure 7. Predicted fugacity of HCl and SO_2 for flower-rich wild plant species harvested in 2021 and 2022, compared to *Miscanthus* and *Sida*. The error bars show the standard errors.

Greater Burdock and Mugwort Discrepancies: This minimal discrepancy is not true for greater burdock and mugwort. Greater burdock's DMY shows considerable variation: one of the lowest values in the 2021 crop year, but one of the highest in 2022. Specifically, the DMY was higher in 2022, despite a smaller cultivation area (0.64 m^2 in 2021 vs 0.42 m^2 in 2022). This discrepancy might be due to collecting only a single sample annually, reflecting individual values rather than accurate (representative) mean values. Additionally, different plant parts, with varying dry matter properties, could have resulted in distinct sample characteristics between the two years, causing significant overall value variation.

Moreover, mugwort values showed a pronounced two-year discrepancy. Compared to Jasinskas et al., 2022[61] the value for 2021 (4.9 Mg ha^{-1} ± 1.4) is more realistic than the 2022 value of 12.4 Mg ha^{-1} ± 1.4, which is distant from Jasinskas et al.'s 4.1 Mg ha^{-1}[61] and represents the maximum observed value across different fertilization levels in the study of Jasinskas et al., 2014.[67] Different soil types might contribute: Jasinskas et al.[67] used naturally more acidic Moraine loam (pH 4.2–4.4), whereas this research used Luvisol (average pH 6.55). However, their study[67] found no significant influence on yield, instead highlighting the role of N fertilization (120 kg N ha^{-1} at the highest yield of 4.3 Mg ha^{-1}).

Other factors like location and harvest time may also influence results. The field trial by Jasinskas et al.[67] involved harvesting plants in Lithuania in the second half of September. This location is further north than this study's trial, suggesting climatic conditions may have influenced outcomes. Nevertheless, these values require further examination, as Jasinskas et al.[67] emphasize mugwort's remarkable productivity in their region.

Soil Type and Other Influences: Emmerling et al.[68] found that soil quality improvement from perennial plants, such as WPM, is only evident in silty to loamy soils, with less pronounced impact in sandy soils or under dry climatic conditions. It is plausible that the resulting disparate soil quality from establishing plants on varying soil types may influence DMY.

Emmerling et al.[68] reported two distinct total WPM DMYs at two locations: 10.13 Mg ha^{-1} on Luvisol and only 6.63 Mg ha^{-1} on Stagno-Cambisol. In comparison, the DMY of the various WPS in this trial ranged from 1.55 Mg ha^{-1} ± 1.69 to 8.17 Mg ha^{-1} ± 1.38 in 2021, and from 4.62 Mg ha^{-1} ± 1.38 to 15.33 Mg ha^{-1} ± 2.39 in 2022. This suggests differences between WPS may have a comparable influence to that of soil type. Therefore, future research should investigate WPM DMYs on other soil types. Results for harvesting of vital, green biomasses in late summer for biogas are available,[26] but spring harvesting of dead and dried biomasses is less documented.

Furthermore, preculture is known to exert an influence, as shown by Emmerling et al.[68] This aspect was considered but is of lesser relevance in this study since the WPM have been established since 2014.

The combined effect of different plant species may also beneficially impact DMY in this trial, unlike the single-crop plots (only mugwort) examined by Jasinskas et al.[67]

Von Cossel et al.'s[35] 2020 harvest year samples showed mugwort achieved 8.2 Mg ha^{-1} ± 1.9, indicating DMY variability year-to-year. Common tansy values in this work are slightly lower than their 2020 studies, while common knapweed values are significantly lower. The aforementioned challenges in area measurement are a potential explanation for this discrepancy.

Comparison with Other Plants: The DMY of WPS is generally lower than that of *Miscanthus*. Nevertheless, common tansy and wild teasel exhibit relatively comparable values. *Sida* values in this study are comparable to those of the WPS, but fall within the lower end of the literature range (8.7 to 19.6 Mg ha^{-1}) obtained from various fertilizer trials.[69] The DMY values determined for *Miscanthus* in the trial align with recent studies, such as 13.5 Mg ha^{-1} recorded in a Brandenburg trial.[70]

4.1.3. Ash Content

Ash content adversely affects the calorific value and emissions of combustion plants, requiring increased maintenance and thus impairing combustion efficiency.[65]

