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Exploring the Potential of Perennial Nectar-Producing Wild Plants for Pellet Combustion

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Perennial nectar-producing wild plant species (WPS) cultivation for biogas production helps improve ecosystem services such as habitat functioning, erosion mitigation, groundwater protection, and carbon sequestration. These ecosystem services could be improved when WPS are harvested in late winter to produce pellets and briquettes as solid energy carriers for heat production. This study aims for gaining first insights into the use of WPS biomass as resource for pellet and briquette combustion with focus on two perennial WPS common tansy (*Tanacetum vulgare* L.) and mugwort (*Artemisia vulgaris* L.), and two biennial WPS yellow melilot (*Melilotus officinalis* L.) and wild teasel (*Dipsacus fullonum* L.). All WPS are found economically viable for pellet combustion. The main drivers are i) low cultivation costs, ii) subsidies, and iii) low pellet production costs due to low moisture contents. However, high ash contents in WPS biomass justify the need of i) blending with woody-biomass or ii) supplementing with additives to attain international standards for household stoves. This approach appears technically feasible providing a research field with significant potential impacts. As 70% of the pellet market is demanded as household level, public concern about the legal framework of alternative plant biomass pellets must be overcome to develop this market.

1. Introduction

Agroecosystems can provide food, feed, raw materials, pharmaceuticals, fuels and biomass in general, that are essential for human consumption.[1–3] This provisioning nature of agroecosystems relies on other ecosystem services than biomass provisioning such as pollination, climate regulation, erosion prevention, nutrient cycling and hydrological services.[1] Depending on the management practices, agroecosystems can also provide different ecosystem services, including water and soil regulation, carbon sequestration, support of biodiversity and cultural services.[4] They can also be the source of biodiversity, protecting from habitat loss, nutrient runoff, sedimentation of waterways and air pollution.[5,6] There is an evident trade-off between the provision services at farm level for immediate satisfaction of material human needs, and regulating habitat and cultural services that support the maintenance of the biosphere capacity to provide these goods and services in the long run.[7] Therefore, a transition toward a sustainable bioeconomy faces the challenge of managing these trade-offs, ensuring a growing supply of biomass while protecting biodiversity, wildlife habitats, landscapes and the quality of air, water and soil[8,9] to achieve the United Nations Sustainable Development Goals 6, and 12–15 (https://www.globalgoals.org/goals/), among others. In this direction, one of the most challenging services from agricultural systems is the provision of biomass for bioenergy purposes, e.g., for high temperature heat demand.[10–13]

1.1. Perennial Wild Plant Mixtures as a Social-Ecologically more Benign Bioenergy Cropping System

Nowadays, bioenergy cropping systems are often controversially discussed due to social-ecological threats,[14,15] and realizing its full potential still requires further achievements on the part of the developer (PUSH) and market (PULL) sides.[16–18] Nevertheless, competition for land between food crops, bioenergy crops and biodiversity conservation are expected to increase as a result of world population growth and climate change.[19] In addition, there is political pressure to further develop renewable energy sources and thus not depend on unstable imports, making bioenergy crops a strategic resource in this matter.[20–22]

In the quest of providing biomass for energy, but also beneficial social-ecological contributions such as biodiversity

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DOI: 10.1002/adsu.202300599

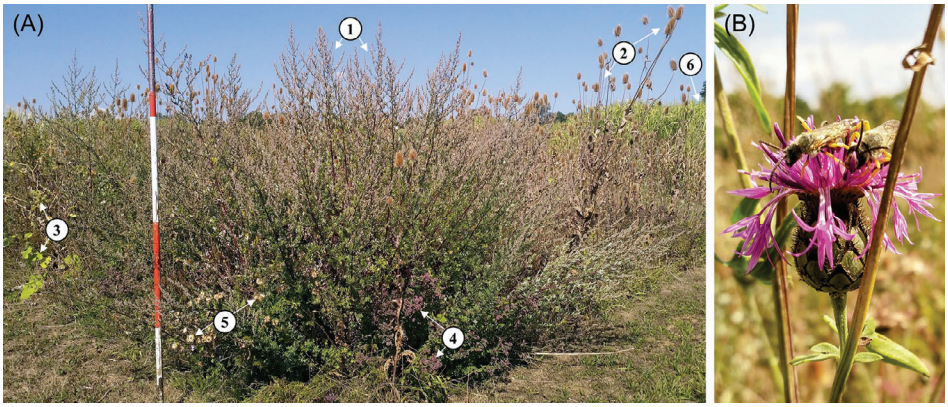


Figure 1. Impression of a several years old mugwort (*Artemisia vulgaris* L.) (A1), representing one of the yield-relevant perennial wild plant species (WPS) within the wild plant mixtures cultivated for biogas production at a field trial site of University of Hohenheim (48°42'55.8"N 9°12'54.0"E). The scale is divided into 50 cm segments. Surrounding mugwort are other WPS such as wild teasel (*Dipsacus fullonum* L.) (A2), greater burdock (*Arctium lappa* L.) (A3), oregano (*Oreganum vulgare* L.) (A4), and greater knapweed (*Centaurea scabiosa* L.; after seed maturity has already occurred) (A5). In the background on the right is another plot where miscanthus (*Miscanthus* x *giganteus* Greef et Deuter) (A6) is grown as a reference bioenergy crop. Inflorescence of a greater knapweed with two individuals of an unidentifiable wasp species, probably belonging to the paper wasps (*Polistinae* Lepeletier, 1836) (B).

conservation,[23] biocontrol[24] and landscape aesthetics,[25] perennial wild plant mixtures (WPM) can play a major role. This has been or is currently being investigated in Germany within the framework of nationally funded projects such as "Biodiversity for Biogas Plants",[26] "Energy from Wild Plants",[27] and "Energy from Wild Plants: Wild, Colorful, Strong!".[28] WPM consist of native, flowering and mostly wild plant species (WPS) with annual, biennial and perennial life cycles, which can be cultivated in polyculture cropping systems (**Figure 1**), aiming at both providing biomass for bioenergy purposes and supporting biodiversity conservation.[29]

These WPS provide numerous ecosystem services that could support the overall agroecosystem resilience. Indeed, WPS are seen to improve landscape aesthetics, provide habitat for wildlife and support pollinator, accumulate carbon in the soil, mitigate soil erosion and improve soil fertility.[23,25,29–32]

Although there are important social-ecological advantages of including the cultivation of WPS in agroecosystems, there are also concerns about their productivity in terms of providing sufficient biomass.[23,33,34] Von Cossel et al. (2021) compared the substrate-specific methane yield and lignocellulosic composition of three perennial WPS that dominate the biomass yield performance in WPM cultivation.[35] All these WPS showed significantly lower specific methane yields (SMY) (up to 27% lower) when compared with maize as the most prominent crop for biogas generation.[35] Furthermore, Lask et al. (2020) conclude that the favorable ecological aspects of WPM are not enough to outperform maize for biogas production, because the lower yields of WPM could result in potential indirect land use impacts, which may outweigh the numerous direct and indirect benefits mentioned above.[5,36] This was contradicted by Janusch et al. (2021), who found that the cultivation of WPM could be reasonable despite the lower biomass yields compared with other biogas cropping systems such as silage maize,[33] because of the enhancement of ecosystem services other than biomass supply for biogas production.

Following Von Cossel et al. (2019), the lower SMY of WPS is mainly associated with high lignin and low hemicellulose contents in WPS.[37] In return, this is a more desirable composition for other energy end uses, such as combustion.[35]

1.2. Combustion Instead of Biogas Production

Combustion is defined as a thermochemical conversion technology capable of producing heat and power through moderate- to high-temperature (800–1600 °C) by rapid reaction of fuel and oxygen from which thermal energy and flue gas is obtained.[38] For selected WPS, it has also recently been shown that thermochemical conversion could approximately double the energy yield compared to biogas production, which would contribute to a much better land use efficiency.[35] This would be of decisive advantage in times of increasing land use conflicts.

When compared to other thermochemical conversion technologies, such as gasification, pyrolysis and solvent liquefaction, direct combustion of biomass has the advantage of using well-developed and commercially available technologies, even for household employment.[39,40] On the other hand, direct combustion faces three main disadvantages: reduction of efficiency associated with burning high-moisture fuels, ash fouling and agglomeration due to alkali compounds found in biomass and the provision of sufficient supplies of bulky biomass.[40,41]

For a profitable and efficient WPS biomass-to-energy conversion, several parameters need to be considered. While some of these parameters are given by the crop characteristics, the cultivation procedures and harvest regime (agronomy), others depend on the treatment of the biomass and type of combustors (conversion pathway):

i. From an agronomic perspective, higher content of lignin in the WPS biomass is achieved through a delayed harvest of the crops.[42,43] A later harvest of WPS can also provide additional ecosystem services such as an extended protection of wildlife and feed provision.[12,23,35] Nevertheless, WPS have only been cultivated in practice for biogas production, but not for combustion, and in mixture, but not in sole cultivation. Thus, it re-

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mains unclear how perennial WPS perform in long-term under a winter harvest regime aimed at using the WPS biomass for combustion.

ii. From a conversion pathway perspective, the type and size of combustors, the WPS composition, moisture content, heating value and density[44] will determine i) if the thermochemical conversion through direct combustion of WPS is technically viable at pilot scale and in terms of time, and ii) what types of pretreatment are necessary before the final thermochemical conversion of the biomass.[45] Therefore, the varying WPS composition over the years[46] may be a crucial aspect of using WPM instead of specific WPS. This could also have an impact on the pellet production process, which places great demands on the biomass, as recently exemplified for alternative woody and non-woody biomasses.[47–49]

Environmental impacts and pollutant emissions also play a tremendous role when considering this bioenergy pathway.[50] Carbon monoxide, volatile organic compounds, polycyclic aromatic hydrocarbons and particulate matter can be controlled by reducing feedstock moisture and proper combustion management to provide the conditions to a more complete burning at sufficient temperature.[51] In this direction, the pretreatment of biomass through densification or pelletization/briquetting and the use of automatic combustors, can significantly reduce emissions and enhance efficiency of direct combustion.[44]

Due to a majority of available literature and data, this study focusses primarily on the use of pellets. Even though the combustion technology and infrastructure for briquette combustion differs partly, we also consider briquettes in our study as a condensed form of biomass used as a solid fuel for combustion. Therefore, in many cases throughout this article the term "pellets" should represent both pellets and briquettes, without being explicitly mentioned. Accordingly, and for a first approach to the topic, this study focuses on the biomass-to-energy pathway of using WPS biomass for pellet combustion or co-combustion.[48]

WPS pellet combustion could be a competitive biomass-to-energy pathway when comparing to existing alternatives on the market (e.g., biomass-to-product pathways).[52,53] As outlined above, many advantages of WPS are associated with certain social-ecological benefits such as recreational values or habitat functions. In other words, WPS are promising to be a more sustainable feedstock for bioenergy from combustion compared with, for example, miscanthus (*Miscanthus* x *giganteus* Greef et Deuter) or willow (*Salix* spp.). While there are declared preferences for environmentally more benign bioenergy in Germany at a household level, also reflected in the customers willingness to pay for them,[54] there is no evidence suggesting that this is also true for energy-intensive industries with large-scale combustor systems. And since Germany's nuclear phase-out until 2023,[55] the energy needs of industrial companies have become one of the most existential issues facing the German economy. Therefore, it would be of great advantage if biomass from WPS could offer solutions here as well. Nevertheless, energy-intensive companies in Germany are even eligible for green energy subsidies in order to protect their international competitiveness, which in 2016 favored 2100 companies.[56] Furthermore, there are differences of ≈80 € Mg^{-1} between a purchase quantity of 20 Mg pellet delivery and the 15 kg pellet bag, which is popular among owners of pellets stoves at residential level.[57] With a price reference of 0.39 € kg^{-1},[58] this difference represents 20.5% of the price per kg. This outlines the importance to evaluate the applicability of sustainably produced and locally available non-woody biomass in small scale units under the presented circumstances of rising energy costs.[58–60]

1.3. Research Objective and Aim of this Study

Consequently, this research focus on WPS pellet combustion at household and commercial level with small-scale combustion systems. Pellet stoves´ efficiency ranges from 85% to 90%, and they are user-friendly, with automatic pellet ignition and built-in fuel tanks.[61] Yet, different technical (pellet combustion quality) and economic (costs, availability) factors influence the final pellet consumption within a household.[62] Thus, the potential analysis of a new biomass utilization concept like WPS pellets for combustion must include not only the annual average biomass yield but also the long-term biomass yield stability (variance and trend of biomass yield over time). This is important so that consumers can rely on the availability of the product. The same applies to the large combustion units in the commercial sector. Therefore, the aim of this study is to take a preliminary systematic approach to the question of whether pellet combustion could be a technically and economically viable option for generating heating energy from WPS in the residential and commercial sectors, focusing on the two perennial WPS common tansy (*Tanacetum vulgare* L.) and mugwort (*Artemisia vulgaris* L.) as well as the two biennial WPS yellow melilot (*Melilotus officinalis* L.) and wild teasel (*Dipsacus fullonum* L.).

2. Experimental Section

To achieve a systematic overview, this study referred to a broad presentation of different fields of action that should be considered in the future evaluation and development of WPS pellet production and use. These fields of action are i) agricultural production, ii) the market settings and demands, iii) the processing industry, and iv) terms of energy efficiency and profitability. The preliminary assessment of WPS suitability for pellet production was then used to i) estimate the economic viability, and ii) to run a SWOT and stakeholder analysis. Where appropriate, concrete investigations are related exemplarily to the German federal state of Baden–Württemberg (BW) due to sufficiently available and reliable data for this region.

