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Comparison between Two Strategies for the Collection of Wheat Residue after Mechanical Harvesting: Performance and Cost Analysis

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Abstract: The growing population worldwide will create the demand for higher cereal production, in order to meet the food need of both humans and animals in the future. Consequently, the quantity of crop by-products produced by cereal cropping will increase accordingly, providing a good opportunity for fostering the development of the sustainable supply chain of renewable solid fuels and natural feedstock for animal farming. The conventional machineries used in wheat harvesting do not guarantee the possibility to collect the chaff as additional residue to the straw. The present study investigated the possibility to equip a conventional combine with a specific device, already available on the market, in order to collect the chaff either separately (onto a trailer), or together with the straw (baled). The total residual biomass increased by 0.84 t·ha^{-1} and 0.80 t·ha^{-1} respectively, without negatively affecting the performance of the combine when the chaff was discharged on the swath. Farmers can benefit economically from the extra biomass collected, although a proper sizing of the machine chain is fundamental to avoid by-product losses and lower revenue.

Keywords: biomass; bioenergy; straw; combine harvester; chaff; by-product

1. Introduction

1.1. Framework

The use of non-renewable sources for meeting the fast-growing energy demand worldwide could trigger negative effects on the environment in terms of pollution. On the other hand, as the worldwide population is expected to exceed 9 billion people by 2050 (FAO), the production of several key commodities will also increase accordingly, in order to meet the fast-growing demand for food. The production of cereals is expected to grow from the annual 2.1 billion tons up to 3 billion tons by 2050 if animal feeding is also included [1]. Consequently, the ongoing conflict on land use for food and non-food crops will be more serious if new strategies are not promptly undertaken. Regarding the bioenergy production, the European policy is keen to promote the utilization of agroforestry residues over the plantation of energy crops [2], by applying stringent regulations, in order to meet the climate and energy targets set in the EU 2030 framework [3,4]. Hence, a possible strategy could be improving the collection and the utilization of residual biomass that is normally produced in cereal cropping, but not effectively exploited yet [5]. During the harvesting of cereals, for example, in addition to the collection of grains, a large quantity of residual biomass is usually produced as straw and chaff. Among them, straw has been exploited for a long time as natural bedding for animals [6] and, recently, as a valid source for energy production or as raw material for industrial processes. In terms of energy, one hectare of cereal straw is approximately equivalent to 200 L of oil [7] if considered as solid biofuel. However, the biochemical properties of ligno-cellulosic materials, as straw, make it suitable for further industrial processing. For instance, Fang and Shen [8] reported the suitability of straw for paper and paperboard production, Hýsek et al. [9] highlighted the possibility to exploit cereal residues for composite material production, while Swain et al. [10] investigated the hydrolyzation of cellulose and the hemicellulose of straw into fermentable sugars, which are particularly attractive for bioethanol production industries. Recently, it has been found that winter wheat straw can be returned to soil as biochar to enhance the yield in corn and peanut cultivation [11]. Conceptually, the development of a comprehensive, efficient and sustainable straw supply chain can bring benefits to many sectors and to developing countries as well [12].

On the other hand, the chaff, as the finest part of the grain residue, is normally lost on the ground after mechanical harvesting. In wheat crops, chaff is available at the rate of the 17% of the grain yield [13], and if considering the European annual production of wheat and spelt estimated in, approximately, 138 Mt [14], the whole European biomass supply chain could benefit from the collection of 23 $Mt \cdot yr^{-1}$ more of biomass. This would contribute to increase the availability of solid biofuel for the production of energy, particularly if baled with the straw [15]. Chaff palletization is also possible, but only if provided as loose product [16], as well as for the production of second generation bioethanol [17].

Nevertheless, the collection of chaff has already been investigated in agriculture, as a promising tool in organic farming of cereal grain for reducing the accumulation of weed seeds in the soil over time [18,19]. In Australia, different mechanical devices were invented and tested on field, with the specific purpose of removing the chaff for decreasing the amount of weed seeds [20–22]. The chaff was then arranged in small hips or in narrow strips for being burnt afterwards. The possibility to collect chaff for purposes different from weed seeds control, has already been investigated under the economic aspect by Unger and Glasner [23], whose study revealed that the exploitation of that kind of residue is feasible. Although the simultaneous harvesting of wheat grains and chaff has been recently investigated [19,24–26], the literature still lacks of specific data from in-field experiment.

