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The Energy and Environmental Potential of Waste from the Processing of Hulled Wheat Species

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Abstract: Organic farmers farming on arable land have often had, in addition to the cultivation of common species of cultivated crops (such as wheat, rye, triticale or potatoes), interest in the cultivation of marginal crops such as hulled wheat species (Einkorn, Emmer and Spelt wheat). The production of marginal cereals has seen significant developments in the European Union related to the development of the organic farming sector. Just the average annual organic production of spelt in the Czech Republic reached more than 9000 tons in 2018. The cultivation of these cereals requires post-harvest treatment in the special method of dehulling. The waste emerging after dehulling of spikelet (i.e., chaff) accounts for about 30% of the total amount of harvest and can be used as an alternative fuel material. When considering the energy utilization of this waste, it is also necessary to obtain information on the energy quality of the material, as well as environmental aspects linked to their life cycle. For evaluating the energy parameters, the higher and lower heating value, based on the elemental (CHNS) analysis, was determined. The environmental aspects were determinate according to the Life Cycle Assessment (LCA) methodology where the system boundary includes all the processes from cradle to farm gate, and the mass unit was chosen. The SimaPro v9.1.0.11 software and ReCiPe Midpoint (H) within the characterization model was used for the data expression. The results predict the energy potential of chaff about 50–90 TJ per year. The results of this study show that in some selected impact categories, 1 kg of chaff, as a potential fuel, represents a higher load on the environment than 1 kg of lignite, respectively potential energy gain (1 GJ) from the materials.

Keywords: hulled wheat species; energy; life cycle assessment

1. Introduction

The production of marginal cereals has seen significant developments in the European Union related to the development of the organic farming sector. The typical marginal wheat species in the Czech Republic are Einkorn, Emmer, and especially Spelt wheat [1,2]. They can be defined as the cultural hulled wheat species, which replace, expand, and supplement the existing range of cereals and contribute to broadening the spectrum of crop production [3]. These marginal cereals have usually lower harvest index but have less input intensity requirements. Thanks to this aspect, these grains are particularly suitable for organic farming systems [3–5]. The benefits of introducing these marginal

cereal species include extending the food spectrum, maintaining the production capacity of the soil, and the efficient use of marginal and less-favored areas [6,7]. However, the disadvantages are low yields (low harvest index) and uneven ripening, which causes large losses during harvesting [5,8]. The processing of these hulled wheat species generates a relatively large amount of waste-chaff [9], which can be used in various ways, for example, can be composted [10], used as litter [9] or as an additive to building materials [11], or could be directly put back to the agricultural land to help to maintain the soil fertility [2,5]. Due to the high content of mycotoxins, however, it is not recommended to use chaff from hulled wheat as litter and it is preferable to use it for energy production and to burn it [9], optimally in the form of pellets [12,13]. The energy use of such residual agricultural biomass has great potential not only across the EU [14]. The potential for energy utilization, the energy parameters of chaff and the removal rate, including pelleting issues, have been summarized for Spelt and Emmer in some studies [9,10,13,15]. However, the crop residue removal for biofuel production can have a significant impact on crop productivity, soil health, and greenhouse gas emissions [16].

In addition to Spelt and Emmer wheat, this manuscript also evaluates the energy parameters of Einkorn chaff. The energy use of chaff of these marginal cereal species is often perceived as an environmentally friendly source of energy, because it is energy from biomass. However, it has to be considered in terms of inputs into the cultivation process. This work aims to point out environmental aspects related to hulled wheat chaff and quantitative and qualitative parameters of individual wheat species using the Life Cycle Assessment (LCA) method.