A systematic literature review was carried out following "The Preferred Reporting Items for Systematic reviews and Meta-Analyses 2020" statement.[63] The latter is widely considered a useful guideline in order to ensure that all recommended information is captured, assess the suitability of the methods and, consequently, the reliability of the results.[63]

Scopus was selected as the preferred database to carry out the review. The following search algorithm was used: "TITLE ("biomass" AND "pellet") AND TITLE-ABS-KEY ("combustion" OR "composition" OR "wild plant") AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "AGRI"))", resulting in 235

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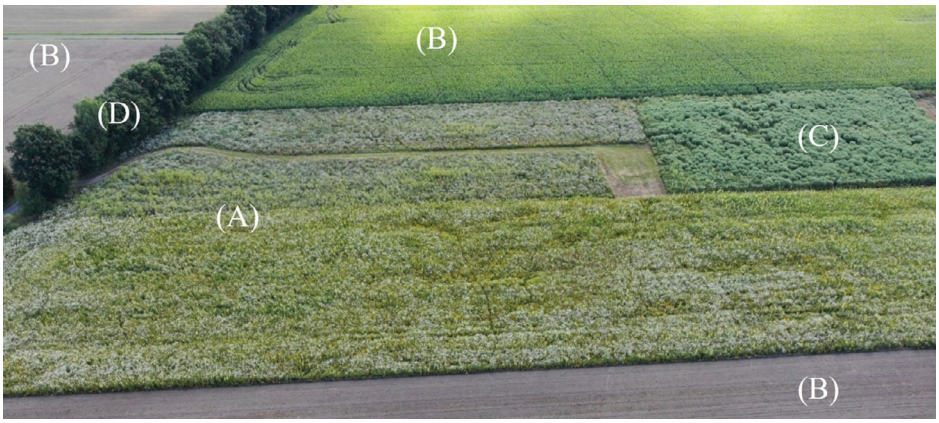


Figure 2. Aerial view of one of the larger wild plant mixture (WPM) areas already cultivated in Germany. The WPM area (A) was embedded in the agroecosystem between arable crops (B), the perennial biomass crop miscanthus (C), and natural woody elements of a hedgerow slope (D). In this regard, WPM can be viewed as a land-sharing approach that combines functions of biomass production and biodiversity conservation. The photo was taken on a farm near Würzburg, Germany, in summer 2020 (Source: Michael Bischoff).

documents. In order to meet the requirement of being as up-to-date as possible while at the same time providing sufficient hits, the documents found in the initial step of the literature search were limited to the period 2018–2024 as well as to the English language resulting in a set of 140 documents. After a cautious selection based on relevance, 28 documents were identified as suitable for the present analysis. In addition, the reference lists of these 28 documents were also considered. A total of 47.8% of the analyzed papers dealt with the composition of biomass pellets, pure and blended feedstock; 25% with pre-treatment and 28.57% with the use of additives. For the compilation of current topic-relevant information on producers (agricultural perspective), markets (energy prices, pellet use), and the processing industry (quality requirements), the above-mentioned documents and their references and otherwise Google (Google LLC, Mountain View, California, United States) were used.

3. System Relevant Aspects of Agricultural Production for the WPS Pellet Value Chain

As proposed by Von Cossel et al. (2021),[35] the utilization of WPS for combustion requires a late harvest regime, which is the most fundamental difference to the current common cultivation practice of WPS when used as a biogas (co-)substrate. This section deals with potential environmental benefits in the light of a late WPS biomass harvest regime. In addition, this section provides an overview of the process of agricultural production of WPS for combustion purposes.

3.1. General Aspects

The one-sided, unbalanced and high input use of agriculture is recognized with growing concern.[64–66] Further, the changes in the farming landscape that accompany agricultural intensification (e.g., the increase and consolidation of agricultural areas) are leading to a decline in biodiversity and impoverishment of the landscape.[67–70] WPM cultivation has been explored as an additional renewable resource comprising many ecological benefits,[23,30,31,33,46] combining alternative or complementary biogas production with the provision of habitat for wildlife and other ecosystem services.[31,71,72] Concomitantly, WPM plantations resulted in more resilient agroecosystems through the diversification of crops[29] (**Figure 2**). A life cycle assessment of the perennial bioenergy crop Virginia mallow, also known as *Sida hermaphrodita* L. var. Rusby (in the following referred to as *Sida*) used as a solid biofuel indicated that the use of its biomass in combustion processes is a valuable alternative to the use of established solid biofuels like wood-based energy sources.[73]

From a political perspective, two recent regulatory changes are relevant for the agricultural production of WPM. First, the German federal state of Baden–Württemberg (BW) introduces subsidies for WPM cultivation as part of the Funding Program for Agroecology, Climate Protection and Animal Welfare program for the period 2023–2027.[74,75] Second, the European Union (EU) recently published new rules to reduce the risk and use of pesticides in the EU,[76] requesting farmers to reduce the application of pesticides by 50% until 2030. This EU regulation could also be beneficial for WPM cultivation, because WPM not only require very little or no pesticides (herbicides) but could also have positive (spill-over) effects on the flourishing of arable crops in neighboring fields by promoting biocontrol agent populations. While this spill-over effect was not always proven to be significant in the literature,[77] most studies nevertheless report significant positive influences of wildflower strips on the biocontrol agent activity of neighboring agricultural fields.[78–82]

The seed production for WPM in Germany is dominated by one seed company, Saaten Zeller GmbH, which serves ≈75% of the market.[71] The most common seeding mixture for biogas production consists of a mixture of 25 different, mainly wild native species with annual, biennial and perennial growth patterns.[83] The species composition from this seeding mixture observed on the field varies significantly over the cultivation period (**Figure 3**).[46,84] Additionally, the number of species is decreasing over the years.[46] From the third year onward, perennial and biennial shrubs have established and dominate the stands, while in the first two years, annual and biennial species contribute in majority to the total biomass yield within the wild plant

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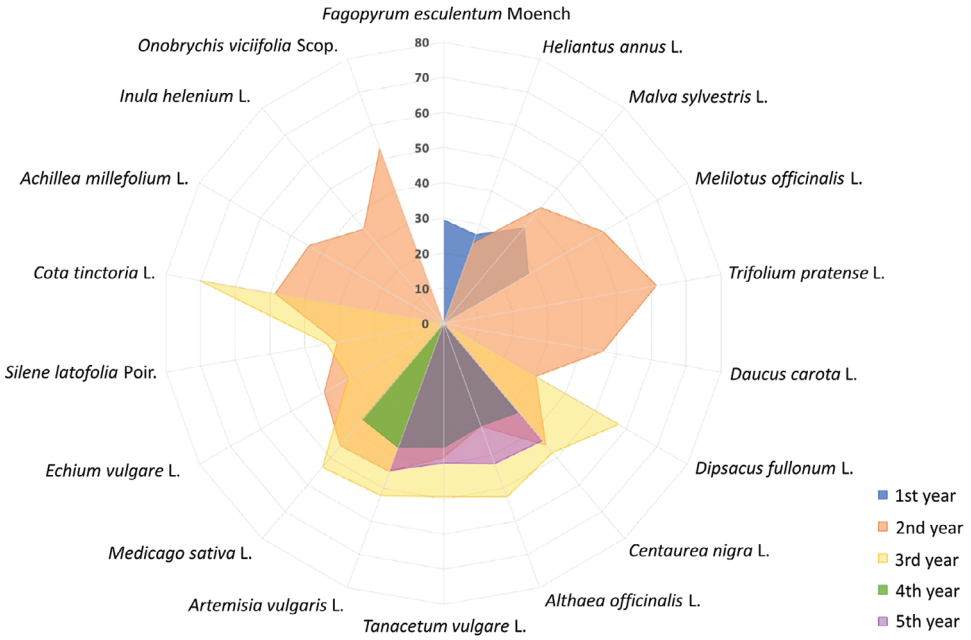


Figure 3. Community of wild plant species over five consecutive years as measured by their respective average percentages of total dry matter yield (adapted from Von Cossel and Lewandowski[46]). The data are composed of field trials at different locations, therefore the yield shares of all species together per year add up to more than 100%.

stands.[85] This dynamic change of species composition is accompanied by a decline in WPS richness the older the WPM stand gets (Figure 3).[46] The literature reports that certain WPS dominate in the development of WPS composition, whether due to their perennial nature (e.g., common tansy, mugwort) or the ability to produce seeds that can withstand the biogas production process and germinate in the field after the application of digestate (e.g., yellow melilot). This could help achieving some long-term persistence in the WPS stand through self-seeding.[46,84–87] Considering continuous changes in WPS composition due to varying dominances of specific WPS may in the longer-term challenge further biomass processing and needs to be considered at final application as a solid fuel. However, in a recent study it was demonstrated that the elemental composition of numerous WPS considered in this study was highly beneficial to reduce ash melting at higher temperatures.[35]

Four of the most prevalent WPS for biogas production in Germany are common tansy, mugwort, wild teasel, and yellow melilot (**Figure 4**).[29] Many wild bee species feed on these WPS. For instance, common tansy offers pollen and nectar to 21 wild bee species such as *Colletes similis*, *Heriades truncorum*, and *Andrena flavipes*.[88] Yellow melilot serves eight wild bee species with its nectar and pollen.[88]

3.2. Environmental Aspects

3.2.1. Landscape, Flora, and Fauna

One of the most important ecological advantages of WPS is the provision of habitat and food for animals in the field.[23,31,34,89] WPS provide seeds for birds and nectar and pollen for a variety of insects.[23] The seed quantity is estimated to reach ≈300 kg ha^{-1} year^{-1}.[90] Especially when comparing the biodiversity of insects to monoculture maize fields, WPS fields are inhabited by a much higher quantity and diversity of insects like ground beetles, butterflies and bees.[23,90,91] In addition, the landscape beauty over the surrounding areas provided by mixed wild flowers is a recognized advantage over conventional crops.[25]

With a winter harvest regime, it is expected that all the services mentioned in the previous paragraph will be expanded.[12] Most of the selected plants could flower 2–3 months longer than with a regular harvest time in July/August (Figure 4). The pollen, nectar and seeds would be available during autumn and winter times with little alternative seed supply for birds. The same can be assumed for the habitat function. In winter, when a majority of agricultural land is not cultivated, animals value shelter even more due to the lack of available places in open landscapes.

3.2.2. Soil Fertility and Soil Erosion

Unlike in annual cropping systems, WPS offers the advantage of longer soil dormancy because there is no tilling from the second year onward until the end of the cultivation period. This is beneficial for soil fertility,[37] because the rooting system of the plants (**Figure 5**) mitigates soil erosion, promotes soil microorganism activity,[9] and preserves the soil moisture.[30] Furthermore, there is a strong humus formation due to the accumulation of organic material due to both aboveground and belowground plant structures.[92,93]

The late harvest regime could have potential benefits on erosion, especially for the mitigation of wind erosion, due to the higher stands on the field. In addition, more organic material

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Common name	Botanical name	Life cycle	Habitus in summer	Habitus in winter	Supply of nectar	Supply of pollen	Flowering period: June	July	August	September	October	November
Common tansy	*Tanacetum vulgare* L.	Perennial			+	+						
Wild teasel	*Dipsacus fullonum* L.	Biennial			++	+						
Yellow melilot	*Melilotus officinalis* L.	Biennial			+++	++						
Mugwort	*Artemisia vulgaris* L.	Perennial			+	++						

Figure 4. Overview of morphological and physiological characteristics of four WPS common tansy (*Tanacetum vulgare* L.), mugwort (*Artemisia vulgaris* L.), wild teasel (*Dipsacus fullonum* L.), and yellow melilot (*Melilotus officinalis* L.) which were proposed by Von Cossel et al.[12] The additional information is based on other references.[27,33,64] The inflorescences of the four selected species are shown as vital plants during the summer months and as dry biomass during winter. Furthermore, it shows flowering phenology and the advantage of the plant to provide pollen and nectar, which is valid for all of them.

could be accumulated in late harvest above the soil due to plant detritus, e.g., fallen leaves, etc.

3.2.3. Further Ecological Advantages

Perennial cropping systems, like WPS cultivation, can cause lower nitrous oxide emissions, one of the major sources of greenhouse gas emissions in agriculture, than annual cropping systems.[94] In addition, nutrient leaching can be lower[92] with perennial crops like WPS due to an ealier start of vegetation and a better established rooting system compared with annual crops.[90] Moreover, WPS are potentially suitable for agricultural land near water bodies where a normal use of mineral fertilizers or synthetic pesticides is not allowed.[90]

3.2.4. Potential Impact of Extending the WPS Cultivation Period to more than Five Years

Many of the ecological advantages of the WPS cultivation system arise from the perennial nature of the plants.[95–98] In most liter-

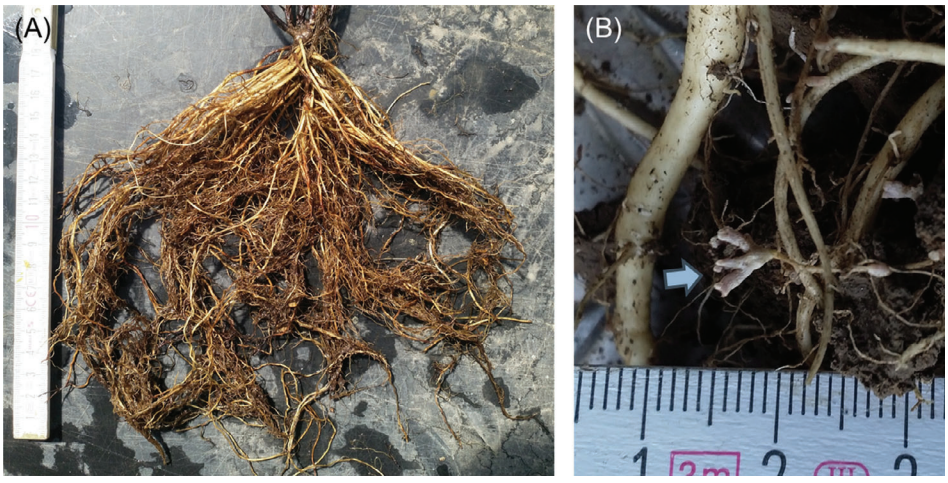


Figure 5. Washed roots of a 1.5-year old common tansy grown with five other individuals of the same species in a pot experiment (6 kg luvisol from the field) (A). Washed roots of a six-month-old yellow melilot grown on a shallow stony loam soil under rainfed conditions (B). The arrow in (B) shows a nodule containing the rhizobacteria with which melilot as a legume plant lives in symbiosis for atmospheric nitrogen (N_2) fixation. The units of the scales are in cm.