Actually, mainly due to the lack of knowledge on the specific devices already available on the market, uncertainty on the harvesting system to adopt and due to the lack of a dedicated supply chain for an effective exploitation, the chaff still remains an untapped biomass. There is a real need to evaluate the cost effectiveness and the performance of systems for harvesting chaff in order to foster the utilization of this biomass, depending on the final use, and to stimulate the development of a dedicated value chain. According to this, the aim of the study consisted in filling this knowledge gap and providing a deeper understanding of the possibility to enhance the current wheat harvesting method, in order to improve the quantity of biomass collected, including the chaff.

1.2. Main Chaff Utilization

The chaff from cereal crops can be handled differently according to its final utilization. More recently, the chaff is thought as a source of biomass for energy use, but others are known in literature. For instance, in Australia, harvest weed seed control (HWSC) systems have been developed and tested for years, providing good results in terms of alternative strategy for weeds control. Walsh, Newman, and Powles in 2013 [20] reviewed the following systems: chaff chart, narrow windrow burning, bale direct and Harrington seed destructor (HSD). The first two of them accumulate the chaff, either in heaps, or in a narrow windrow (50–60 cm wide) on the field for direct burning. Among the other two systems, apart from the HSD that mechanically destroys the seed weeds, the direct baling strategy provides multiple choices for chaff utilization. In fact, the chaff is baled with the straw as soon as they exit the cleaning shoe of the combine harvester. Indeed, baling them addresses two main problems: the removal of weed seeds and the collection of biomass for livestock (both feeding [6,13] and natural bedding). The presence of chaff into straw bales also increases the adsorbent capacity of natural bedding [27]. Even poultry farming can benefit from loose chaff availability on the market. A direct interview with a local farmer in France highlighted the positive effects, noticed by farmers, on the welfare of the animals that could scratch around in search for broken kernels and weed seeds, which, in turn, contributed to overall feeding. The same experience was reported by Italian farmers. The use of similar cereal residues is reported in literature as a valid source for littering. Anisuzzaman and Chowdhury reported that rice husk was a good litter material for rearing broilers [28] and it also has a high adsorbent capacity if compared with sawdust [29]. Chaff could also be suitable for further processing, like briquetting, and used for multiple purposes. Akerlof [30] reported the possibility of producing briquettes of soybean chaff for meeting the needs of livestock in providing complete feeding, whereas spelt chaff has been proven to be a good raw material for the production of briquettes for non-feeding purpose, who exhibited different mechanical properties according to the temperature of compression applied [31]. Wheat chaff applications are not fully studied in the sense of both feeding or not-feeding purposes. The unviability of specific mechanical machines able to collect it without increase in the harvesting costs, has probably limited the research in that direction. For this reason, this study addresses an important issue for the development of new production chains based on cereal residues, showing two possible chaff collection logistics, the limits and operating costs of the technologies used, laying the foundations for the development of possible supply chains that are currently underdeveloped or, in some cases, non-existent. In the framework of the H2020 AGROinLOG project [32], a specific test in the Halland region (Sweden) was carried out, to provide evidences on the possibility of improving the conventional supply chains in wheat harvesting, for increasing the overall residual biomass collectable in the field. Specifically, the aim of the test was to evaluate if it is possible to accomplish such a task by equipping a conventional harvester combine with a dedicated device for chaff recovery, already available on the market and manufactured by the Thierart firm (Thierart, Le Châtelet-sur-Retourne, France) [33]. The device permitted one to flow the chaff, either onto a towed trailer, or on the straw swath produced by the combine harvester. Therefore, both chaff collection methods were tested: loose in a towed trailer (CoT), or baled together with the straw (CoS). The trailer was connected to the combine harvester, therefore no tractor was required for towing it. The amount of biomass potentially collectable as grains, straw and chaff was quantified, as well as the performance and quality of the work of all machines involved in the two supply chains. The loss of seeds, straw and chaff were recorded and an evaluation of the harvesting operating costs was carried out.

2. Materials and Methods

2.1. Field Site and Experimental Design

The test was performed at Lilla Bösld (Halland region, Sweden) (56°35′48″ N 12°57′33″ E) in the 35th week of 2019 (Figure 1). The field, 15 m a.s.l., exhibited a negligible value of slope.