2. Materials and Methods

2.1. Field Trails

Data for evaluation was based on field trials (the University of South Bohemia, Faculty of Agriculture, location: Zvíkov, GPS 48.9758531N, 14.6245594E; production region: cereal production region; altitude: 490 m; year temperature: 7.2 °C; year rainfall: 634 mm; type of soil: brown soil; sort of soil: loamy soil—medium) realized in the regime of organic farming. The field trails are used to assess yield potential, environmental, and economic aspects of cultivation. The fieldwork methodology was chosen based on commonly used organic farming technologies. Selected cultivation practices are typical for the conditions of the Czech Republic [2]. The design of randomized field trails in three replicates with an average area of an experimental plot of 10 m^2 was used. The growing period related to this study was from September 2017 to August 2018. Fodder pea—winter type was the preceding crop. Organic fertilizers were applied to the soil before sowing (6.6 ton ha^{-1} of manure/solid cattle; organic production) and the soil was loosened with a mid-deep ploughing to a 14–18 cm depth and levelled with a cultivator within the framework of pre-sowing preparatory works. Sowing of Spelt (winter type) was carried out in October 2017. Sowing of Emmer and Einkorn was carried out in April 2018 (spring types). The sowing depth was 3–4 cm. The amount of seed was 180 kg per ha. The harvest was performed during the July and August 2018. After harvest were taken samples from each replication and homogenized (hammer mill PSY MP 20/MP 40). Individual operations are shown in Table 1.

Table 1. Input data inventory.

Input	Unit	Investigated Crop		
		Spelt ^{W}	Emmer	Einkorn
Manure (solid cattle)	ton ha^{-1}	6.6	6.6	6.6
Solid manure loading and spreading	ton ha^{-1}	6.6	6.6	6.6
Tillage, ploughing	ha	1	1	1
Tillage, cultivating, chiselling	ha	1	1	1
Sowing	ha	1	1	1
Seeds, organic	kg ha^{-1}	180	180	180

Table 1. *Cont.*

Input	Unit	Investigated Crop		
Tillage, rolling	ha	1	-	-
Tillage, harrowing	ha	1	1	1
Combine harvesting	ha	1	1	1
Transport, tractor and trailer	tkm	50	50	50
Electricity for processing	kWh ton^{-1}	0.3	0.3	0.3

Transport included in the process as a flat rate 50 tkm. It is calculated with the same weight for all crops (max 8 tons per load); ^{W} = Winter Spelt wheat.

2.2. Analysis of Phytomass

For the purposes of this study, the elemental composition of chaff that remained after the dehulling of grains of Spelt, Emmer, and Einkorn was determined. The design of randomized field trails in three replicates for Spelt, Emmer, and Einkorn was used. After harvest, samples of chaff were taken from each replication and homogenized. For the elemental composition of chaff, two homogenized samples were used from each hulled wheat species. The CHNS analysis (the elemental composition of chaff) was carried out using the elemental analyzer (Vario EL CUBE). The method of direct jet injection of oxygen and combustion in the high furnace temperatures of up to 1200 °C with a complete conversion of the sample to measuring gas was used. The higher heating value (HHV) was calculated using the Mendeleev's equation (Equation (1)) [17], as well as lower heating value (LHV) from the equation (Equation (2)) [18], where Qv is the heat of combustion in kcal kg^{-1} [18]. Based on the observed elementary composition and empirical formulas, the HHV and LHV of the chaff were determined.

$$Q_s^r = [81 \times C + 300 \times H - 26 \times (O - S)] \times 4.186 \text{ (kJ kg}^{-1}\text{)}, \quad (1)$$

where: * Q_s^r = HHV [kJ kg^{-1}]; C = carbon in the sample (%); H = hydrogen in the sample (%); O = oxygen in the sample (%); S = sulphur in the sample (%); 4.186 = conversion factor from kcal kg^{-1} to kJ kg^{-1}

$$Q_u = Q_v - 5.85 \text{ (W} + 8.94 \times \text{H)} \times 4.186 \text{ (kJ kg}^{-1}\text{)}, \quad (2)$$

where: * Q_v = HHV in kcal kg^{-1}; Q_u = LHV in kcal kg^{-1}; W = moisture (%) in the sample (average amount of moisture in the sample of chaff was determined according to Beloborodko et al. [19] and Žandeckis et al. [20]); H = hydrogen in the sample; 4.186 = conversion factor from kcal kg^{-1} to kJ kg^{-1}.