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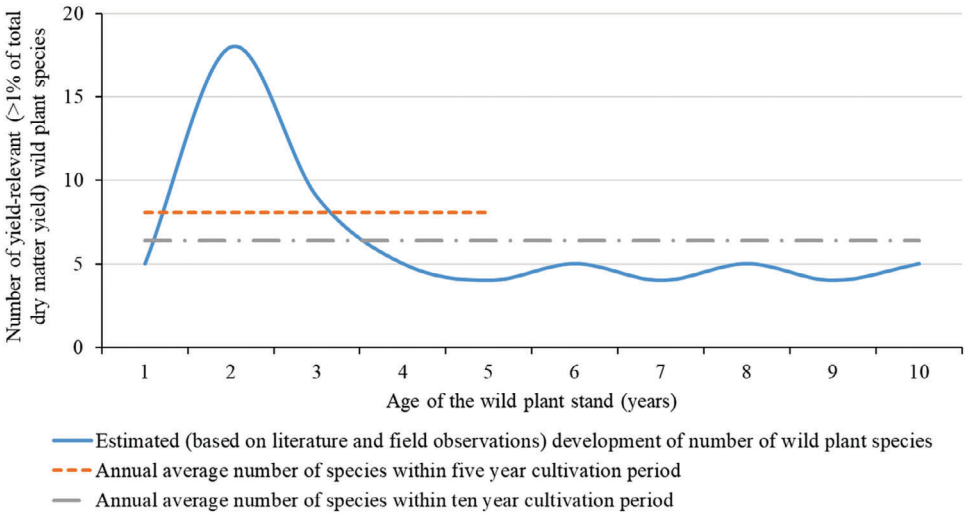


Figure 6. Estimated development of the numbers of yield-relevant (>1% of total dry matter yield) wild plant species in wild plant mixture stands over the years (blue line). These estimates are based on literature and field observations. The dotted lines indicate the calculated annual average numbers for a 5-year-cultivation-period (orange) and a 10-year-cultivation-period (grey).

ature, a cultivation period of five years is chosen for WPS.[30–32,46] In contrast to annual crops like maize used for bioenergy production, WPS need very low agricultural input from the second year after sowing onward.[29] This aspect is likely to have also positive implications on the necessary energy input for the cultivation of WPS in general.[29] From an agronomic perspective it is possible to extend the usually applied lifecycle of a WPS field from 5 to 10 years.[12,29,90] This extension is accompanied by even more pronounced positive effects on soil health as outlined above associated with time.[90]

However, some studies observed a diversity decrease starting in year four.[46,89,91] There is a significantly higher number of species in years 2–3 compared to 4–5 after sowing (**Figure 6**). From a seed mixture that initially contained about 20 species, the number of species on the field is most likely reduced to 4–5 dominant ones after four years (Figure 6). This effect will assumingly be extended over a 10-year lifecycle. For example, if the average number of WPS per year for the five-year cropping cycle is 8.2 (Figure 6) and there are 4–5 species left after the third year, the 10-year cropping cycle results in an average number of 6.4 species. This represents a 22% lower long-term WPS-richness compared to the five-year cropping cycle (Figure 6). It is yet unknown to what extend this could lead to a reduction in fauna diversity and a possible trade-off related to certain habitat, pollination, and further ecosystem services.[23,72] Due to this gap of knowledge, it is strongly recommended to carry out long-term on-farm studies focusing on species dominance and interaction, and dominant species influence on soil and outlined ecosystem services.

3.3. Cultivation Practices

3.3.1. Summer and Winter Harvest Regime

The current most prevalent harvesting regime for WPM in BW is the summer harvest regime, where the vital biomass is mowed in late July or August to be used as biogas feedstock.[30,32,90] At this stage, the water content of the harvested WPS biomass accounts for ≈80%.[30,33,34,37,99,100] However, for dry conversion processes like pelletizing and combustion the biomass should be as dry as possible. As proposed by Von Cossel et al.,[35] late harvest in winter results in a low moisture content and other positive quality criteria such as lower nitrogen content, and higher lignin content. This sub-section elaborates on the cultivation process of WPM and WPS, respectively, considering changes due to the shift in harvest regime (from summer to winter) and the extension of the cultivation period from 5 to 10 years.

3.3.2. Agricultural Practice and Operations

Practical experience shows that WPS can be cultivated with conventional process technology.[32,34,101] A look on the required cultivation steps of a 10-year WPS cultivation phase (**Figure 7**) reveals that machinery employment on the field is necessary twice per year during year 2–9: Once for applying fertilizer (e.g., digestate) and once for harvesting (Figure 7). This is quite similar to the cultivation of miscanthus despite the longer cultivation period for miscanthus.[102]

Crop Establishment: The preparation of the soil for WPS is the same as for other crops, like wheat or maize, including ploughing and harrowing. Before sowing it is recommended to prepare the soil with a roller in order to obtain a homogeneous seeding bed and seeding depth.[32] To improve the seed's contact with the soil, it can be rolled one more time after sowing.[90] WPS offers the great advantage that tillage and seeding only need to be done once during the growing season, which can help both conserve resources[29] and reduce labor peaks.[102]

Fertilization: Under social-ecologically aspects and under considerations of greenhouse gas mitigation it is possible and worthwhile to cultivate WPS with low-input agricultural practices by substituting synthetic N-fertilizer with organic, residues-generated fertilizers such as digestate from biogas production.[32,34,101] According to best management practice, this

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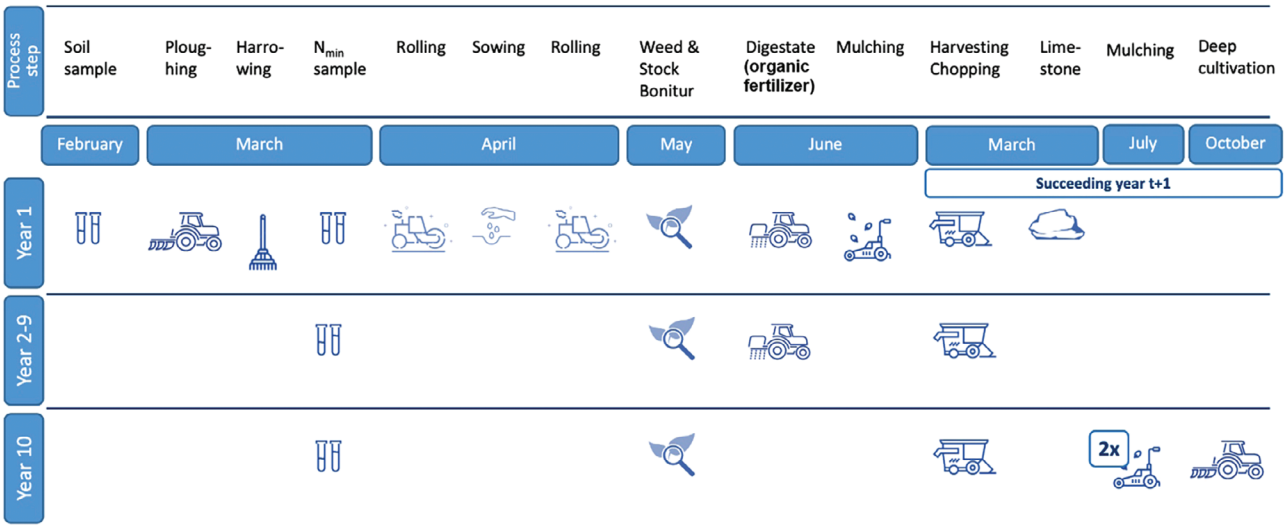


Figure 7. Cultivation procedure under late harvest regime and a 10-year lifetime (adapted from[170] Kuhn et al., 2014; Von Cossel, 2020).

should replace the amounts of nitrogen removed by harvesting the above-ground biomass. On average, this accounts for 50 to 150 kg N ha^{-1} per year.[34]

For the winter harvest regime (harvest in February or March), studies about miscanthus indicate lower nutrient needs with shift of harvest,[43] allowing for a translocation of assimilates and nutrients like nitrogen into the root storing organs of the plants and therefore a recycling of higher amounts of nutrients compared with late summer harvest regimes.[103,104] Future work is needed to determine whether this is also the case for perennial WPS, and in how far nitrogen fertilizer use can be further reduced. In addition, further work is needed to assess whether a single application of fertilizer, e.g. via digestate, is sufficient for stand safety if the plants are harvested only in winter. This would relieve peak workloads at summer times when the cultivation of other arable crops is at its peak.

Crop Protection: In general, WPS cultivation does not require insecticides,[71] which would also contradict the beneficial effect of WPS on the broad insect fauna. The very selective application of herbicides becomes sometimes necessary in the first cultivation years in areas with high weed pressure. Practitioners report about issues with grasses such as field foxtail grass (*Alopecurus pratensis* L.) that migrate into the WPS from the edges of the field. Wurth et al.[84] further mentioned the occurrence of Kentucky bluegrass (*Poa pratensis* L.), timothy grass (*Phleum pratense* L.) and cocksfoot (*Dactylis glomerata* L.).[34] In such cases, the application of a grass herbicide might be indicated.[90]

Von Cossel and Lewandowski[46] reported that the second cultivation year was especially affected by weed occurrence. According to Hahn et al.,[85,87] weed density decreases significantly over the cultivation period due to the increasing WPS density. One preventive measure for fields with high weed pressure is summer sowing after a well-grown winter cereal.[32,90] With this method the strong spring growth period for weeds is simply avoided.[32] Another way to prevent weeds is to perform a mulch cut during the first year.[30,32]

Harvesting: In summer harvest, WPS biomass is usually harvested using a self-propelled forage harvester with a maize harvesting header to produce chaff (**Figure 8**). According to the literature, this technique is also used for winter harvest of miscanthus[105] or *Sida*).[106] It can be assumed that this also applies to the winter harvest of WPS[107] but this is yet to be tested on-farm.

Although winter harvest of WPS remains challenging due to the uncertain and possibly wet weather during February and March, farmer could use the frosty days for harvesting to prevent severe compacting of the soil, rendering another advantage compared with summer harvest.[90]

Crop Removal: Deep cultivation and two times mulching becomes necessary in the last cultivation year to lay the soil ready for the next crop rotation.[108] In conventional farming practices, (soil active) herbicide application might need to be considered in addition to the mechanical treatments. However, first results of an organic farm in southwest Germany have shown that reintegration of arable crops (e.g., silage maize, winter wheat) in fields where common tansy was grown can be both practicable and successful without herbicide application.[108]



Figure 8. Conventional harvesting method of a wild plant mixture stand in its second year by means of a self-propelled forage harvester with maize harvesting header. (Source: Michael Bischoff).

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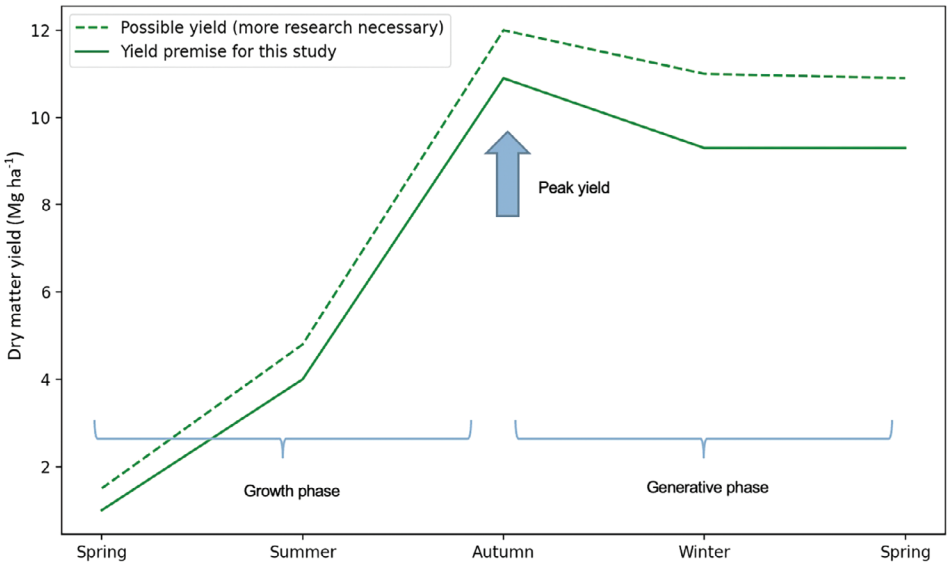


Figure 9. Schematic description of the expected yield change of WPM due to shift in harvest regime from summer (solid line) to winter harvest regime (dotted line). The concept was adapted from a study on miscanthus cultivation by Lewandowski et al.[110]

3.4. Yield Potential of WPS

3.4.1. Dry Matter Yield for Summer Harvest

As WPM yields differ strongly depending on the species composition, location, and cultivation year it is not possible to talk about exact yield figures at species level (WPS), and rather provide ranges of the yield potential.[23,29,30,33,34,84,99,101,109] For this study, an average of this data, considering only studies with a minimum of 3 cultivation years, is assumed, resulting in annual average WPM dry matter yields of 10.9 Mg ha^{-1}.