Ash Content and Combustion Quality: Ash content determines the quantity of inorganic material in a sample. It often indicates combustion quality, as inorganic material in biomass increases the likelihood of ash-forming substances (e.g., alkali and alkaline earth metals) being present, which affect combustion. However, high ash content doesn't universally indicate poor combustion or high operational costs, as the ash may also contain combustion-promoting substances like Ca and Mg. Therefore, a general statement about combustion quality cannot be derived solely from a sample's ash content.[71, 72]

Experimental Results: The ash content of yellow melilot and common tansy was notably low, though still higher than the ashes from the two *Miscanthus* establishments. These low *Miscanthus* ash contents align with other studies.[35, 61, 63, 64]

In contrast, common evening primrose (4.95 ± 0.32%) and wild teasel (4.99 ± 0.26%) exhibited slightly elevated ash contents. Nevertheless, all tested species, including *Miscanthus*, *Sida*, and the other WPS under consideration, meet the criteria for Class A pellets (below 6%) as outlined in DIN EN ISO 17225-6:2021.[65] This confirms all examined species are suitable for combustion.

Comparison with Prior Data: Comparing with data from the identical field trial in 2020, the ash contents of common tansy, common knapweed, and mugwort were largely consistent with this study's values.[35]

Mugwort ash content averaged 4.5 ± 0.3% over the 2021 and 2022 harvest years. The discrepancy is greater for common tansy: the 2021 and 2022 mean was 2.4 ± 0.26%, compared to 4.7 ± 0.2% for the 2020 harvest. This reduction may be due to a later harvest in March instead of February.[73] Conversely, common knapweed values increased from 2.2 ± 0.2% in 2020 to an average of 3.5 ± 0.3% in 2021 and 2022.

Given the absence of comparative literature values for the other species, variance over time can only be assessed using the aforementioned three species. The observed variance for these species is within a realistic range.

Comparison with WPM: A preliminary comparison value for the entire mixture is an ash content of 9.5%, determined by Emmerling et al.[68] for a WPM. However, an individual species' average value cannot be easily compared to a mixture's value because: 1) the species in the Emmerling et al. mixture[68] are not definitively known, and 2) the species combination can influence combustion properties.[71] This figure, therefore, serves only as an approximate guide.

Nevertheless, based on this orientation value, it can be posited that *Miscanthus* generally has a lower ash content than WPM. The *Miscanthus* ash contents determined practically in this study were mostly in line with literature.[35, 61, 63, 64]

4.1.4. Ash Melting Behavior

Although empirical indices exist to predict ash behavior during biomass combustion,[74] experimental characterization is essential. A comprehensive understanding of the chemical interactions, specific concentrations, and resulting combustion issues is currently lacking. Experiments provide crucial insight into the actual behavior of solid fuels in practice.

Experimental Ash Melting Results: A clear distinction in ash melting behavior was observed between all WPS and *Miscanthus* across all temperature treatments and HSM measurements.

WPS and *Sida* ash demonstrated comparable, less critical behavior.

Miscanthus ash showed significantly higher scoring values (approximately double), and all *Miscanthus* ashes melted in the HSM.

This confirms that the ash melting behavior of the WPS is much less critical than that of *Miscanthus*, supporting previous findings.[35, 36]

Among the WPS, there was little to no variation in scoring values between the 800 and 900 °C temperature treatments, which aligns with the relatively small change in the coefficient h_x/h_0 in HSM. In contrast, *Miscanthus* showed increasing intervals between scoring values from 900 to 1100 °C. In this range, all *Miscanthus* ash pellets exhibited a significant, characteristic increase and subsequent decrease in the coefficient in HSM, indicating an increasing melt fraction.

Influence of Elemental Composition: Previous research indicates that Mg and Ca influence ash melting.[75] *Miscanthus* consistently has significantly lower Mg and Ca content than WPS, but significantly higher silicon (Si) content. P and K values in *Miscanthus* are either lower or comparable to WPS.

To further evaluate these elements, the molar ratio (Si + P + K)/(Ca + Mg)) was used to assess ash melting risk for P-rich fuels.[74] A ratio above 1 indicates a higher melting tendency.

- WPS ratio: 0.5 ± 0.1 (2021) and 0.8 ± 0.1 (2022).
- *Miscanthus* ratio: 7.4 ± 1.1 (2021) and 9.2 ± 0.9 (2022).

Consistent with the experimental HSM results, the index shows a very high melting risk for *Miscanthus* and a very low risk for WPS. This suggests the positive influence of Mg and Ca is a dominant factor.