2.3. Environmental Aspects

A life cycle assessment method was used for environmental load quantification. This method is defined by the international standards of ČSN EN ISO 14 040 [21] and ČSN EN ISO 14 044 [22]. The system boundaries are set within the chaff from the cradle to the farm gate and within the lignite from the cradle to the gate (from mining to raw material ready for use). The results of this study are related to the 19 impact categories (characterization model). SimaPro v9.1.0.11 software and ReCiPe Midpoint (H) V1.13/Europe Recipe H., an integrated method, were used for environmental load quantification. One GJ of energy (from potential energy profit) was used as the defined unit/functional units (FU). The technological processes of growing the hulled wheat species were set up based on primary data (field trials carried out on plots at the University of South Bohemia) and secondary data (data gained from the Ecoinvent v3.6 database [23] and commonly used cultivation practices of organic farming [2]). Mass allocation approach was used (grain/straw/chaff). Data geographically related to central Europe was used. The primary data was collected between 2018 and 2019. The data selected for modelling is based on the average of commonly applied organic farming technologies [2,24]. Agrotechnical operations from seedbed preparation, the number of seeds, the use of agrotechnological operations for plant protection, treatment and application of organic

fertilizers to harvesting, transporting of the harvested grain and processing the grain were included into the model system.

The usage of mineral and organic nitrogenous fertilizers and lime application results in the release of so-called direct and indirect emissions of N_2O, CO_2, NH_3, NO_3^- and NO_x. The following were taken into account in the monitoring of field and agricultural emissions: liming, NH_3 and NOx volatilization, and nitrogen loss from leaching and surface outflow. The emission load was determined following the IPCC (Intergovernmental Panel on Climate Change) methodology called Tier 1 [25,26], and with Nemecek and Kägi [27] and the national greenhouse gas inventory report of the Czech Republic (the agricultural section) [28]. Emissions of phosphorus due to leaching and run-off were estimated following recommendations from Nemecek and Kägi [27].

The individual steps determined by the methodology are shown in Figure 1.

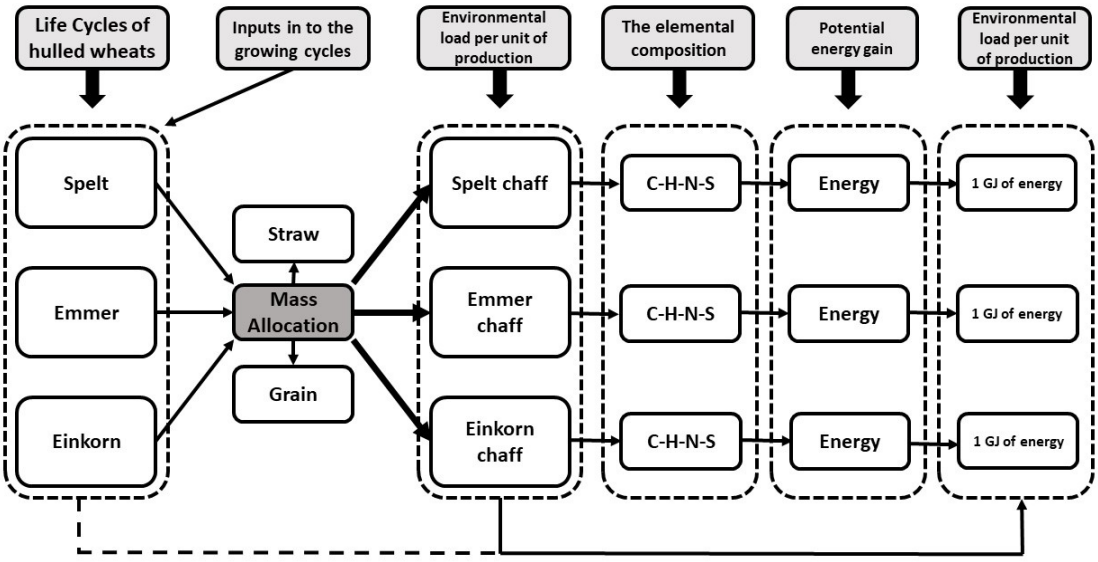

Figure 1. Workflow scheme.