3.4.2. Dry Matter Yield for Winter Harvest

So far, there are only preliminary indications in the literature of a possible yield potential of selected WPS. For example, Von Cossel et al.[35] report annual dry matter yields of 8.3 to 13.1 Mg ha^{-1} for the winter harvest of WPS common knapweed and common tansy, respectively. To estimate the yield for the winter harvest regime, two aspects need to be considered. First, the peak yield for WPS is in autumn when the growth phase of plants is over (**Figure 9**). During the months until winter harvest, the plants lose not only moisture but also plant material, which leads to decreasing dry matter yields (Figure 9).

For miscanthus, the difference of dry matter yield between summer and winter harvest are reported to be ≈28–35%, depending on genotype and location.[103,104,110–112] This yield difference gets even higher with increasing time gap, mainly induced by detachments of foliage and parts of the stem.[103,112] This observation could be similar for WPS, but scientific data are missing to date allowing for a sound estimation of yield decline due to winter harvest. However, the late harvest enables biennial and perennial plants to relocate assimilates into the rhizomes/root systems.[103,112] This effect could partly offset the negative effect of a summer harvest if it occurs similarly for WPS (Figure 9). While there are no indications for a significant yield decrease due to the shift in harvest regime so far,[35] long-term studies on WPS winter harvesting regime are needed to clearly quantify both yield losses during autumn and winter (due to falling leaves or stem parts) and long-term biomass yield stability changes; the latter due to better relocation of nutrients and assimilates to the rhizomes of the biennial and perennial WPS.

Considering the yield data for summer harvest[33,34,37,46] and the aspects explained in this section, the authors choose a conservative approach assuming a dry matter yield reduction of 15% compared to the average dry matter yield of summer harvest (previous section), resulting in a dry matter yield of 9.3 Mg ha^{-1}. For comparison, miscanthus harvested in winter has a yield of ≈18.7 Mg ha^{-1}.[103]

4. Market Analysis

Modern pellet firing systems represent an economically attractive, convenient and environmentally friendly alternative for heat supply.[54,113] With CO_2-neutral combustion, they make an important contribution to climate protection.[54,113] The following section analyses the application forms of woody pellet combustion in the household sector, the energy demand, and prices, as well as the pellet production in the state of BW, Germany.

4.1. Thermal Energy Demand in Baden–Württemberg

In southern Germany, pellet firing is a traditional source of thermal energy.[114–116] Yet, in BW, oil (40.7%) and gas (26.6%) are still the predominant thermal energy sources in central heating systems, while pellet or wood heating systems account for only 3.6% of the local heating systems.[117]

By 2022, almost 21% of the country´s total pellet heating systems were installed in BW – making the federal state the second

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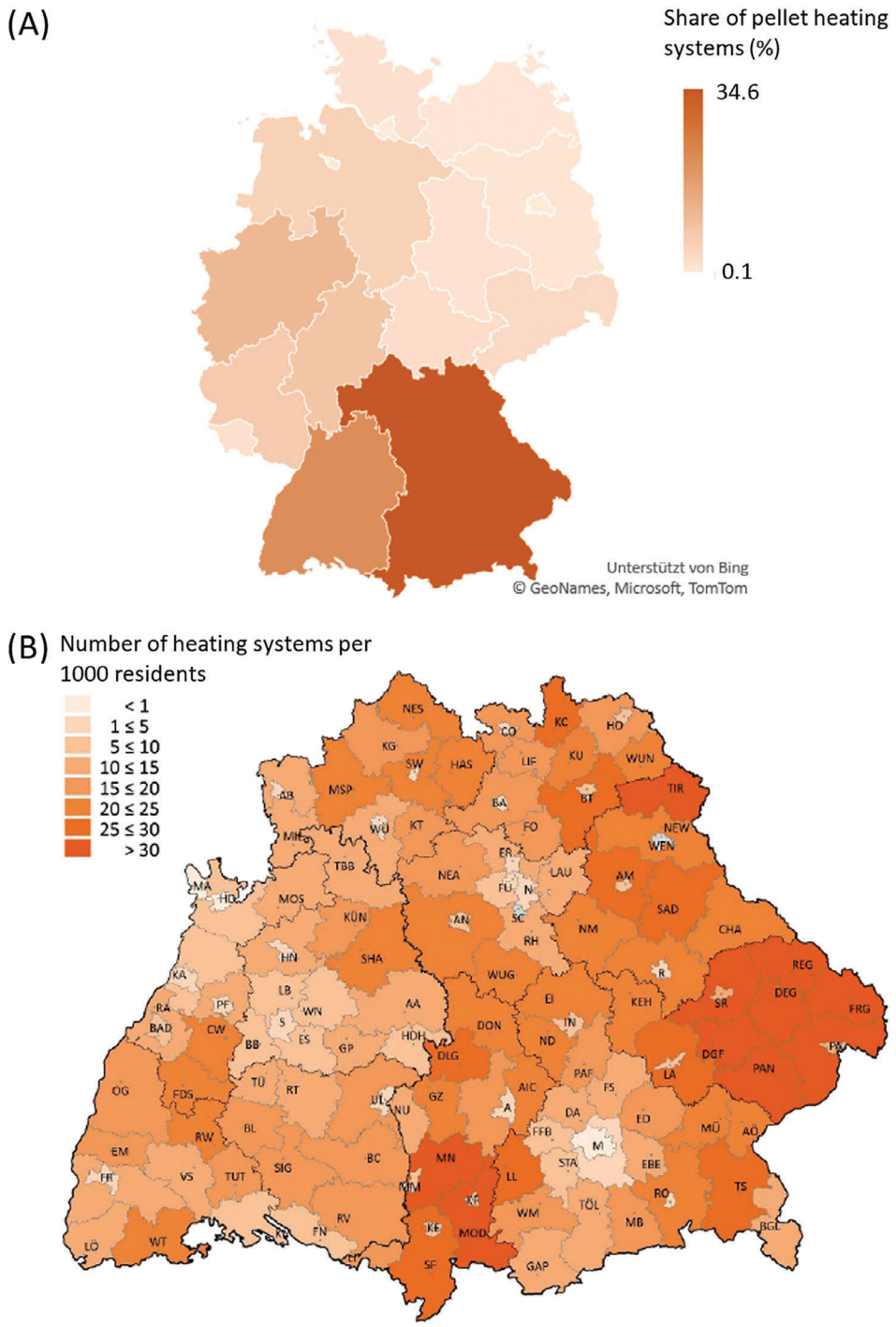


Figure 10. Distribution of pellet heating systems across Germany[119] (A), and the number of pellet heating systems per 1000 residents in BW and BY[119] (B).

largest pellet consumer after Bavaria (34.6%)[116] (**Figure 10**A). The number of pellet heating systems per 1000 residents are ranging from 1 to 25[116,118] (Figure 10B).

In 2021, a total of 517 500 Mg of pellets were consumed in BW, enabling CO_2 emissions savings of 777 500 Mg.[118] This data represents an increase of 25% in total pellet consumption, when compared to 2016. The increased pellet consumption between those years may be associated with the rise of almost 40% in heating stoves installations between 2016 and 2021.[118,119]

In BW, final energy[118] consumption for heating reached 156 TWh in 2021, from which 15% (23.5 TWh) came from renewable energy sources, an increase of only 0.5 percentual points regarding 2020. Solid biomass combustion contributed the most to the thermal energy supply: 7696 GWh (4.9%) for traditional solid

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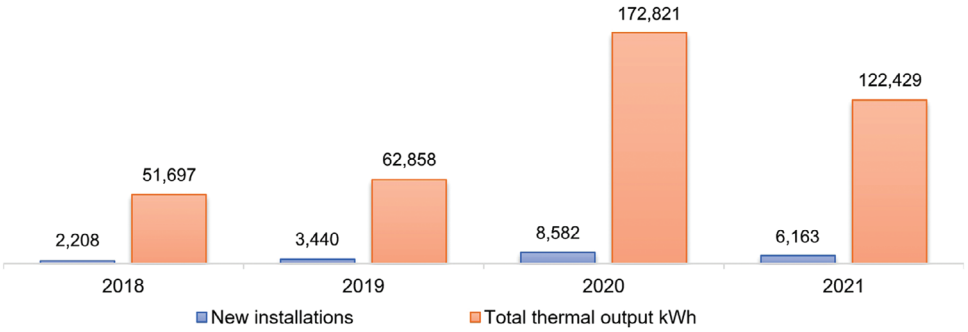


Figure 11. New boiler installations and total thermal output in Baden–Württemberg during 2018 to 2021 (adapted from Biomasseatlas, https://www.biomasseatlas.de/index.php?id=1).

biogenic combustion methods and 9774 (6.3%) GWh for modern ones. Other renewable energy sources, such as solar, wind, and geothermal contributed less than 2% each to the thermal energy supply (Umweltbundesamt, 2022).

4.2. Energy Demand for Residential Heating in Baden-Württemberg

The thermal output originating from stoves of up to 50 kWh more than three-folded between 2018 and 2020 (**Figure 11**). In the period under analysis, the stove installations increased by more than 288%.

4.3. Pellet Production in Baden–Württemberg

The current use of wood energy in Germany is covered up to 98.3% by the domestic supply of wood energy products. At 1.7%, the foreign trade balance accounts for a small part of the domestic supply. Yet, given the increasing demand for pellets and wood energy, higher imports from, e.g., USA and Canada may be expected.[120]

Data from the German Pellet Institute (GPI) shows that more than 95% of the country´s woody pellet production is ENplus certified.[121] German pellet production has more than six folded during the last 15 years, from 470 000 Mg in 2006, to 1 930 000 Mg in 2016, and up to 3 355 000 Mg in 2021. In 2022, the production is expected to reach 3 600 000 Mg and a capacity of ≈10% more.[118]

As displayed in **Figure 12**, from the 58 ENplus certified pellet production plants in Germany, 12 are located in BW, which makes the federal state the second largest producer after BY. Two more plants are to be constructed, with a production capacity of 60 000 and 120 000 Mg a^{-1}, respectively.[121] In 2020, BW was responsible for the production of 480 000 Mg of pellets, i.e., 15.5% of the country´s total production. The region supplies itself almost entirely with pellets: over 90% of the pellets used come from local production plants. The remainder is obtained from plants in neighboring federal states close to the border.[116]

4.4. Pellet Prices

Pellet prices have been characterized by low dynamics in the last decade. The average annual price increased by 0.24% from 2012 to 2021; adjusted for inflation, prices even fell by 1.44%. During this period, there were some significant price increases in the energy sector, especially for oil, without the pellet price reacting to this. This suggests that there is no interdependency between the price development of pellets and fossil fuels. It is exceptional in the early summer of 2022 that the price of pellets has continued to rise, as it is usually declining at this time of the year.[118] The reasons for this lie in the war-related global upheavals in the energy market[122,123] and, consequently, in the pellet market.

When compared to other thermal energy sources, such as oil and gas, pellets still offer the consumers the most favorable prices (**Figure 13**). Based on data from Deutsches Pelletinstitut (2022),[124] Figure 13 compares the thermal energy prices in ct kWh^{-1} between April 2022 and June 2022. Thermal energy prices for fossil fuels have risen by 22% in two months, while pellet prices increased by 16%.[124] By 2023, pellets have maintained a price advantage of ≈30% compared to heating oil and natural gas.[124]

Finally, pellet prices per 1 Mg diverge within the country´s regions. The lowest prices are offered in southern Germany, where ample feedstock reserves are available. Here, the price per 1 Mg is on average 3.4% lower than in the center federal states and 6.4% lower when compared to northern and eastern Germany. The discrepancies can be greater or smaller, according to the amount (3, 6, or 26 Mg) being bought by the customers.[124] The current average pellet prices are 350.93 € Mg^{-1} for 6 Mg and 330.54 € Mg^{-1} for 26 Mg containers.[124]

4.5. Legal Framework

The regulatory framework is considered an essential part of the basic requirements to scale up the cultivation of perennial biomass crops as well as the use of their biomass in a sustainable way.[17] In recent years, the German government has taken several legal initiatives to promote more sustainable practices in the heating sector, both on a federal and state level.[125] New regulations regarding, for example, the installation of pellet stoves have been implemented in an effort to decarbonize the industry.[120,126]

4.5.1. Renewable Energy Directive II

At European level, the Renewable Energy Directive II encourages the use of renewable energy forms to comply with the goal of re-

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Figure 12. Pellet production in Germany (adapted from[119]).

ducing greenhouse gas emissions by at least 40% until 2030. To do so, the EU must ensure that by 2030, at least 32% of its final energy consumption is generated by renewable resources. Moreover, the directive seeks to promote technological development and reduce the investment costs for renewable energy production to ensure the Member State´s contribution to the 2030 goals.[127] Since the heating sector accounts for ≈70% of the temperature-adjusted household energy consumption in BW,[128] it plays a key role in the decarbonization and energy security strategy at a European and national level.[127]

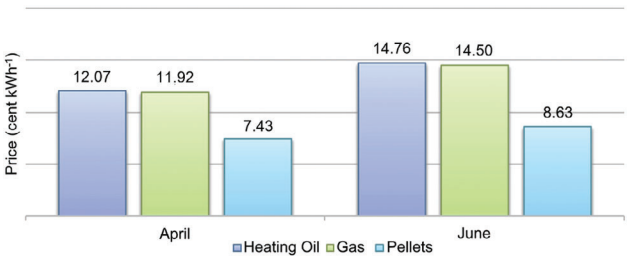


Figure 13. Thermal energy price development between April and June 2022 in ct kWh^{-1} (adapted from[124]).

4.5.2. Building Energy Act, 2020

Within the national legal framework, the Building Energy Act[129] combines the Energy Saving Act,[130] Renewable Energy Heat Act[131] and Energy Saving Regulation[132] and creates a new, uniform, coordinated set of rules for the energy requirements for new and existing buildings and the use of renewable energies for heating and cooling of buildings.[133] Article 1 of the act describes the goal, which is to encourage a more economical use of energy in buildings and increase the share of renewable energy sources used for heating, cooling, and electricity generation.[129]

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It can be assumed that this Act, together with further regulations, such as the Federal Funding for Efficient Buildings,[134] will increase the demand for solid biomass thermal energy boilers and stoves, and therefore the demand for pellets.