The wheat (*Triticum* spp.) variety "Julius" was sown in medium clay soil type (24–29% of clay) in September 2018, with a seeding rate of 220 kg·ha^{-1} and cultivated in conventional farming. Fertilization was carried out with 150 kg·ha^{-1} of PK 11–21 and 500 kg·ha^{-1} of Nitrogen fertilizer (27% N + 9% SO3) and 200 kg·ha^{-1} of calcium nitrate. For the weed control 1 L·ha^{-1} of MCPA and 15 g·ha^{-1} of Express 50 (wetting agent 0.1 L·ha^{-1}) were used. For the fungus control, 0.5 L·ha^{-1} of Ascra Xpro was applied.

Within the field, a homogeneous area of 3 ha was preliminarily selected. The surrounding wheat was harvested and the whole biomass removed, in order to avoid edge effects and biased measurement. The selected area was then divided into three blocks, each of them sub-dived in two rectangular shaped plots measuring approximately 0.5 ha. Thus, three random replications per treatment were obtained, for a total of six plots. The chaff was collected in two different ways (treatments): either discharged on the swath (CoS) or collected on a trailer (CoT).

Figure 1. Map of the experimental field in Halland region of Sweden.

2.2. *Pre-Harvest Tests: Theoretical Biomass Assessment*

For management reasons, the test was split into two consecutive days: the first day was dedicated to the pre-harvesting activities and combine harvesting; the following day occurred the baling operation and post-harvesting activities. Before harvesting, the whole plants of 10 samples areas of 1 m^2 randomly chosen were hand harvested. Culms and spikes were weighed separately. Successively, all spikes and a representative sample of culms were put in sealed bags and shipped to the laboratory of Research Centre for Engineering and Agro-Food Processing (CREA) for further measurements as: theoretical yield of grain and chaff, dry weight and moisture content.

In the laboratory, by using a stationary thresher (PLOT 2375 Thresher, Cicoria Company, San Gervasio, Italy), kernels were separated from the rest of the spikes (rachis, lemma, glumes and palea). The dry weight and moisture content of culms, kernels and chaff was assessed according to the EN ISO 18134-2:2017 [34] standard.

2.3. *Equipment*

The contractor provided all the machines required for the test. Settings of the combine harvester, as well as the baler, were maintained at a constant rate throughout the experiment.

2.3.1. Combine Harvester and Recovery System

A combine harvester New Holland TX68 with a conventional threshing drum, straw walker and cleaning shoe was used to perform the test. The header was 7.27 m width and it was specifically designed for cereal harvesting. The machine was driven by a 209 kW diesel engine and the chassis was comprehensive of a dedicated hitch for trailer towing.

The device for the chaff recovery was installed at the end of the cleaning shoe of the combine harvester. As shown in Figure 2, the device is made of a tank that receives the chaff from the cleaning shoe; within it, there is a steal-made screw that delivers the chaff to the two-stage turbine which, in turn, blows it through the outlet. According to the company Thiérart [33], the device requires a minimum of 45 L·min^{-1} of hydraulic oil flow rate to work properly and the cutting bar of the combine harvester should not exceed 5.5 m in width to properly manage the chaff flow.