Corrosion Risk (HCl): While a 10 ppm concentration of HCl in the gas phase is relatively low, 100 ppm significantly increases the risk of corrosion. For example, high corrosivity in boilers burning municipal waste was attributed to flue gas levels typically ranging from 100 to 1000 ppm HCl in the gas phase.[76] A concentration of 500 ppm of HCl in the gas phase is considered harsh[77] and has been shown to actively accelerate the oxidation of stainless steel.[78]

4.1.5. Potassium (K) Content Comparison

Elevated K and P concentrations detrimentally impact combustion by reducing melting temperature. These elements promote unwanted by-products like sintering and corrosion, which impair efficiency and cost-effectiveness. High concentrations, especially with other ash-forming elements, also lead to elevated gaseous and particulate emissions.[35, 71–73, 79, 80]

WPS investigation showed no significant species × year interaction for P, but a significant interaction for K. Therefore, P values were summarized as mean values over the two harvest years, while K values were considered individually. Except for *Miscanthus*, all species showed higher K content in the second harvest year (2022) than in the first (2021). The K content was particularly high in 2022 for wild teasel, common evening primrose, and oregano. Given the impact of harvest year on species quality, year-related factors are essential to consider. For instance, climatic discrepancies may have caused K accumulation in 2022. K can passively leach from stems following prolonged rainfall, though leaching rates vary based on species' stem composition. However, this doesn't explain the declining K levels in *Miscanthus*, which contrasts with other species' trends. Methodology, specifically the ratio of stems and inflorescences, may have varied and played a role. The harvest date can be excluded, as harvests occurred on highly similar dates.

WPS K contents varied. Yellow melilot, common knapweed, common tansy, and oregano (2021) had K levels similar to *Miscanthus*. Conversely, common evening primrose, greater burdock, mugwort, and wild teasel (2022) exhibit higher values, classifying them as less suitable for combustion. In comparison, the K contents of *Sida* exhibited relatively low values, with a range of 2.72 mg g^{-1} ± 1.04 to 5.25 mg g^{-1} ± 1.06 across the two harvest years. These values fall within the range of 1.55[81] to 24.7 mg g^{-1},[50] which encompasses the comparative values documented in the existing literature.

4.1.6. Phosphorus (P) Content Comparison

Increased P levels in solid fuels are associated with increased ash-related problems.[64, 71, 79] P contents were comparable over both harvest years; thus, only mean values were analyzed. Compared to K content, P content analysis revealed fewer inter-species differences. Nevertheless, discernible trends allowed species classification into analogous value groups (see Figure 4). *Miscanthus* showed the lowest P content, while mugwort and greater burdock showed the highest. Yellow melilot, common evening primrose, oregano, and common tansy exhibited P values lower than *Miscanthus*. Common knapweed, wild teasel, and *Sida* fell within the medium P range. Overall, P levels in *Miscanthus* were notably low compared to other examined species. The P content of *Sida* was within the literature range of 0.4 to 2.8 mg g^{-1},[50] though its values tended to be higher.

4.1.7. Calcium (Ca) and Magnesium (Mg) Contents

Ca beneficially affects biomass melting point and simultaneously inhibits low-melting alkali silicates. Mg shows comparable behavior.[75]

No significant year × species interaction was found for either Ca or Mg; thus, mean values are representative of the entire period. *Miscanthus* exhibited the lowest Ca and Mg contents among all species tested. *Sida's* Ca literature range is 3.4 to 22.6 mg g^{-1}.[50, 81] This study's value (12.0 mg g^{-1} ± 1.0) is in the upper range compared to Von Gehren et al., 2019[81] but in the middle range compared to Cumplido-Marin et al., 2020.[50] Literature Mg contents for *Sida* biomass range from 0.4 to 1.9 mg g^{-1},[50, 81] confirming the value determined in this study (1.2 mg g^{-1} ± 0.1).

4.1.8. Final Classification

With regard to dry matter content, the WPS exhibiting the most favorable values were yellow melilot, common evening primrose, greater burdock, mugwort and common knapweed with dry matter contents of over 88%. This meets the requirements for class A pellets according to DIN EN ISO 17225-6 2021.[65] In contrast, *Miscanthus* (*Miscanthus* REF) was only able to meet the requisite value for class A in 2022, while the remaining values met the criteria set forth in DIN EN ISO 17225-6 2021.[65] However, given the considerable inter-annually variability in dry matter content of the plant species, no definitive conclusion can be drawn at this time. Mugwort and greater burdock also demonstrate particularly favorable values, however, a paucity of supplementary data precludes their classification.