In April 2023, the Federal Ministry for Economic Affairs and Climate action took a further step toward decarbonizing the heating sector.[135] The draft law amending the Building Energy Act establishes that from January 1, 2024, every newly installed heating system should be operated with at least 65% renewable energy. Existing heaters can continue to run and be repaired. There are generous transition periods and exceptions, a strong social balance – and extensive funding. By 2045, heating systems may no longer be operated with fossil fuels.[135]

5. Processing of WPS Biomass

Von Cossel et al.[35] argue that winter harvest of selected WPS might turn into promising bioresources for other bioenergy conversion pathways than anaerobic digestion. The results indicate that the energy yield for combustion was 1.5–2.8 times higher compared to anaerobic digestion.[35] However, in addition to the substrate-specific energy yield potential, there are a number of other quality criteria to consider for pellet or briquette production and application,[47,136–138] which will be explored in more detail in this section.

Given the lack of scientific research on WPS pellets, the literature search was expanded to include biomass types that are comparable to WPS as well as briquette classifications. This is to pursue the aim of this study to gain initial insights into the qualitative and quantitative variables for the applicability of WPS pellets for direct combustion. Note that this study addresses the influence of the biomass characteristics on pellet quality, such as composition, needed additives, and pre-treatments. The effects of process parameters (such as temperature, pressure and holding time) on pellet features are not covered. In addition, the focus here is on the application of WPS pellets used within residential areas as well as in the commercial sector.

5.1. Pellet and Briquette Quality Standards

International pellet and briquette[139] quality standards were developed by the International Organization for Standardization (ISO). In particular, the DIN EN 14961–2 and ISO 17 225 support the use of classified non-wood pellets and briquettes, respectively, in residential, small commercial and public buildings.[140,141]

The standard ISO 17225–7 refers to pellets and briquettes made from the raw materials i) semi-commodity biomass, ii) biomass of fruit, iii) aquatic biomass, and iv) defined and undefined mixtures. Defined and undefined mixtures are mainly origin-based groups of solid woody biomass, stalky biomass, fruit biomass, and aquatic biomass. Furthermore, defined blends are intentionally mixed biogenic fuels, while undefined blends are randomly mixed biogenic fuels.[140]

Households and small commercial and public sector buildings or industrial applications demand the use of fuels with specified quality that are expressed by classes A1 (households), A2 (small commercial sector) or B (industrial applications)[140] (**Table 1**). It turns out that the WPS for pellet combustion must meet much stricter quality criteria than for briquette combustion (Table 1).

5.2. Biochemical Composition and Calorimetric Value of WPS Biomass

Regarding the biochemical ingredient requirements of WPS, previous studies have provided promising indications that there may be many WPS candidates with particularly good burning properties among the many available.[12,35] This was evident from the fact that significantly better ash melting behavior was observed for three of the most yield-relevant perennial WPS common tansy, mugwort, and common knapweed.[12,35] Multiple replicates of the analysis, as well as the use of additional field replicates (including those from multiple years) and the addition of more species, confirmed these results.[142] The difference in ash melting behavior between the WPS and miscanthus was explained by significant differences in contents of Ca and Mg in the biomasses. The contents of these elements were higher in the WPS and lead to a significant increase of the ash melting point temperature compared with miscanthus biomass, even though the contents of less favorable elements like P and K were at a same level like miscanthus.[142] Another study showed that the ash melting behavior of WPS can be used to create positive effects of blending with other biomass types of a lower ash melting behavior such as miscanthus.[12]

Furthermore, ongoing studies (unpublished) indicated that the WPS selected here exhibited an increased alkali metal volatilization temperature compared to miscanthus or wood. This is to be judged as particularly positive from environmental as well as operational aspects and would clearly speak for the use of WPS biomass as cosubstrate in pellet or briquette production. However, the high ash content in WPS biomass may mask the abovementioned potential advantages of WPS biomass for pellet combustion.

Generally, the ash content should be as low as possible (Table 1), because it negatively influences the higher heating value (HHV) and combustion efficiency.[143–146] However, three perennial WPS investigated by Von Cossel et al.[35] showed ash contents ranging between 2.2 and 5.7% of dry matter (**Table 2**). The ash content generally depends on the species[147] (Table 2), the maturity level and overall morphological condition (e.g., leaves fallen off or not) at harvest,[30] as well as contamination with soil that might occur during harvest.[30]

However, other pellet cosubstrates also showed a comparably (regarding the pellet requirements shown in Table 1) high ash content of biomass pellets (**Table 3**). For instance, ash content of pure non-woody pellets made of elephant grass was 6.48%,[151] for miscanthus 5.9% and wheat straw 7.3%[150] rendering unsuitable for most of the pellet and briquette quality gradations (Table 1). Likewise, the effect of ash content on HHVs was observed in the case of miscanthus, where it decreased to 17.7 MJ kg^{-1} for pure pellets that does not meet the quality standard "Grade 1".[152] However, a difference can be seen between the values obtained by Mirowski et al.[153] where the ash content for miscanthus pellets accounted for 1.7%. This difference can be attributed to differences in the structural constituents of the plant[143] and harvest technology, which very likely will also be true for the various WPS as well due to their wild nature.[46]

To find indications of potential ways to improve WPS biomass performance in pellet combustion, blended pellets of various substrates and substrate mixtures were reviewed (Table 3). Out-

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Table 1. Specification of quality requirements for classified non-wood pellets and briquettes. For each parameter (except those related to dimensions), color scaling was added to illustrate differences in quality requirements between pellets and briquettes, or the respective gradations (A1, A2, B), from high (green) to low (red) quality.

		Pellets DIN EN 14961-2		Briquettes DIN EN ISO 17225-7_2020		
Quality parameter	Unit	Enplus A1	Enplus A2	A1	A2	B
Diameter (or height and width)	mm	6 (± 1) or 8 (± 1)	6 (± 1) or 8 (± 1)	≥ 25	≥ 25	≥ 25
Length	mm	3.15≤L≤40	3.15≤L≤40	≥ 25	≥ 25	≥ 25
Net calorific value, Q, ISO 18125	MJ kg^{-1}	≥ 16.5	≥ 16.3	≥ 14.5	≥ 14.5	≥ 14.5
Moisture, M, ISO 18134-1, ISO 18134-2	Wt.-%[a)]	≤ 10	≤ 10	≤ 12	≤ 12	≤ 15
Ash, A, ISO 18122	Weight-%	≤ 0.7	≤ 1.5	≤ 3	≤ 6	≤ 10
Ash melting temperature	°C	≥ 1200	≥ 1100	n.a.[b)]	≥ n.a.	≥ n.a.
Chlorine, Cl, ISO 16994	Weight-%	≤ 0.02	≤ 0.02	≤ 0.05	≤ 0.1	≤ 0.3
Sulfur, S, ISO 16994	Weight-%	≤ 0.03	≤ 0.03	≤ 0.2	≤ 0.2	≤ 0.3
Nitrogen, N, ISO 16948	Weight-%	≤ 0.3	≤ 0.5	≤ 1.5	≤ 1.5	≤ 2
Copper, Cu, ISO 16968	mg kg^{-1}	≤ 10	≤ 10	≤ 20	≤ 20	≤ 20
Chromium, Cr, ISO 16968	mg kg^{-1}	≤ 10	≤ 10	≤ 50	≤ 50	≤ 50
Arsenic, As, ISO 16968	mg kg^{-1}	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1.5
Cadmium, Cd, ISO 16968	mg kg^{-1}	≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.5
Mercury, Hg, ISO 16968	mg kg^{-1}	≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.1
Lead, Pb, ISO 16968	mg kg^{-1}	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10
Nickel, Ni, ISO 16968	mg kg^{-1}	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10
Zinc, Zn, ISO 16968	mg kg^{-1}	≤ 100	≤ 100	≤ 100	≤ 100	≤ 100

[a)] weight percentage; [b)] not applicable

comes demonstrated that blending WPS biomass might be a reasonable approach in terms of ash melting behavior. This is because blending biomasses of different sources many of which would not meet the quality standards (e.g., elephant grass, miscanthus and straw) succeeded in creating biomass mixtures that meet the quality requirements (Table 3).[154,155] The blending ratios strongly varied depending on the sources of suitable (wood) and less suitable biomass sources (miscanthus, elephant grass and straw): 70% wood and 30% miscanthus,[150] 50% elephant grass and 50% eucalyptus wood,[151] 70% straw and 27% willow wood and 3% lime[156] (Table 3).

Table 2. Biomass calculator for blended WPS pellets (adapted from[35,148–150]). The colors indicate which quality criteria of the pellets are fulfilled, from dark green (threshold values for all quality grades) to dark brown (threshold value for only one quality grade is fulfilled).

Substrate components and blended mixtures	HHV [MJ kg^{-1}]	Ash [wt.%]	Moisture [wt.%]
Common tansy (CT)	16.8	4.7	14.9
Common knapweed (CK)	16.1	2.2	7.2
Mugwort (MG)	16	5.7	12.5
Miscanthus (MIS)	17.7	2.3	10.7
Straw	18	5.7	12
Wood	19.3	0.3	9
Sawdust (SD)	18.5	0.3	8
Wild plant species (WPS = 33.33% CT + 33.33% CK + 33.33% MG)	16.3	4.2	11.5
70% SD + 30% WPS	17.8	1.5	9.1
50% SD + 50% WPS	17.4	2.3	9.8
50% MIS + 50% WPS	17	3.3	11.1
70% MIS + 30% WPS	17.3	2.9	11

Another important factor for pellet quality is the moisture content of the raw material (Table 2), as it is one of the basic determinants of the density and durability of the pellets[47,157,158] as well as the binding mechanisms in the pellets.[159] A moisture content beyond the optimum value has a negative impact on the physical properties of the pellets.[159] Xuya et al.[160] and Cui et al.[155] report optimum moisture contents for biomass from wood and herbaceous plants of ≈12%, while other studies found suitable moisture contents of below 10%[150,151,153,156,160,161] (Table 3). Along with this, the authors also demonstrated that pellet density and heating value are related with the content of moisture, with lower moisture content corresponding to higher heating values. Consequently, the WPS biomass should be harvested at a stage when most of the inner water contents of the stem and leaves has desiccated. For other herbaceous bioenergy crops such as *Sida* and miscanthus, this is usually during February and March, when frost has occurred at least once and wind has dried the aboveground parts of the plants.[102,106] Following the first studies on WPS for combustion, the water content of

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Table 3. Composition and main parameters of pellets made of different biomass sources and mixtures (values rounded, "n.a." = not available).

Feedstock	Lignin [%]	Moisture [%]	Ash content [%]	HHV [MJ kg^{-1}]	Pellet length [mm]	Pellet diameter [mm]	Milling size [mm]	Comments	Reference
70% wood + 30% miscanthus	n.a.	7.3	1.2	18.8	n.a.	n.a.	30	Significant reduction of the slagging risk in the bottom ash during combustion can only be achieved for very high blending ratios	[150]
50% elephant grass + 50% eucalyptus wood	24.9	8.1	2. 9	18.5	17.9	6.1	5	Pellets produced with mixed biomass compositions obtained better performance	[151]
70% of straw + 27% of willow wood + 3% of lime	n.a.	6–8	3.0	16.3–20.7	n.a.	8	n.a.	Problems with burning this material caused by the accumulation and melting of bottom ash on the grate, which damaged the furnace	[156]
2.68% wheat flour + 37.30% cherry pits + 34.12% sunflower seed shells + 5.90% wood ash	n.a.	5.8	n.a.	5.8	5	15	n.a.	Have a longer combustion time than commercial pellets	[161]
Miscanthus	n.a.	6.5	1.7	17.2	n.a.	n.a.	n.a.	Addition of solid catalyst to improve combustion and reduce NOx.	[153]
Pine sawdust, maize straw, peanut shell		12, 12, 14						Optimum moisture content, pellet density and heating value are related with it.	[160]

WPS ranges from 7.2 to 14.9% (Table 2),[35] which is close to the optimum. But it should be considered to further reduce the water content of the WPS during harvest.

5.3. Potential Pre-Treatments for WPS Biomass for Pellet Combustion

One pre-treatment approach to be tested with WPS is the thermal degradation of the structural constituents using Microwave (MW) pre-treatment. It can be used to improve the thermochemical conversion of different origin lignocellulosic biomass blends. This technology has the potential to provide uniform spatial heating of biomass with a faster thermal destruction of hemicelluloses and cellulose and a faster thermochemical conversion of pre-treated biomass.[162] Previous research has shown that MW pre-treatment of pellets increases pellet weight loss, porosity and reactivity, enhancing their thermal composition during gasification. Along with increasing the pre-treatment temperature, it promotes CO_2 yield up to peak levels, resulting in faster and more complete volatile combustion. By increasing the volume fraction of CO_2 in the products, the mass fraction of polluting NO_x emissions was reduced while overall combustion efficiency was increased.[163,164] Goldšteins et al.[164] discovered that wheat straw pellets had the highest structural variations and elemental composition during MW pre-treatment, with a 40–50% increase in combustion efficiency. Since straw ash contents[165] range around the same level like WPS (Table 2), it might be worth testing the suitability of MW pre-treatment on WPS biomass.