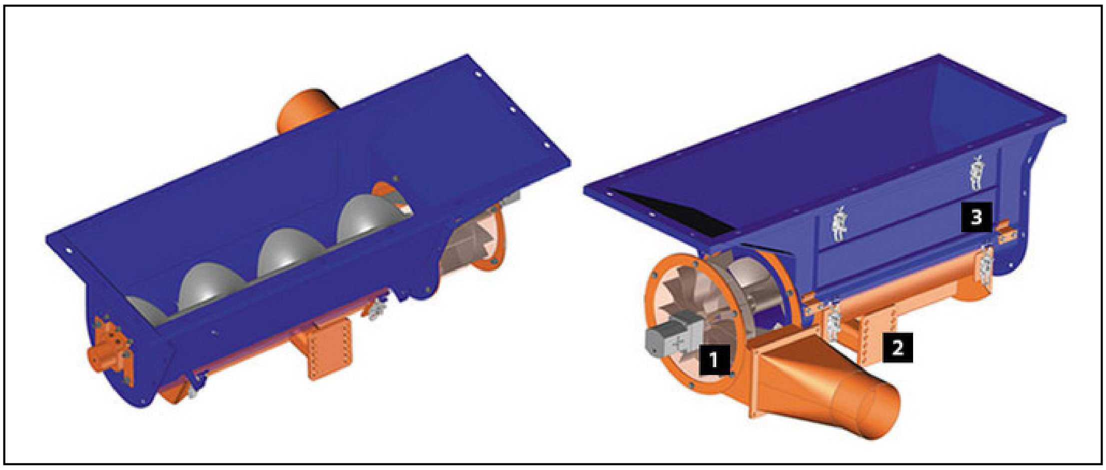

Figure 2. Device developed and patented by Thierart for chaff recovery: (1) two stages turbine; (2) specific support for the installation; (3) access hatch to the screw for inspection (source: https://www.menuepaille.fr/materiels/turbine-a-double-etage/).

Here, a PVC pipe is connected, in order to permit the discharge of the chaff, either on the swath (Figure 3a) or onto the trailer (Figure 3b). The screw and the twin-stage turbine are driven by the dedicated hydraulic system.

The trailer used was a single-axed wagon, with a pivoted drawbar directly connected to the hitch of the combine (Figure 3a). The loading capacity of the trailer was 6 m^3. The upper part of the trailer was closed with a thick plastic film, in order to prevent accidental loss of chaff due to wind interference. The combine harvester was also equipped with auxiliary hydraulic connections, for controlling the movements of the trailer while discharging the chaff.

Figure 3. (**a**) Loose in a towed trailer (CoT) = chaff recovery system mounted in New Holland TX68, for the discharging of the product on a towed trailer (Trailer Agrohill Maskin AB, Halmstad, Sweden); (**b**) CoS = chaff recovery system mounted in New Holland TX68, for the discharging of the product on top of the swath.

2.3.2. Residual Biomass Harvesting

In treatment CoT, the chaff collected during the harvesting was systematically discharged into an auxiliary trailer parked outside the field, then weighted at the end of every plot, using a local scale. In both treatments, the straw were baled using a round baler John Deer 550 towed by a tractor John Deere 6830. The baler was completely empty at the beginning of each plot. At the end of each experimental unit, the machine was forced to close the bale, even if undersized. The last bale was included in the calculation of the residue production per plot, but not in the calculation of the mean weight of the bales, in order to avoid biased mean weights. In treatment CoS the straw swaths, that also included the chaff, were baled, according to the same methodology applied in CoT. In both treatments the fuel consumption registered by the on-board computer of the tractor was recorded for a fuel consumption calculation.

2.4. Harvesting and Baling Performance

Every plot guaranteed the formation of four swaths after harvesting, with minimal overlapping between the passes. In treatment CoT, the combine had to stop at least once, in order to empty the trailer and complete the harvesting. At the end of the plot, the trailer was emptied again for total chaff weight. The time required for discharge operations was recorded as accessory time. To measure the grain yield, the collected grain was discharged on a trailer and weighted for each plot.

The performance of the machines was evaluated through the study of the working times, performed according to the Comité International d'Organisation Scientifique du Travail en Agriculture (CIOSTA) methodology and the recommendations from the Italian Society of Agricultural Engineering (A.I.I.A.) 3A R1 [35]. The evaluation of the field speed allowed the determination of the theoretical field capacity (TFC, ha·h^{-1}), the effective field capacity (EFC, ha·h^{-1}), field efficiency (FE, %) and material capacity (MC, t·h^{-1}). Gathered data were used to define the performance of the machines and the operative costs. Fuel consumption during baling was recorded by using the measuring system of the tractor. In the following paragraphs, the biomass unit (t) refers to fresh weight.

2.5. Post-Harvesting Test: Biomass Collected, Losses and Bulk Density

After baling, all bales produced within the plots were weighed singularly for total biomass baled assessment and average fresh weight measurement (here, the last bale was not included in the calculation). In treatment CoT, the quantity of the chaff collected was determined by weighing the chaff collected in each plot on an in situ scale.