Ash content allows a reliable assessment of suitable species, as no significant year × species interaction was found. Common tansy and yellow melilot demonstrated particular suitability due to their notably low ash content. Yellow melilot performed best overall in tests for dry matter content, yield, and ash content; common tansy and mugwort also exhibited very good suitability. In addition to common tansy and mugwort, predominant due to substantial biomass,[26] other WPS species significantly contribute to biodiversity. This study corroborates excellent combustion properties for wild teasel, common evening primrose, and oregano. Although not high-yielding, these species improve combustion through suitable mineral concentrations (e.g., advantageous Ca and Mg levels in wild teasel, common evening primrose, and oregano).

Common evening primrose and oregano, along with common tansy and yellow melilot, exhibit notable P content. K content trends were less evident, as yellow melilot and common knapweed values fluctuated considerably year-to-year, indicating seasonal variability in biomass composition and associated ash melting behavior. This is especially clear in greater burdock and common evening primrose ash melting data; in contrast, common tansy showed relatively constant values across both years. To fully assess combustion properties, further data is required for promising species like greater burdock, common evening primrose, and oregano.

4.2. Transfer into Practice

Once the findings have been contextualized within the extant body of knowledge and evaluated for both their veracity and potential limitations, the potential for the practical implementation of the knowledge gained deserves a critical discussion in terms of

- the potential forms, advantages and disadvantages of WPS cultivation for bioenergy purposes,
- the suitability regarding further processing possibilities and value chain integration,
- and the possibilities for further developing the concept of using WPS for combustion.

4.2.1. Crop Cultivation

WPS cultivation is typically a straightforward agricultural process, aiming for domestic species that offer numerous ecosystem services. Plants are harvested annually in spring before regrowth, with N-fertilization only applied from the second year onward. Agrochemicals aren't required to protect beneficial effects on pollinators.[28, 40]

Beyond successful establishment, balanced species development is essential to maximize biodiversity, a key objective. Vollrath et al., 2016[26] observed a species diversity decline from the third year, accelerating as perennial shrubs establish. Less competitive species are eventually displaced by dominants like common tansy, mugwort, and common knapweed. Further research into long-term performance and biodiversity is needed for optimal effect.[26]

A paramount concern is avoiding invasiveness or other adverse effects on subsequent crops. Vollrath et al., 2016[26] specifically noted mugwort issues: its prolific self-seeding in light, sandy soils led to repeated appearance in subsequent crops, necessitating increased pesticide use.[26] This negates the initial positive biodiversity impact.

Additionally, mugwort is a potential rattle virus vector, excluding it from potato-growing regions.[26] It also causes allergic reactions, potentially contributing to its social unacceptability. These points suggest mugwort's rejection from a WPM. Nevertheless, mugwort's role in biomass formation necessitates striking a balance in its use. Furthermore, its traditional spiritual use in European folk medicine and mystical traditions is not addressed further here, but should not be omitted from a holistic comparative evaluation of WPM ecosystem services.

Accepting lower biomass yield allows a focus shift from pure stands to WPS utilization for favorable combustion properties. This can be implemented as a mixed crop with *Miscanthus*, in flower strips, or as pure cultivation. Here, the area is a "biodiversity area" with added value from producing natural solid fuel additives. Further investigation is needed into the most effective practical implementation of these forms, considering social and economic factors.

Biomass for combustion is generally harvested later than for anaerobic digestion aiming for biogas generation. Late-summer biomass contains more combustion-problematic elements, leading to a lower ash melting temperature. Conversely, moisture content is typically lower in winter/spring, which is beneficial for combustion.[82] Dry biomass offers easier storage than "fresh" biomass if moisture is below 20%.[83] This holds true for the examined species, meaning drying is not a a necessary practical step, simplifying logistics.[50, 82]

Harvesting can also be done during a more flexible period in winter. This contrasts with earlier anaerobic digestion harvests requiring specific biomass quality. Kiesel and Lewandowski[83] state that later harvesting reduces substrate-specific methane yield due to lignification, lowering digestibility. Conversely, higher dry matter content benefits combustion, allowing harvesting even on frozen ground, which further facilitates the process.