Another pre-treatment would be blending WPS biomass with other types of biomasses (Table 3) such as sawdust, a residual material from forestry that has recently been shown to be a techno-economic substrate for pellet combustion.[166] As shown above, the ash contents of pure WPS feedstock exceed the allowable limit for most of the pellet- and briquette quality gradations (Tables 1 and 2). Therefore, WPS biomass blending with sawdust and miscanthus were estimated. Adding 50% of sawdust results in a decrease of ash by 46% and simultaneously increase the HHV to 16.3 – 17.4 MJ kg^{-1}. A blending of 30 wt.% WPS with 70 wt.% of miscanthus reduces the ash content up to acceptable values (Table 3) and it could improve the ash melting behavior of miscanthus as well.[12] Furthermore, the moisture content reaches the range of values considered optimal (10–15%) to obtain good physical properties. The chlorine and sulphur content meet ISO standards, yet it is important to note that the chlorine values were obtained during the winter harvesting season. In addition, particle size has to be taken into consideration, as the fines generation increases with the reduction of particle size.[167]

However, whether pretreatment really makes sense will only become apparent after calculating the total expense of WPS seeding, lease fees, harvesting and storage, and pellet processing at the end. This will be discussed in more detail in the following two sections "Energy return on investment", and "Economic viability".

6. Energy Efficiency and Energy Return on Investment

As WPS are proposed as energy crops, it is important to compare the energy that is required to produce WPS pellets with the energy that can be obtained from the pellets, which is the objective of this section. The term "Energy efficiency" according to the EU Energy Efficiency Directive can be defined as "the ratio of output of performance, service, goods or energy to input of energy".[168] Energy Return on Investment shows exactly the relationship of achieved and consumed energy[169] and is therefore a suitable tool to assess the energy efficiency. For the energy consumption, the focus in this work is on three main energy consuming processes in the supply chain: 1) agricultural production, 2) transport of the biomass, and 3) processing at the pellet production

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Table 4. Energy demand of the agricultural production of WPS (adapted from[171] with parameters field size = 5 ha, mechanization = 67 kW, and field to farm distance = 2 km).

No.	Process step	Step derived from crop	Energy demand (in MJ ha^{-1})		
			Planting year	2nd to 9th (4th) year	Recultivation year
1	Soil sampling	Cup plant	3		
2	Ploughing	WPS	1270		
3	Harrowing	WPS	331		
4	N_{min} sampling	Miscanthus	20	20	20
5	Rolling of seedbed (preparation)	Grassland	238		
6	Sowing	WPS	615		
7	Rolling of seedbed	Grassland	238		
8	Weed bonitur	Cup plant	18	18	18
9	Stock bonitur	Cup plant	14	14	14
10	Digestate application	Cup plant	188	188	188
11	Mulching (weed suppression)	WPS	665		
12	Chopping (incl. transport)	Miscanthus	1665	1665	1665
13	Limestone application	Miscanthus	626		
14	Mulching	Miscanthus			551
15	Mulching	Miscanthus			551
16	Heavy tine cultivation	Miscanthus			791
Total			5890	1905	3798
Average energy demand per year (10 years cultivation)				2493	
Average energy demand per year (5 years cultivation)				3080	

facilities. Other aspects, such as the generation and possible handling of dust during harvesting and post-harvest processing of WPS biomass, are not considered here due to the generally still low level of knowledge in this area.[167] However, future studies on this are advised, as biomass of herbaceous plants such as the WPS are generally more prone to dust formation than biomass of wood and sawdust.[167] For the quantification of the energy supply of WPS pellets the HHV is used.

6.1. Energy Consumption for Agricultural Production of WPS

The process for agricultural production of the biomass has been discussed in Section 2.3. Based on this and additional data of energy consumption for each cultivation step from KTBL,[170] an average energy demand per year of 2,493 MJ ha^{-1} for a cultivation period of 10 years can be anticipated (**Table 4**). With a cultivation period of 5 years the energy demand would be 3,080 MJ ha^{-1}, all other premises remaining the same (Table 4).

An average dry matter yield of 9.3 Mg ha^{-1} and an energy consumption of 268 MJ Mg^{-1} for the step of agricultural production over 10 years cultivation (5 years: 331 MJ Mg^{-1}) is assumed.

6.2. Energy Consumption for Transportation from Farm to Producer

For the calculation of energy demand for transport, the authors use as a first step a very simple "best case scenario" that assumes the production facility of the pellet producer is within a 20 km average distance to the WPS farmer. Due to the short distance no intermediate storage is necessary and the farmer uses his existing equipment, which is a tractor with two 10 Mg-trailers to transport the chopped biomass. Further development of more complex transportation scenarios is necessary to include WPS supply from longer distances.

Due to the missing data availability for WPS bulk density, values for miscanthus[105] are used for this calculation. This results in an energy demand of 370.3 MJ Mg^{-1} for transport in the "best case scenario" (**Table 5**).

6.3. Energy Consumption for Pelletizing

For the calculation of energy consumption for pelletizing based on WPS biomass it was assumed that the energy demand for all process steps incl. grinding, cooling, pelletizing is similar between sawdust and WPS biomass. Nevertheless, a significant difference can be estimated for the drying process because WPS biomass contains much less water than sawdust.[158] Kristöfel and Wopienka[149] argue that no additional drying is necessary for straw with a moisture content of 15%. Therefore, the same can be assumed for WPS biomass with a residual moisture content of 15%.[35] However, using the precautionary principle, and setting the premise for "dryness" equal to the energy calculation of sawdust by Obernberger & Thek[174] a drying step to reach a moisture content of 10% is required. While for sawdust, a moisture content reduction of 45% (from 55% to 10%) is the premise

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Table 5. Energy consumption for transportation from farm to pellet producer.

	Calculation	Premise	Value	Unit	Reference
(A)		Average distance farm to pellet producer	20.0	km	–
(B)		Speed in km/h	30.0	km h^{-1}	–
(C)		Fuel consumption	11.0	L h^{-1}	[172]
(D)		Conversion factor Diesel	40.9	MJ L^{-1}	–
(E)		Weight capacity 2 trailers	20.0	Mg	[173]
(F)		Volume capacity of 2 trailers	10.8	m^3	[173]
(G)		Bulk density WPS	150.0	kg m^{-3}	Data for miscanthus adapted from[105]
		Calculation			
(P)	(A)/(B)	Average duration farm to pellet producer	0.7	h	
(R)	(C)*(P)*2	Fuel consumption roundtrip	14.7	L	
(S)	(F)*(G)/1000	Maximum load (limitations in volume capacity considered)	1.6	Mg	
(T)	(D)*(R)	Energy demand for 1 roundtrip	600	MJ	
(U)	(T)/(S)	Energy demand in (from farm to production facility)	370.3	MJ Mg^{-1}	

Table 6. Energy consumption for pelletizing.

	Calculation	Premise	Value	Unit	Reference
(A)		Total energy for sawdust pelletizing	1315	kWh Mg^{-1}	[174]
(B)		Ratio of drying in overall energy demand for sawdust pelletizing	93%		[174]
(C)	(A)*(B)	Drying for sawdust	1224	kWh Mg^{-1}	
(D)		Moisture content in sawdust before drying	55%		[174]
(E)		Moisture content in sawdust after drying	10%		[174]
(F)	(D)-(E)	Reduction in moisture content of saw dust by drying	45%		
(G)		Moisture content in WPS before drying	15%		[35]
(H)	(G)-(E)	Necessary reduction in moisture content of WPS to achieve same level as saw dust (10%)	5%		
(I)	(H)*(C)/(F)	Assumed drying for WPS according to moisture content reduction ratio	136	kWh Mg^{-1}	
(J)	(A)-(C)+(I)	Estimated total energy for WPS pellet production	227	kWh Mg^{-1}	
	(J) * 3.6	Estimated total energy for WPS pellet production	816	MJ Mg^{-1}	

of the energy demand, for WPS the reduction is only 5% (from 15% to 10%). After applying a simple rule of three, the remaining energy demand for drying WPS from 15% to 10% is estimated to be 136 kWh Mg^{-1} that is only 11% of the energy demand for sawdust drying (**Table 6**). This calculation results in an energy demand for producing WPS pellets of 816 MJ Mg^{-1} (Table 6).

6.3.1. Results of Energy Consumption Assessment

The part of agricultural production has the least impact on energy consumption (10 years: 268 MJ Mg^{-1}; 5 years: 331 MJ Mg^{-1}), whereas the pellet production accounts for the largest share 816 MJ Mg^{-1} (**Table 7**).

The logistics "best case scenario" has a slightly higher impact than the agricultural production but should not be seen as representative for whole BW. The step of drying holds the main advantage of wild plants compared to wood pellets. Mainly due to this advantage WPS pellets have a lower energy consumption over the whole process of biomass production, logistics and processing than pellets from sawdust require for the processing part only (1315 kWh Mg^{-1} equals to 4734 MJ Mg^{-1} for sawdust versus 1455 MJ Mg^{-1} for WPS) (Table 7).

6.3.2. Energy Supply from WPS and Conclusion of Energy Return on Investment

As presented earlier in a study by Von Cossel et al.[35] the higher heating value of WPS accounts for 16 to 16.8 MJ kg^{-1} depending on the plant species. The average 16.4 GJ Mg^{-1} is considered

Table 7. Results of the energy consumption assessment to produce wild plant pellets.

Process step	Value (in MJ Mg^{-1})
1) Agricultural production of biomass (10 years)	268
2) Logistics from farm to processing facility	370
3) Pellet production	816
Total energy demand	1455

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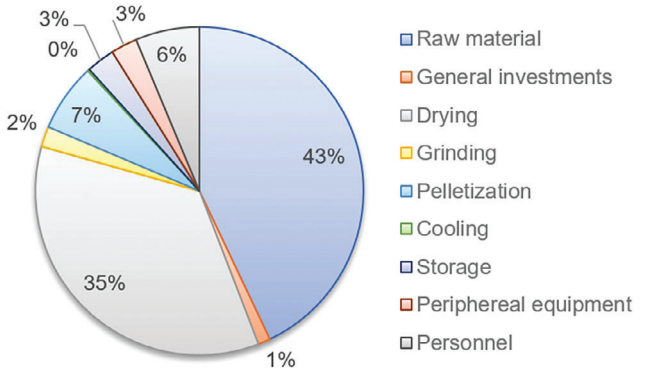


Figure 14. Overall pellet production costs when sawdust is used as raw material (adapted from[174]).

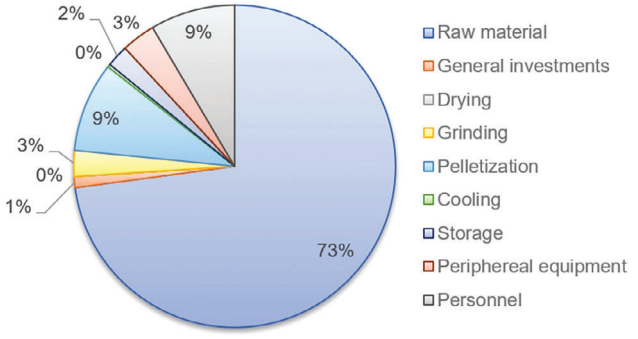


Figure 15. Overall pellet production costs with dry wood shavings as raw material (adapted from[174]).

(mugwort and common tansy), being aware of the associated data limitations here since only two species are represented in this value. More research on various WPS and their individual HHV needs to be conducted to have more reliable data allowing further for general conclusions. Considering this energy yield and comparing it with the energy input, an energy return on investment of WPS of 11:1 can be derived. This means that the energy return of WPS pellets is 11 times higher than the energy required for their production.

7. Economic Viability

In order to understand the marketing potential of WPS for pellet production, an economic comparison between the regular woody biomass pellets and WPS biomass pellets was developed in this section, taking into account the results of the previous sections. To do so, a cost-analysis of both types of pellets and a final consumers prices comparison is presented. Also, consumers' preferences and concerns about WPS pellets are considered.

7.1. Costs Analysis of Wood Pellets

Although there are several costs included in the processing of biomass into pellets, such as investment costs, processing costs (drying, grinding, palletization, cooling, storage), personnel, and raw materials,[174] most of them are indifferent to the raw materials used (**Figures 14** and **15**). Nevertheless, up to 84% of the production costs are related to the raw materials considering the influence of the drying costs of biomass with high moisture content.[57,174,175]

From electricity and heating cost, over 93% constitutes thermal energy for drying the biomass, and the remaining 7% correspond to electricity for grinding, palletization, cooling, and peripheral equipment, from which the palletization process alone demands 3.9% of the total electricity requirements.[174] Important to notice is that these percentages are based on calculations using sawdust as feedstock with a moisture content of 55%[174] that is one of the main raw materials used in the German pellet industry.[176] If wood shavings are considered as dry biomass feedstock, the representing costs of the raw material on the overall pellet production cost increase from 43% to 73%, while the drying cost decrease from 35% to 0%.[174] Other researchers used woody biomass with a moisture content of 30–35% as primarily feedstock, and concluded that the drying process can take up to 70% of total energy demand.[177,178]

Between 43% and 80% of the pellet production costs depend on the raw material prices. Sawmills by-products represent over 90% of the raw materials used for pellet production in Germany.[176] In order to reduce their transportation costs, pellet producers are located near sawmills.[174] Two thirds of sawmills by-products are wood chips and one third is sawdust. The remaining 10% of pellet feedstocks comes from industrial waste-woods (shavings and wood dust) with an average moisture content of 10%.[176,179] For 1 Mg of pellet, between 6–8 m^3 of sawmills' by-products are needed.[176]

The price of sawmills by-products has experienced fluctuations in recent years, and the erratic prices fluctuated from 16 € m^{-3} in 2013, through a peak in 2014 of 19, to 4 € m^{-3} in 2020.[180] Through 2021 and 2022, a steady increase of sawmills by-products' prices was observed, accounting for 4–5.2 € m^{-3} at the end of 2020, to 10–12.5 € m^{-3} at the end of 2021.[181] The offers of sawdust and wood chips are sensitive to the changes of sawmills' primarily production. A cut in sawmills activities during 2021, likely associated with Covid-19 pandemic, reduced the offer of sawmills by-products between 30–40%.[181] The increased demand of pellets put further pressure on the sawmills by-products' prices during the beginning of 2022. Between June 2021 and June 2022, the purchasing price of pellet feedstock in south Germany increased by 94.96%,[181] going along with a steep price increase of fossil energy carriers also fueled by the Russian invasion in Ukraine.[182,183] It is important to mention that selling price and production costs are not perfectly correlated. The reasons are that both feedstocks and pellet prices can be contracted in advance, leading to differences between spot and contract price. Both demand and supply of production feedstocks and pellets can have different behaviors, leading to imbalances between production cost and selling prices.[179]

A sensitive analysis of the production costs was developed by Obernberger and Thek.[174] Their results showed that from a 2.2% difference in the raw material price, a 1% difference would result in the pellet production costs. Also, a 3.1% change on the specific heat cost and 10% in the price of electricity would result in 1% difference on the pellet production costs. The production

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Table 8. Key factors for the cost analysis of WPS pellets.