Losses of biomass were assessed for stubble, straw and chaff. By knowing the cutting height of the combine header, stubbles were reconstructed in the laboratory by cutting the basal part of culms previously harvested for pre-harvest analysis. Straw and chaff losses were determined as the difference between the theoretical biomass available derived from the pre-harvest analysis and the effective biomass weighted at the end of the test. The moisture content of each biomass fraction was measured according to the standard methodology described above. The bulk density (kg·m^{-3}) of the loose biomass stored in the trailer was assessed by taking 10 randomly selected samples of chaff and was measured according to ISO 17828:2015 [36]. In each plot, all bales were weighed singularly, and three of them were randomly selected and their sizes measured for volume assessment. Bulk density was successively calculated by dividing the mass in kilograms by the volume in cubic meters.

2.6. Cost Analysis

In the economic analysis, the following parameters have been taken into account: purchase and operating costs that were provided by the contractor via a interview, performance of the machines derived from the field tests as primary data, and standard values reported in CRPA methodology [35]. Hourly costs of machines were calculated on the basis of the market value of the agricultural machinery [37,38]. The prices of the machines have been discounted to 2019, applying the lending rate of 3% provided by Banca d' Italia Institute [39]. The parameters used during the cost analysis are reported in Tables 1 and 2.

Table 1. Parameters used for the economic analysis in CoT treatment. Harvesting stage with the collection of chaff on a towed trailer and straw baling stage.

		Unit	**Harvesting**			**Baling**	
Machine			Combine harvester			Tractor	
	Power	[kW]	208.8			115.6	
	Operating machine			Thierart	Trailer		Baler
Financial cost	Investment	[€]	230,980	10,000	7000	110,127	30,463
	Service life	[y]	10	10	10	10	8
	Service life	[h]	3000	3000	3000	14,000	2500
	Resale	[%]	19	18	18	32	23
	Resale	[€]	44,139	1768	1238	40,524	6878
	Depreciation	[€]	186,841	8232	5762	69,603	23,585
	Annual usage	[$h \cdot y^{-1}$]	480	480	480	307	307
	Interest rate	[%]	3	3	3	3	3
	Workers	[n]	1	-	-	1	-
Fixed costs	Ownership costs	[$€ \cdot y^{-1}$]	18,684.09	823.16	576.21	11,009.49	2948.11
	Interests	[$€ \cdot y^{-1}$]	4126.79	176.53	123.57	1652.39	560.12
	machine shelter	[m^2]	62.30	0.00	10.20	9.12	6.93
	Value of the shelter	[$€ \cdot m^{-2}$]	100.00	0.00	100.00	100.00	100.00
	Value of the shelter	[$€ \cdot y^{-1}$]	124.59	0.00	30.60	27.36	20.79
	Insurance (0.25%)	[$€ \cdot y^{-1}$]	577.45	0.00	17.50	275.32	76.16
Variable costs	Repair factor	[%]	40.00	45.00	80.00	80.00	90.00
	Repairs and maintenance	[$€ \cdot h^{-1}$]	49.28	2.40	2.99	1.38	10.78
	Fuel cost	[$€ \cdot l^{-1}$]	0.57			0.57	
	Fuel consumption	[$L \cdot h^{-1}$]	32.51			11.60	
	Fuel cost	[$€ \cdot h^{-1}$]	18.66			6.66	
	Lubricant cost	[$€ \cdot l^{-1}$]	3.03			3.03	
	Lubricant consumption	[$L \cdot h^{-1}$]	0.14			0.09	
	Lubricant consumption	[$€ \cdot h^{-1}$]	0.44			0.27	
	Worker salary	[$€ \cdot h^{-1}$]	11.50			11.50	
	Cost of baling string	[$€ \cdot h^{-1}$]					32.32

Table 2. Parameters used for the economic analysis in baled together with the straw (CoS) treatment. The chaff collected with the twin-stage turbine is discharged on the swath and baled afterward.

		Unit	**Harvesting**		**Baling**	
Machine			Combine harvester		Tractor	
	Power	[kW]	208.8		115.6	
	Operating machine			Thierart		Baler
Financial cost	Investment	[€]	230,980	10,000	110,127	30,463
	Service life	[y]	10	10	10	8
	Service life	[h]	3000	3000	14,000	2500
	Resale	[%]	19	18	32	23
	Resale	[€]	44,139	1768	40,524	6878
	Depreciation	[€]	186,841	8232	69,603	23,585
	Annual usage	[$h \cdot y^{-1}$]	480	480	307	307
	Interest rate	[%]	3	3	3	3
	Workers	[n]	1		1	
Fixed costs	Ownership costs	[$€ \cdot y^{-1}$]	18,684.09	823.16	11,009.49	2948.11
	Interests	[$€ \cdot y^{-1}$]	4126.79	176.53	1652.39	560.12
	Machine shelter	[$m^{2]}$	62.30		9.12	9.89
	Value of the shelter	[$€ \cdot m^{-2]}$	100.00		100.00	100.00
	Value of the shelter	[$€ \cdot y^{-1}$]	124.59		27.36	29.67
	Insurance (0.25%)	[$€ \cdot y^{-1}$]	577.45		275.32	76.16