3. Results and Discussion

3.1. Field Trial Results

The basic data source were field trials established according to the methodology plan. The data obtained from field trials are included in Table 2.

Table 2. Field trials results.

	Yield Range (t ha^{-1})	Grain Average Yield (t ha^{-1})	Straw Average Yield (t ha^{-1})	Chaff Rate (%)	Grain Net Yield (t ha^{-1})	Chaff Yield (t ha^{-1})
Spelt	2.80–3.27	2.96	4.75	33.23	1.98	0.99
Emmer	1.77–2.90	2.40	3.73	23.82	1.83	0.57
Einkorn	1.17–1.84	1.65	3.13	26.16	1.21	0.43

The results are based on one-year field trials under the organic farming system. The study aimed to obtain samples of waste material (chaff) and information about its quantity independence on yield level. The largest amount of chaff is produced during the peeling of Spelt wheat (average 1.45 t ha^{-1}), reps. the removal rate was 33.23%. This corresponds to the results reported in the study by Weiss and Glasner [13], which reported the removal rate of about 33%, and according to Wiwart et al. [9], of about 30%–35%. In the comparison of selected hulled wheat species, spelt wheat is also the most represented in the Czech Republic (3400 ha) [29]. This represents only 0.35% of the sowing areas of all

winter cereals in the Czech Republic [29]. The lowest removal rate was recorded for Emmer wheat (23.82%), but the lowest chaff yield was for Einkorn (0.43 t ha^{-1} on average), given the lowest grain yield per hectare (1.65 t ha^{-1} on average).

3.2. Elemental Composition and Statistical Evaluation

For the study, elementary analysis of representative samples was carried out according to the methodology (Section 2.2). The results of elemental analysis are an essential source of information for the determination of HHV and LHV. The results of this analysis are included in Table 3.

Table 3. Elemental composition of chaff.

		N		C		H		S	
Sample	**Sample Weight (mg)**	**Ø%**	**S.D.**	**Ø%**	**S.D.**	**Ø%**	**S.D.**	**Ø%**	**S.D.**
Emmer	4.8545	0.6025	0.000707	41.5810	0.098995	6.1008	0.002121	0.0896	0.016971
Spelt	5.4315	1.1434	0.072832	42.3710	0.098995	6.4031	0.002121	0.0915	0.023335
Einkorn	5.1870	0.9230	0.028991	41.0150	0.007071	6.3185	0.002828	0.0697	0.054447

The average values of the homogenized samples; S.D. = standard deviation; Ø% = average percentage.

Based on the results of the elementary analysis, statistical evaluation was carried out. The ANOVA and Tukey HSD test were used. Individual samples within the percentage content of C, N, H, and S were shown to be statistically demonstrably different from each other at a significance level of $p = 0.05$ (Table 4).

Table 4. Statistical evaluation—variance analysis ANOVA.

C	$F_{2.3} = 141$; $p = 0.001075$
N	$F_{2.3} = 72.268$; $p = 0.002900$
H	$F_{2.3} = 38.5$; $p = 0.007272$
S	$F_{2.3} = 49.794$; $p = 0.005001$

p = level of significance ($p = 0.05$).

The following post-hoc Tukey HSD test (Table 5) showed that all crops differed within percentage content of C and N. However, within the percentage content of H, the samples of Einkorn and Spelt chaff did not differ from each other and within the percentage content of S, the samples of Einkorn and Emmer chaff did not differ from each other.

Table 5. Statistical evaluation—post-hoc Tukey HSD test.