4.2.2. Implementation during Processing and Combustion

Later harvesting offers potential benefits for cultivation and combustion. WPS studies show a reduction in problematic N and S levels.[35] Overwintered grasses yield less biomass but have lower K and Cl levels.[35, 64, 73] Ultimately, later harvest timing reduces moisture and total mineral content, which is advantageous for combustion.[64]

The examined species were from WPM developed for biogas (co)substrates, prioritizing late or low lignification.[84] Conversely, combustion utilization should prioritize early or highly lignifying species. Future studies should thus select WPM species based on early lignification and chemical components conducive to combustion and ash melting, rather than high biomass yields and late lignification. The species mixture could be rearranged based on these characteristics. Other interesting crops include the fiber nettle (*Urtica dioica* convar. fibra),[85] *Artemisia dubia* Wall.,[86] or the wild artichoke (*Cynara cardunculus*), which is co-combusted with solid biofuels in Southern Europe.[87–89] Fiber hemp, a lignin-producing plant with high fiber content,[90–93] is another possibility. The suitability of these plants for cultivation in Germany requires further investigation, considering climatic conditions and invasiveness potential.

Solid fuel combustion typically involves processing biomass into briquettes or pellets. Market standards, such as DIN EN ISO 17225-6 2020 (latest: DIN EN ISO 17225-6 2021),[65] govern requirements. This study's species generally fulfill criteria for moisture and ash content. However, standards also guide other combustion parameters (e.g., calorific value, N, S, Cl, and trace elements); thus, further research is recommended to collect this data.

Fineness of ground biomass affects subsequent processing; finer, more even grinding facilitates easier pressing and pellet suitability.[67] Although a uniform sieve thickness was used, the degree of fineness varied by species. Yellow melilot, common knapweed, and wild teasel required a second grinding pass for laboratory fineness. Further data on the grindability of WPS is needed for practical implementation.

Beyond standard requirements, emissions generated by ash-forming substances should be investigated.[39] In the anticipated circular economy, utilizing combustion residue is imperative. Ash from uncontaminated biomass can be used as fertilizer, returning nutrients to the soil. However, the content of persistent organic pollutants in ash is a critical factor.[94] Contaminated ash is only suitable for limited controlled use (e.g., cement in construction). Contaminants exceeding permitted concentrations are generally observed in waste materials. The potential for WPS to accumulate pollutants (relevant to phytoremediation) and their subsequent use as solid fuels remains an open research question.

5. Conclusion and Outlook

WPS utilization as a solid biofuel source holds considerable potential in various respects. The investigated WPS performed superiorly to *Miscanthus*, particularly regarding Mg and Ca factors and ash melting behavior. Additionally, WPS positively affect biodiversity in agricultural landscapes. Given the species extinction crisis, prioritizing biodiversity (SDG No. 15: Life on Land) and enhancing energy crop cultivation is imperative.

Encouraging ash melting findings for common tansy, wild teasel, common evening primrose, and oregano suggest these species can enhance diversity while simultaneously improving solid biofuel combustion properties, allowing for economic and ecological sustainability. Conclusively, WPS could help enhance agricultural biodiversity and serve as beneficial co-substrates for alternative biogenic energy sources.

The upscaling of WPS cultivation requires secure financial resources, user-oriented quality assurance/control concepts and political support. To establish a data basis, combustion-relevant parameters must be observed over an extended period and across a range of site-specific conditions. Further investigation is warranted for additional combustion minerals (S and Cl), heavy metals, and pollutants. From a marketing perspective, these parameters are crucial for compliance and industrial residue utilization. Future work plans to measure emissions from WPS combustion. Beyond combustion specifics, further investigation is also needed into the biodiversity-promoting properties of WPS, focusing on others specifically selected for combustion.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.C.: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Validation, Visualization, Writing—Original draft preparation, Writing—Review and Editing, Supervision, Funding acquisition, Project administration. **C.H.**: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Visualization, Writing—Original draft preparation, Writing—Review and Editing. **Y.I.**: Validation, Writing—Review and Editing. **E.B.**: Validation, Writing—Review and Editing. **F.L.**: Methodology, Formal analysis, Investigation, Resources, Data curation, Validation, Visualization, Writing—Review and Editing. **M.M.**: Methodology, Formal analysis, Investigation, Resources, Data curation, Validation, Visualization, Writing—Review and Editing. **N.D.J.**: Validation, Writing—Review and Editing, Project administration.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article (Tables S1–S5, Supporting Information).

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