Item	Rate / costs	Source
Interest	3% (3 months)	[171]
Labor	13.25 € h^{-1}	[171]
Seeds	30 € kg^{-1}	[189]
Lime	40.7 € Mg^{-1}	[171]
Diesel	1.87 € l Mg^{-1}	[188]
Discount rate	1.75% (10-year average)	[190]

costs amount to ≈80% of the retail price, while transport (delivery) and storage account for 20% of its share.[174,179]

The relative importance of feedstocks in the pellet production value chain makes the price of raw materials and the scarcity of it the two main preoccupying difficulties as perceived by pellet producers in Germany. However, in line with the results of Fritsche et. al.,[184] the lack of demand is the less preoccupying one.[185]

7.2. Cost Analysis of WPS Pellets

As seen in the previous section, an important share of wood pellet's cost comes from the thermal energy demand related to the drying process of the raw materials, which takes up to 35% of the total production cost in Germany.[174,176]

After studying the economic viability of 14 alternative pellets, the project "MixBioPells"[186] lead by the German Biomass Research Centre (DBFZ), concluded that alternative pellets were on average 25% cheaper than wood pellets, mainly due to the low drying costs during pellet production.[149,187] These results are in line with the ones presented by the Central Network for Energy and Marketing of Agricultural Raw Materials (C.A.R.M.E.N. e.V.).[187] Based on these results, WPS biomass should not exceed a threshold of 80 € per ton of dry matter in order to be competitive, which is the price of a dry ton of miscanthus and straw chips.[187]

To calculate the cost of the WPS biomass, the KTBL calculator was used following the production steps.[171] As two of the WPS are perennial crops, major savings in the production can be generated, as no soil sampling, ploughing, harrowing, seedbed rolling, sowing, mulching, and limestone application must be applied between the 2nd and 9th year of cultivation. However, in the 10th year mulching and heavy tine cultivation must be carried out. Taking into account the 10-year cultivation timeline, average annual costs were considered to calculate the net present value (NPV).[149] The interest, labor, and lime costs were given by the KTBL calculator,[171] while the diesel price was taken from Statista,[188] WPS's seeds from the research of Netzwerk Lebensraum Feldfur,[189] and the discount rate from the German Commercial Code[190] (**Table 8**).

As part of a strategy to enhance biodiversity and ecological services within farms, the Ministry of Food, Rural Areas and Consumer Protection of BW provides subsidies for WPS cultivation as alternative biomass production systems for the period 2023–2027. These subsidies correspond to 500 € ha^{-1} for the cultivation of perennial WPS and 260 € ha^{-1} for strip cultivation of perennial biomass plants and WPS.[74,75] It is important to notice that the subsidies are planned for the period 2023–2027, while the WPS cultivation period considered for economic reasons has a 10-years' timeline. Therefore, three scenarios are proposed in the following:

i. 1st scenario: no subsidy is considered, only costs
ii. 2nd scenario: the subsidy covers 5 years of WPS cultivation (2023-2027)
iii. 3rd scenario: the subsidy covers 10 years of WPS cultivation

Table 9 resumes the results of the KTBL calculator costs per year and the three given scenarios.

As shown in Table 9, the average NPV costs of WPS cultivation in a 10-years' timeline in the first scenario amount to a loss of 191 €, in second scenario a plus of 50 €, and in third scenario a plus of 272 €. It is important to underline the potential savings in the cost structure when considering the use of WPS biomass for combustion purposes. Compared to the costs of biogas production, there are potential savings from the combustion pathway that amount to 490 € ha^{-1} given the reduction of work load from late harvest and the lack of ensilage.[189]

To calculate the selling price of a unit of WPS dry biomass, the opportunity cost from profitable crops must be considered, as WPS cultivation would compete for the use of land. The opportunity cost of farm land use depends on different factors, being the yield, costs and selling price the most important ones.[191] Also, considering the results of Section 3.4.2, a yield of 9.3 Mg ha^{-1} of dry mass was assumed. An average profitability of 500 € ha^{-1} was considered based on different investigations.[102,189,191–196]

Considering the cost per hectare and subsidies, opportunity costs and yield, the minimum revenues per hectare and minimum price per ton of WPS dry biomass were calculated (**Table 10**).

If an average of 500 € ha^{-1} y^{-1} is the attainable profitability of land use in BW, then a price of 74.3 € Mg^{-1} would be necessary to cover the gap between costs and revenues needed in the first scenario (no subsidies at all), while only 48.4 € Mg^{-1} and 24.5 € Mg^{-1} would cover it for the 5-years and 10-years subsidies scenarios, respectively.

These results do not include the transportation costs. One disadvantage of alternative biomass when comparing with wood-waste pellets is the missing infrastructure at place where plant biomass is harvested, which could lead to higher transportation costs. In comparison, commercial pelletizing plants are often located nearby sawmills, avoiding therefore extended transportation of the raw material. The costs of biomass transport were assumed to be 0.14 € Mg^{-1} km^{-1}, considering the diesel price in 2022.[43,188] **Table 11** presents the costs of transportation per ton in a 10, 50 and 100 km case scenario.

The transport costs (Table 11) between the farms and the pelletizing plants in BW increase the final price of 1 Mg of dry matter of WPS accordingly (**Table 12**).

Considering the threshold of 80 € Mg^{-1} of WPS dry matter, based on the results of C.A.R.M.E.N. e.V. and DBFZ,[149,187] WPS cultivation seems to be competitive (Table 9). A 10-year subsidy and a minimum transport is the most suitable scenario for WPS production for combustion purposes, while no subsidies and long distances for transporting the biomass is the less competitive scenario. The subsidies have the biggest impact on WPS selling price, reducing the minimum price per ton up to 160%,

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Table 9. Calculated costs of WPS cultivation per year in € (adapted from[171]) for three scenarios (no subsidies, five years subsidies, ten years subsidies) (NPV = net present value).

Year of cultivation	Costs	Costs (NPV) 1st case	Subsidies (NPV) – 2nd case	Subsidies (NPV) – 3rd case	1st case (NPV)	2nd case (NPV)	3rd case (NPV)
1	−1014 €	−1014 €	500 €	500 €	−1014 €	−464 €	−464 €
2	−88 €	−87 €	491 €	491 €	−87 €	405 €	405 €
3	−88 €	−85 €	483 €	483 €	−85 €	398 €	398 €
4	−88 €	−84 €	475 €	475 €	−84 €	391 €	391 €
5	−88 €	−82 €	466 €	466 €	−82 €	384 €	384 €
6	−88 €	−81 €	–	458 €	−81 €	−81 €	378 €
7	−88 €	−79 €	–	451 €	−79 €	−79 €	371 €
8	−88 €	−78 €	–	443 €	−78 €	−78 €	365 €
9	−88 €	−77 €	–	435 €	−77 €	−77 €	359 €
10	−286 €	−244 €	–	428 €	−244 €	−244 €	183 €
Average					−191 €	50 €	272 €

Table 10. Overview of profitability scenarios.

Subsidies scenario	Cost (€ ha^{-1} y^{-1})	Minimum profit (500 € ha^{-1} y^{-1})	Minimum price Mg^{-1} (at 9.3 Mg DM ha^{-1})
1st scenario	−191	691 €	74.3 €
2nd scenario	50	450 €	48.4 €
3rd scenario	272	228 €	24.5 €

Table 11. Transportation costs per ton at different field-farm distances, given costs of 0.14 € Mg^{-1} km^{-1}.

	Field-farm distance (km)		
	10	50	100
Total costs	1.4 € Mg^{-1}	7 € Mg^{-1}	14 € Mg^{-1}

followed by the transportation distance that increases the minimum price per ton up to 30.2%.

7.3. Consumers Preferences on WPS Pellets

In all three scenarios calculated (Table 9), WPS are competitive to other biomasses for pellet production. However, a higher price for WPS-based pellets can still be preferred when compared to other biomass sources, due to the following reasons: WPS have important ecological advantages by providing several ecosystem services. Between 2017 and 2021, there has been an increase of 33.6% in the highest level of agreement toward the statement 'I am willing to spend more on a product if it is environmentally friendly' in Germany.[115] In the same period, 3.5 million people fully agree or mostly agree with a higher willingness to pay for "green" products.[115] German energy consumers have expressed an implicit willingness to pay ≈16% more for renewable sources, which is a significant premium price payment for upgrading their default fossil-fuel based energy into an environmentally friendly mix.[54] If there is a 16% higher willingness to pay for more ecological sources of energy, then WPS in all scenarios could be competitive.

Table 12. Final price per 1 Mg of dry matter of WPS under the given scenarios of field-farm distance and subsidy duration.

Scenario	10 km (1.40 € Mg^{-1})	50 km (7.00 € Mg^{-1})	100 km (14.00 € Mg^{-1})
No subsidy	75.70 €	81.30 €	88.30 €
5-years subsidy	49.80 €	55.40 €	62.40 €
10-years subsidy	25.90 €	31.50 €	38.50 €

However, to create a market for WPS pellets, alternative biomass sources for pellet combustion must be accepted. According to the MixBioPells project, the overall social acceptance of alternative biomass pellets appeared to be good, yet, particularly in Germany, there are concerns about the legal framework and negative impacts on landscape.[186] One advantage of WPS pellets comparing with other biomass sources is the highly valuable impact on landscape aesthetics, which can help to overcome this concern. To address the legal framework issues, WPS pellets must comply with current regulations that implies technical challenges because of the higher ash content when compared to woody biomass. Nevertheless, WPS pellets have the potential to fulfil the European standard, especially when mixed. A certification that ensures the fulfillment of the standard for non-woody pellets for non-industrial use to end consumers was developed in 2012 following the labeling system of the European Pellet Council of Wood Pellets (ENPlus).[186]

The "ENagro" labeling and certification[186] system for the production of alternative biomass pellets would guarantee consistently homogeneous quality of pellets, which could relief worries about the legal implications on the use of WPS pellets.[186] Although the potential benefits of having such a certification scheme, the ENagro label is still a draft, as the market in Europe has not yet developed enough to make it economically viable.[197] Other certification schemes under development, such as "Better Biomass" (www.betterbiomass.nl) and "Bee Better Certified" (www.beebettercertified.org), can also have the desirable effects on the social acceptance of alternative biomass pellets, and specifically of WPS pellets.

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As stated in Section 4.2, WPS biomass has a higher content of ash than the one accepted by the current regulation for household users and, therefore, a blend with low-ash content raw materials is needed. Fortunately, the threshold of 80 € Mg^{-1} of dry matter gives WPS pellets space to be competitive, even if a blend with woody biomass is required. On the other hand, pellets for industrial energy production have lower requirements, as the industrial scale-boilers can process biomass in higher combustion temperatures. Therefore, WPS pellets could be a sustainable alternative for industrial energy production, particularly due to their beneficial elemental ash composition promoting higher ash melting temperatures.[12] Nevertheless, industrial use of WPS pellets leads to competitive losses because of the lower relative importance that industry could give to the ecological aspects of WPS cultivation, as their main goal is profit maximization.[56] Tax rebates could provide an incentive for business enterprises to act more sustainably.

8. SWOT and Stakeholder Analysis of using WPS for Pellet/Briquette Production

8.1. SWOT

Considering the results of the previous sections on i) the agricultural aspects of WPS cultivation, ii) the market situation, iii) the technical feasibility of WPS biomass for pellet/briquette production, and iv) the economic viability of the whole WPS biomass toward pellet/briquette value chain, a SWOT analysis was developed to help understand critical points in using WPS for pellet/briquette production:

8.1.1. Strengths

i. WPS provide an environmentally more benign biomass: WPS cultivation helps to enhance agrobiodiversity and provides several ecological services while producing useful biomass. It can be cultivated using relatively low inputs (fertilizers, machinery, no need of pesticides), and therefore, is a less energy intense agricultural production system when compared with annual crops for biomass provision. WPS represents a more resilient bioenergy cropping system when compared with traditional monocultures such as maize or miscanthus, because they are composed of a mixture of native species.
ii. WPS pellets have low production costs: The relative low moisture content of WPS when considering the dead and dried biomass in winter, leads to less energy consumption in the drying process of the biomass prior to the pellet production. WPS biomass has low agricultural production costs, making it competitive toward conventional biomasses for energy generation.
iii. Available subsidies: There are subsidies available for WPS cultivation in BW that makes WPS cultivation an even more competitive biomass.
iv. WPS provides diversified biomass: One of the main concerns of the pellet industry is their dependency on a by-product of another industry, being the pellet production the end of a long chain of cascading uses. WPS can provide sustainable alternative biomass without depending on other industries as was also recently shown for other herbaceous crops.[198]

8.1.2. Weaknesses

i. High level of ash: The level of ash content does not meet most of the quality requirements for pellets and briquettes in the EU (Tables 1 and 2), and therefore, a blend with other biomasses of lower ash contents is needed. The WPS biomass is not homogeneous, potentially leading to difficulties in the processing.
ii. Long-term crop: WPS cultivation needs a long-term decision from farmers (between 5–10 years), associated with uncertainties and imponderables that may deter many farmers from attempting to grow WPS, even on a trial basis.
iii. Lack of research: To date, WPS biomass has been studied mostly for biogas production, but there is only little research about its potential use through combustion.
iv. Undeveloped infrastructure and market: The pellets industry is not as developed as other sources of energy production, being a relatively small pathway of producing energy carriers. The lack of specialized technology for pellet combustion from agricultural raw materials (with higher ash content as woody-biomass), missing certifications schemes and concerns about the legal framework of non-woody pellets play also an important role when considering WPS as a feedstock for pellet production.
v. Low yields: WPS have relatively low yields when comparing to other crops such as miscanthus and *Sida*, and breeding is not an option if the maintenance of the native character of WPS is a goal. This may lead to competitive disadvantages compared with other crops being more profitable for farmers[199] and less land-demanding.[200]

8.1.3. Opportunities

i. Public promotion of sustainable biomass-based energy: The EU and Germany are aiming to increase the amount of energy from renewable and biogenic resources. There are already subsidies available in BW for biodiversity enhancing crops (see Section 5.2), and EU targets pesticides reduction in agricultural production, which could promote WPS cultivation.
ii. Cascading use of WPS: WPS could be used for pharmaceuticals, honey production and other pathways, meeting the principles of a cascading use in the bioeconomy. Further research of the potential cascading uses of WPS is needed to better estimate its cascading use potential and the associated added value.
iii. Sustainable farming: The lower inputs needed for WPS cultivation make it suitable for cultivation on marginal lands. WPS cultivation can also help to enhance the public opinion of agricultural production because of its effects on the landscape, the soil, as well as groundwater protection in regions that are affected by or prone to nitrate leaching.
iv. Demand for sustainable energy: High prices of fossil-fuels and the growing urge for self-sufficiency and autonomy have

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Table 13. Mapping of stakeholders potentially involved in the development and/or implementation of WPS biomass to pellet/briquette production value chain.