Category	C	N	H	S
Emmer × Einkorn	$p = 0.004837$	$p = 0.002753$	$p = 0.007136$	no difference
Einkorn × Spelt	$p = 0.001136$	$p = 0.033646$	no difference	$p = 0.006019$
Emmer × Spelt	$p = 0.012420$	$p = 0.011883$	$p = 0.017988$	$p = 0.007922$

p = level of significance ($p = 0.05$).

The ash content of the sample was derived from the Sheng and Azevedo study [30] and the percentage content of oxygen was determined based on the difference. Moisture in the chaff sample was derived from the study by Beloborodko et al. [19] and Zandeckis et al. [20].

3.3. HHV, LHV and Potential Energy Profit Ha

Based on the data obtained from the elementary analysis, the HHV and LHV were determined. The resulting values are included in Table 6.

Table 6. Energy parameters of hulled wheat chaff.

	HHV (MJ kg^{-1})	LHV (MJ kg^{-1})	Energy Potential (GJ ha^{-1}) E	Energy Potential for CZ (TJ rok^{-1})
Spelt	17.74	15.90	13.21–26.41	50–90
Emmer	16.92	15.14	6.49–10.46	-
Einkorn	16.99	15.16	4.76–7.53	-

E = The energy potential is related to the yield range obtained in the field trials; HHV = higher heating value; LHV = Lower heating value; CZ = Czech Republic.

In the frame of the study, the HHV and LHV of Spelt chaff (17.74 MJ kg^{-1} respectively 15.90 MJ kg^{-1}), Emmer chaff (16.92 MJ kg^{-1} resp. 15.14 MJ kg^{-1}), and Einkorn chaff (16.99 MJ kg^{-1}, resp. 15.16 MJ kg^{-1}) were determined. The HHV and LHV of Spelt and Emmer chaff did not differ significantly from those reported in some earlier studies [9,10,13,15]. For example, according to the study by Wiwart et al. [9] the energy values (HHV and LHV) of Spelt and Emmer chaff were also determined. The chaff of Spelt and Emmer are generally defined by the higher HHV (18.75 MJ kg^{-1} resp. 18.31 MJ kg^{-1}), higher LHV (16.74 MJ kg^{-1} resp. 16.35 MJ kg^{-1}), significantly lower ash content (3.79% resp. 6.16%), and also lower content of the volatile matter (70.3% resp. 74.9%) in comparison with wheat and barley straw. Despite the relatively high Sulphur content (0.148%), the Emmer chaff has significant energy potential. Considering the LHV of 15.1 MJ kg^{-1} and the removal rate of 0.33, winter wheat and Spelt chaff has a theoretical potential of 191 PJa^{-1} in the EU [13]. For the Czech Republic only, the energy potential of Spelt is about 50–90 TJ year^{-1}.

3.4. Environmental Impact Assessment and Economy Aspects

For the study, an evaluation of the environmental load related to individual hulled wheat species and waste (chaff) resulting from their processing was compared with the traditional non-renewable fuel type lignite. The inputs to the growing cycle are part of the Field Trails methodology. The results are generated within the characterization model (Table 7).

Table 7. Environmental load per 1 GJ of potential energy profit.