Table 2. *Cont.*

		Unit	Harvesting		Baling	
Variable costs	Ownership costs	[%]	40.00	45.00	80.00	90.00
	Repairs and maintenance	[€·h^{-1}]	49.28	2.40	1.38	10.78
	Fuel cost	[€·L^{-1}]	0.57		0.57	
	Fuel consumption	[L·h^{-1}]	32.51		10.7	
	Fuel cost	[€·h^{-1}]	18.66		6.14	
	Lubricant cost	[€·L^{-1}]	3.03		3.03	
	Lubricant consumption	[L·h^{-1}]	0.14		0.09	
	Lubricant consumption	[€·h^{-1}]	0.44		0.27	
	Worker salary	[€·h^{-1}]	11.50		11.50	
	Cost of baling string	[€·h^{-1}]				32.32

In the calculation of the operating costs of the two harvesting systems, the time required for each operation, the quantity of the products obtained and the respective market value (Table 3) were considered. The economic allocation in each treatment was derived from the ratio between each product revenue on the total revenues obtained, as shown in the following formula:

$$Ea = \frac{Mp \times Y_i}{\sum_{i=1}^{3} R_i} \tag{1}$$

where:

Ea = Economic allocation of each product or co-product (i.e., grain seed, straw, or chaff) per harvesting phase (combine harvesting or baling)
Mp = Market price of each product or co-product (i.e., grain seed, straw, or chaff)
Y_i = Yield of each product or co-product (i.e., grain seed, straw, or chaff)
R_i = Revenue obtained by multiplying $Mp \times Y_i$

Table 3. Economic allocation used for the cost analysis of straw and chaff harvesting with the Thierart technology in Sweden, for each harvesting phase, and treatment.

Treatment	Product	Market Price [€·t^{-1}]	Yield [t·ha^{-1}]	Revenue [€·ha^{-1}]	Economic Allocation Harvesting [%]	Economic Allocation Baling [%]
CoT	Grain	198.5 [1]	9.83	1951.26	89.2	0.0
	Straw	50 [1]	3.88	194	8.9	100.0
	Chaff	50 [1]	0.84	42	1.9	0.0
	Total			2187.26	100.0	100.0
CoS	Grain	198.5	9.5	1881.78	88.9	0.0
	Straw	50	3.9	194	9.2	83.0
	Chaff	0	0.8	40	1.9	17.0
	Total			2115.78	100.0	100.0

Note: prices retrieved from Camera di Commercio di Modena (2019) [40].

2.7. Statistical Analysis

The statistical analysis was performed in order to discriminate the differences among the treatments. All data were subjected to the analysis of variance (ANOVA), using the R 3.6.1 to separate statistically different means ($p \leq 0.05$) [41].

3. Results and Discussions

3.1. Biomass Fractions

The results of pre-harvesting highlighted that the total aboveground biomass was 18.8 t·ha^{-1}. Spikes represented the 57% (10.78 t·ha^{-1}) of the total (47% seeds and 10% chaff, corresponding to 8.94 t·ha^{-1} and 1.84 [t·ha^{-1}], respectively) whereas the whole culms accounted for the 43% (8.02 t·ha^{-1}). The moisture content was equal to 14.3% (±9.1), 9.0% (±3.5) and 14.6% (±2.7), for straw, chaff and seeds, respectively. After the harvesting, the different fractions of biomass collected are shown in Figure 4.