Stakeholder	Interests	Assessment	Potential issues and concerns
Farmers	Profits; public opinion; ecosystem services	Indifferent/ Advocates	Long-term commitment; profitability
WPS seed suppliers	Profits; market development	Advocates	Undeveloped market
Universities and research centers	Publications; public funding; more sustainable processes	Indifferent	Sustainability aspects; prioritization
Pellet producers	Profits; energy prices; public opinion	Advocates	Legal framework; profitability
Pellet boilers producers	Profits; public opinion	Advocates	Legal framework; technological innovations
Deutsches Pellet Institut	Profits; public opinion	Advocates	Legal framework
Federal Government	Public opinion; sustainable processes; energy sovereignty	Blockers	Sustainability aspects; legal framework
EU-Government	Public opinion; sustainable processes; energy sovereignty	Blockers	Sustainability aspects; legal framework
State Government	Public opinion; sustainable processes; energy sovereignty	Blockers	Sustainability aspects, legal framework
Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk: C.A.R.M.E.N. e.V.	Profits; public opinion	Advocates	Legal framework
Deutsches Biomasseforschungszentrum gemeinnützige GmbH: DBFZ	Funds; publications; sustainable processes; public opinion	Advocates	Legal framework
Certifiers: BeeBetter, BetterBiomass	Profits; public acceptance	Advocates	Undeveloped market
European Pellet Council	Public opinion; sustainable processes	Blockers	Legal framework
Netzwerk Lebensraum Feldflur	Public opinion; sustainable processes	Advocates	Legal framework
FNR: Fachagentur Nachwachsende Rohstoffe e.V.	Energy sovereignty; public opinion; sustainable processes	Advocates	Sustainability aspects, legal framework
Rural communities	Sustainability; cultural services; energy prices	Advocates	Sustainability aspects
Pellet consumers	Energy prices; sustainable processes	Indifferent/ Advocates	Sustainability aspects, legal framework
Producers of alternative and sustainable energies	Profits; sustainable processes; public opinion; energy prices	Opponents	Competitiveness

put pressure on the demand of alternative and sustainable sources of energy (see section 4.4).

v. Improvements on pellet quality: There is the potential of improving the pellet quality from agricultural feedstocks through pre-treatments (microwave), additives and blends (see Section 5.3).
vi. Industrial uses: Industrial-scale incinerators have lower quality requirements for pellet combustion. In addition, the ash from WPS has been shown to have a higher ash melting point,[35] which is of great advantage when combustion temperatures rise, as in industrial plants.

8.1.4. Threats

i. Future of subsidies: Both pellet boilers and WPS cultivation subsidies have an uncertain future and depend on the different political and legal factors that are not controlled by the industry (see Section 5.2).
ii. Other energy sources developments: The development of technologies for other energy sources, such as heat-pumps, and subsidies for other types of energy (e.g., solar) can reduce the competitiveness of pellets as a biogenic fuel.
iii. Food versus energy: The acceptance of WPS cultivation relies on the priorities of the public opinion and the domestic necessity for food security, which can tend to prioritize food before biofuel production.
iv. Breeding of other crops: WPS have low yields comparing with other crops[37,84,109] and higher yields through breeding is not an option when considering the native aspects of WPS. Breeding of other crops is at place, reducing the competitiveness of WPS. A concentration of the WPS seed market in a few companies further reduces the competitiveness of WPS cultivation.

8.2. Stakeholder Analysis

Stakeholders can profoundly influence threats and opportunities and help to overcome weaknesses and consolidate their strengths in the development of WPS-pellet industry. Accordingly, a stakeholder analysis was elaborated in the following section to further understand the involvement of key players. To develop the market of WPS pellets, among other agricultural residues pellets, there is an urgent need to overcome uncertainties about their legal framework. Even though there is a draft of specialized certifications for

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agricultural residues, i.e., non-woody biomass for non-industrial combustion, these certifications have not been adopted. Given the lack of sufficient influence among other stakeholders, it is imperative that universities, research institutes, private associations, and local governments collaborate to advance policies aiming for promoting the growth of the agricultural feedstock-based pellet market. Ultimately, the European Government and European Pellet Council bear the responsibility for either stagnating or developing the industry.

Another related issue concerning research institutes, universities, pellet producers and private associations (e.g., the German Pellet Institute[118]) are the needed developing efforts to improve WPS pellet quality to meet the existing standards. In this regard, the evaluation and validation of potential options such as biomass mixtures, pre-treatments, and additives are crucial measures to be undertaken prior to the authorization of WPS pellets for domestic heating systems by the European Government and European Pellet Council. Alternatively, additional research and development efforts toward combustion technologies can serve as a parallel approach to enhance energy efficiency and curtail emissions resulting from house-level combustion.

Research institutes and universities are also fundamental to understand unexplored ecosystem and economic benefits on other plantations and crops that are affected by WPS cultivations, such as pollination, natural enemies, water holding capacity, soil quality, etc. Likewise, they could analyze novel cascading uses for WPS besides honey production to further support their economic viability. It is also feasible to selectively breed new varieties that strive to provide ecosystem services in conjunction with elevated levels of biomass production. However, it should be first determined if the preservation of wild genetics holds greater significance. To promote the establishment of WPS and agricultural residues as a local, sustainable, and biobased energy source, it is essential for federal and local governments to work together with farmers, pellet producers, and private associations to create a conducive market environment that encourages the development of infrastructure. This could foster a wider consumer acceptance, as there is an urgency to augment the quantity of energy derived from renewable sources at European level. Subsidies are an important first approach, but certainties about their future are vital for farmers to adopt innovative long-term permanent crops like WPS, miscanthus or *Sida*. Additionally, district heating with more powerful combustion systems could be a solution to be explored as a mean to facilitate the use of non-woody biomass pellets. The overall results of the stakeholder mapping are shown in **Table 13**, while **Figure 16** shows the analysis of the importance and influence of the stakeholder matrix.

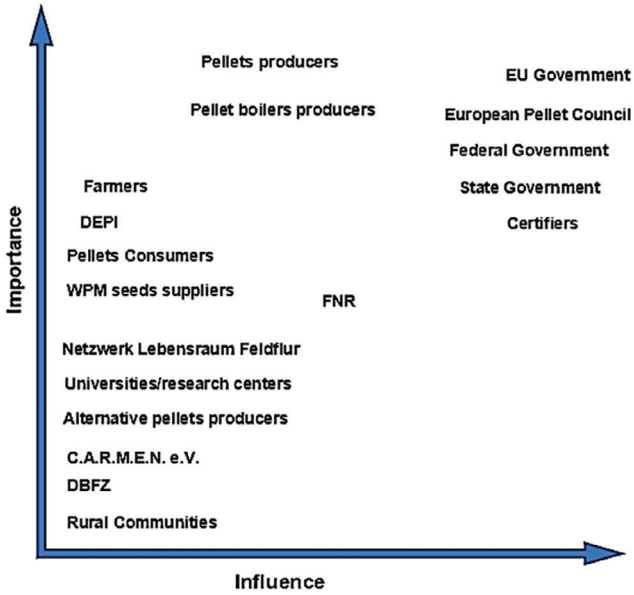


Figure 16. Matrix of estimated stakeholders' importance and influence on the potential use of wild plant species for pellet or briquette combustion in Germany (C.A.R.M.E.N. e.V. = Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V., transl.: Central Agricultural Commodity Marketing and Energy Network, https://www.carmen-ev.de/; DBFZ = Deutsches Biomasseforschungszentrum gemeinnützige GmbH, transl.: German Biomass Research Center non-profit GmbH, https://www.dbfz.de/en/; DEPI = Deutsches Pelletinstitut GmbH, transl.: German Pellet Institute, https://www.depi.de/); FNR = Fachagentur Nachwachsende Rohstoffe e.V., transl.: Agency for Renewable Resources, https://international.fnr.de/; WPM = wild plant mixtures).

9. Conclusion and Outlook

The present investigation aimed to demonstrate that WPS pellets can serve as a technically and economically viable source of bioenergy, albeit with certain limitations. Primary results using existing data show that, considering a threshold of 80 € Mg^{-1} of WPS dry matter and nine subsidies and transport scenarios, WPS could compete with other energy crops as a sustainable source of biomass for pellet production. While WPS can be utilized at the industrial level without technological hindrances, it may not be as economically profitable. However, at the household level, WPS can be marketed at relatively higher prices by highlighting its salient features such as provision of habitat and feed for pollinators, as there is a consumer demand for environmentally friendly products. Nonetheless, WPS biomass pellets lack certification for household level use, as the current combustion technology cannot cope with the amount of ash present in many WPS. Hence, pretreatment, additives or mixture with low-ash-content biomass, such as woody-biomass, is required. This issue is not unique to WPS but applies to most agricultural residues and non-woody biomasses. To address this, further research is needed to improve combustion characteristics of non-woody biomass pellets through mixing,[155] pretreatments, and additives, or explore the feasibility of using powerful boilers for district heating.

Although WPS pellets have prospects as a sustainable and locally produced source of bioenergy, there are legal hurdles to overcome. WPS along with agricultural residues, should be permitted as sustainable biomass for combustion if the technical issues are solved. Important and influential stakeholders such as the European Government and the European Pellet Council have the key to unlock the development of novel sustainable sources of renewable energy that could improve and promote the valorization of beneficial perennial wild plants and agricultural residues as energy feedstocks. Due to the current political and economic context, there is a pressing need for research in this field. The

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escalation of energy costs in Germany in 2022, triggered by the ramifications of the Russian–Ukrainian conflict, has underscored the significance of having access to alternative energy sources. Moreover, political turmoil has highlighted the necessity of seeking domestic alternatives at the local level to secure energy independence and preserve future natural resources. In this regard, WPS have the potential to generate biomass locally, as well as offer ecosystem services, thereby making it a potentially sustainable energy source. Nevertheless, to properly conclude the sustainability of WPS as a feedstock for solid fuels, a life cycle sustainability assessment is necessary. Despite the favorable outcomes of the investigation relative to the biogas production, WPS exhibit certain drawbacks when contrasted with other energy crops. The productivity of WPS is comparatively low, which would necessitate a larger land area to furnish equivalent quantities of biomass. Moreover, WPS should not be improved genetically to preserve the "wild" component. In this context, it could be a viable approach to develop a plant mixture that can offer comparable ecosystem services while augmenting the biomass provisioning ecosystem service. However, further investigation is necessary to explore its bioenergy yield potential while maintaining or improving the concomitant ecosystem services of WPS cultivation.

Acknowledgements

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.C., K.H., G.P.L., and A.A.W. contributed equally to this work. M.C. performed conceptualization, investigation, methodology, and visualization equally, lead the project administration and supervision, and supported in writing original draft and equally reviewed and edited the final manuscript; K.H. performed conceptualization, investigation, methodology, visualization and acquired data curation equally, and equally wrote the original draft and supported in review and editing of the final manuscript; G.P.L. performed conceptualization, investigation, methodology, visualization and acquired data curation equally, and equally wrote the original draft and supported in review and editing of the final manuscript; A.A.W. performed conceptualization, investigation, methodology, visualization and acquired data curation equally, and equally wrote the original draft and supported in review and editing of the final manuscript; M.V.L. supported in conceptualization, investigation, methodology, visualization, acquiring data curation, and writing the original draft; G.G. supported in conceptualization, acquiring data curation, and investigation; N.D.J. supported in visualization and equally wrote, reviewed, and edited the final manuscript. All authors have read and approved the final manuscript.

Keywords

bioeconomy, clean energy, energy return of investment, sustainable intensification, thermochemical conversion

Received: November 24, 2023
Revised: January 4, 2024
Published online: February 6, 2024

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Nicolai David Jablonowski, plant biologist, works as a senior research scientist, group leader and project coordinator. He has a strong background on pesticide residues in soils and the environment, leading over to his recent research on soil-plant interactions with a particular focus on optimized and sustainable plant biomass production. This research is closely associated with the simultaneous upgrading of marginal soils using biogenic residues, biochars, and newly developed fertilizers, aiming for improving soil functions and plant growth. The third pillar of his research activities is the further use of plant biomass for both energy and material utilization and value creation.

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