Impact Category	Unit	Spelt	Emmer	Einkorn	Lignite [EI]
Climate change	kg CO_2 eq	1.35×10^{1}	1.75×10^{1}	2.25×10^{1}	1.60
Ozone depletion	kg CFC-11 eq	6.25×10^{-7}	7.95×10^{-7}	1.02×10^{-6}	1.23×10^{-7}
Terrestrial acidification	kg SO_2 eq	1.21×10^{-1}	1.58×10^{-1}	2.03×10^{-1}	5.22×10^{-3}
Freshwater eutrophication	kg P eq	1.69×10^{-3}	2.15×10^{-3}	2.76×10^{-3}	2.35×10^{-1}
Marine eutrophication	kg N eq	3.57×10^{-2}	4.72×10^{-2}	6.06×10^{-2}	4.92×10^{-2}
Human toxicity	kg 1,4-DB eq	1.30	1.61	2.07	1.32
Photochemical oxidant formation	kg NMVOC	5.04×10^{-2}	6.40×10^{-2}	8.22×10^{-2}	4.48×10^{-2}
Particulate matter formation	kg PM10 eq	2.92×10^{-2}	3.76×10^{-2}	4.82×10^{-2}	2.16×10^{-3}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.17×10^{-3}	1.52×10^{-3}	1.95×10^{-3}	7.64×10^{-5}
Freshwater ecotoxicity	kg 1,4-DB eq	1.61×10^{-1}	2.00×10^{-1}	2.56×10^{-1}	3.28
Marine ecotoxicity	kg 1,4-DB eq	1.44×10^{-1}	1.79×10^{-1}	2.29×10^{-1}	3.13×10^{-1}
Ionising radiation	kBq U235 eq	2.85×10^{-1}	3.59×10^{-1}	4.60×10^{-1}	4.80×10^{-1}
Agricultural land occupation	m^2a	8.46×10^{1}	1.12×10^{2}	1.44×10^{2}	1.17×10^{-1}
Urban land occupation	m^2a	1.06×10^{-1}	1.30×10^{-1}	1.67×10^{-1}	1.19×10^{-1}
Natural land transformation	m^2	1.36×10^{-3}	1.73×10^{-3}	2.22×10^{-3}	1.64×10^{-3}
Water depletion	m^3	7.52×10^{-2}	9.85×10^{-2}	1.26×10^{-1}	6.82×10^{-2}
Metal depletion	kg Fe eq	8.77×10^{-1}	1.06	1.36	8.21×10^{-2}
Fossil depletion	kg oil eq	1.38	1.75	2.24	2.30×10^{1}

[EI] = source from Ecoinvent library (3.6 v); ReCiPe Midpoint (H) method, Characterization model, Results are expressed per GJ of potential energy profit; eq = equivalent; CFC-11 = Trichlorofluoromethane; 1,4-DB = 1,4-dichlorobenzene; NMVOC = Non-methane volatile organic compound; PM10 = Particulate matter <10 μm; U235 = Uranium235; m^2a = Potentially disappeared fraction (PDF)*m^2*year/m^2.

Due to the different material properties (such as combustion rate in the incineration unit), the resulting values are recalculated to potential energy gain (1GJ) compared to 1 kg of lignite with LHV of 9.9 MJ kg^{-1} (resp. 1GJ of potential energy gain). The most significant environmental savings

compared to lignite can be found in the impact categories of freshwater eutrophication (k P eq), human toxicity (kg 1,4-DB eq), freshwater ecotoxicity (kg 1,4-DB eq), marine ecotoxicity (kg 1,4-DB eq) and fossil depletion (kg oil eq). On the other hand, the potential gain of 1 GJ from lignite was associated with lower environmental impacts for the other selected impact categories. The most important difference was determined among the impact categories of climate change (kg CO_2 eq), terrestrial acidification (kg SO_2 eq), photochemical oxidant formation (kg NMVOC), particulate matter formation (kg PM10 eq), terrestrial ecotoxicity (kg 1,4-DB eq), and metal depletion (kg Fe eq). In general terms, the highest environmental load was associated with the Einkorn chaff (within all impact categories). It is caused by the grain yield per hectare and lower LHV compared to Spelt chaff.

The evaluation results are influenced by the selected allocation approach—in this case, mass allocation (Chart 1). In terms of mass allocation, the environmental load associated with Spelt, Emmer, and Einkorn chaff was 12.8%, 9.3%, resp. 9.0% of the total environmental load connected with the growing cycle. On the other hand, the environmental load associated with the production of Spelt, Emmer, and Einkorn chaff would be, according to the economy allocation, 5.8%, 4.6% and 3.8%, respectively, of the total environmental load linked to the growing cycle (Table 8). However, price relations are highly volatile, and the economy has no direct impact on yield relations and therefore the economy allocation is not considered appropriate in this assessment. A comparison of allocation approaches and market price data is also included in Table 8.

Table 8. Allocation approach and market price.

	Product	Field Production (t ha^{-1})	Mass Allocation (%)	Market Price (Eur ton^{-1}) without VAT	Economy Allocation (%)
Spelt	Grain	1.98	25.6	400	78.5
	Straw	4.75	61.5	80	15.7
	Chaff	0.99	12.8	30	5.8
Emmer	Grain	1.83	29.9	560	83.5
	Straw	3.73	60.8	80	11.9
	Chaff	0.57	9.3	30	4.6
Einkorn	Grain	1.21	25.4	680	86.1
	Straw	3.13	65.6	80	10.1
	Chaff	0.43	9.0	30	3.8

VAT = value-added tax.

From the values given in Table 8, the price for 1GJ of potential energy gain and the amount of material needed to obtain the same amount of energy can be predicted (Table 9).

Table 9. Price relations.

	LHV (MJ kg^{-1})	Market Price (Eur ton^{-1}) without VAT	Price (Eur per GJ) (Potential)	Amount of Material to Obtain the Same Amount of Energy (kg)
Spelt chaff	15.90	30	1.88	1
Emmer chaff	15.14	30	1.98	1.05
Einkorn chaff	15.16	30	1.98	1.05
Lignite	9.9	140	14.14	1.61

VAT = value-added tax; HHV = Higher heating value; LHV = Lower heating value.

The results of the environmental impact assessment show that the use of waste material (chaff) arising after processing hulled wheat species for energy purposes does not necessarily mean lower environmental load. This is due to inputs into the growing cycles, yield level, chosen technological processes, and selected allocation approach. The advantages of the lignite are the relatively high yield per area unit, easier logistics and generally better fuel properties, and currently also the price and availability. However, it is a non-renewable energy source that is generally considered to be

very problematic, especially concerning climate change, air quality impacts, landscape, water quality and other environmental categories. Biomass is generally considered to be a renewable source of energy [31], but from the LCA methodology point of view, this is not the case even when organic farming production is involved. The results of this study show that in some selected impact categories (e.g., climate change, terrestrial acidification, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, and metal depletion), 1 kg of chaff, as a potential fuel, represents a higher load on the environment than 1 kg of lignite, resp. potential energy gain (1 GJ) from the materials.

4. Conclusions

In a comparison of the monitored wheat species, the largest amount of the chaff is generated after processing of Spelt wheat (33.23% removal rate) with an average HHV value of 17.74 MJ kg^{-1} and LHV 15.9 MJ kg^{-1}. Compared to that, in the case of Einkorn and Emmer 26.16% resp. 23.82% of chaff with HHV 16.99 MJ kg^{-1} resp. 16.92 MJ kg^{-1} and LHV 15.16 MJ kg^{-1} resp. 15.14 MJ kg^{-1} can be expected. Based on the yields obtained in field trials, a potential energy gain of 26.41 GJ ha^{-1} for spelt wheat, 19.84 GJ ha^{-1} for Einkorn, and 18.03 GJ ha^{-1} for Emmer wheat can be predicted. Only Spelt wheat is grown in the Czech Republic at around 3400 ha per year, and the energy potential of chaff at 50–90 TJ $year^{-1}$ concerning the yield can be estimated. This can be expressed by the lignite equivalent (with LHV of 9.9 MJ kg^{-1}) corresponding to a very rough estimate of 103.3–206.5 boxcars/wagons of lignite. Concerning the environmental aspects, hulled wheat chaff is an interesting alternative energy source, ideally in the region of cultivation and processing. Regarding the assessment of the environmental aspects, it is also necessary to choose an appropriate allocation approach. According to study results, when using the mass allocation principle, the share of the total environmental load associated with the production of chaff is 9.0%–12.8%, but when using the economy allocation principle, it is only 3.8%–5.8%. An appropriate allocation approach can improve the quality of data and their interpretation. The results also show that hulled wheat chaff can be a cheaper source of energy compared to lignite.

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