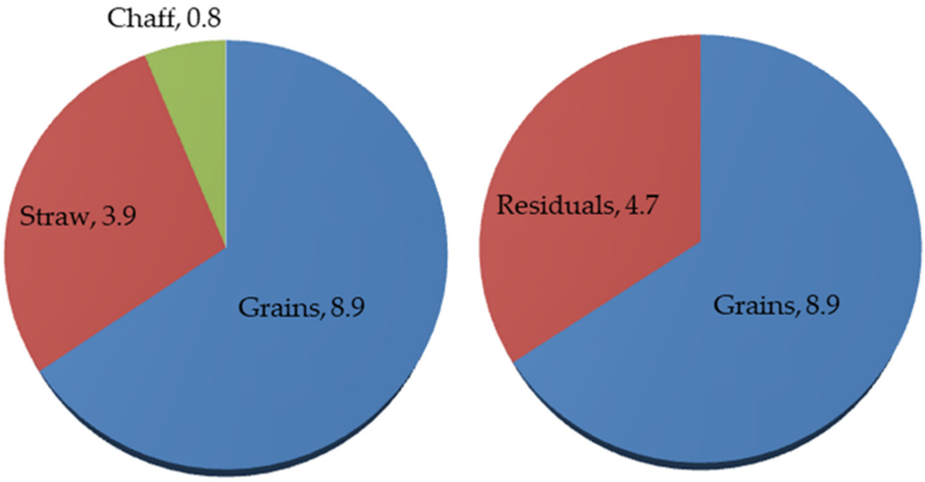

Figure 4. Effective tons of fresh biomass collected in treatment CoT (**left**) and CoS (**right**). CoT permitted one to collect the chaff separately from the straw, while in CoS, the chaff was baled with straw and considered as residual.

3.2. Performance of the Combine

The methodologies studied for chaff collection highlighted some differences in the performance of the machines involved. According to what was anticipated by Glasner et al. (2019) [42], the theoretical field capacity (TFC) of the combine did not variate among the treatments, as its speed was constant during the cutting and cleaning processes, although a reduction of 10–25% of cleaning was reported in the study. Despite that, significant differences were found in EFC, FE and MC (Table 4), where the accessory times, like the time required for unloading the wagon in CoT, were included. In fact, the wagon could collect only 6 m^3 of loose chaff and, considering the low bulk density of 41.75 kg·m^{-3}, the wagon shortly became full of chaff, forcing the combine harvester to stop and exit the field for unloading the wagon. A similar value of 42.88 kg·m^{-3} for chaff bulk density was reported by Bergonzoli et al. [26] and slightly higher values of 56 kg·m^{-3} and 62.08 kg·m^{-3} were found by McCartney et al. [13] and by Suardi et al. [24].

Table 4. Comparison of the performance of the combine harvester among the two treatments. (TFC = Theoretical Field Capacity, EFC = Effective Field Capacity, FE = Field Efficiency, MC = Material Capacity).

Treatment	TFC	EFC	FE	MC	
	[ha·h^{-1}]	[ha·h^{-1}]	[%]	[t_{grain}·h^{-1}]	[$t_{residue}$·h^{-1}]
CoT	2.17 ± 0.20	1.02 ± 0.18	47 ± 5	9.87 ± 0.82	0.84 ± 0.05
CoS	2.34 ± 0.43	1.71 ± 0.36	73 ± 8	16.22 ± 3.49	-
ANOVA	ns	*	**	*	

Note: (ns) not significant; (*) Significant at $p < 0.05$; (**) Significant at $p < 0.01$.

In CoT, the unproductive times of the combine harvester were 233% higher than in CoS where the chaff was continually blown over the swath. In fact, as depicted in Table 4, the FE and the MC of the combine harvester were significantly higher when the CoS system was applied. In Suardi et al. [19], TFC and EFC were respectively 3.72 ha·h^{-1} and 2.28 ha·h^{-1} on average and the combine fuel consumption resulted in 11.8 L·h^{-1}.

Different methods for loose chaff collection have been reported in the literature. For instance, Suardi et al. [24] tested a continuative discharging of chaff onto a trailer towed by a tractor side by side the combine; that the system permitted to collect 1.27 t·ha^{-1} of loose chaff. Differently, Bergonzoli et al. [26] tested a combine harvester equipped with Harcob system, which had an integrated tank of 9 m^3 in volume for storage of the chaff collected and that the system allowed to collect 0.6 t·ha^{-1}. Regardless of the quantity of the chaff collected, neither of them reported negative impacts on the combine performance: the trailer volume available for chaff storage in Suardi et al. [24] was better dimensioned, while the Harcob system allows the simultaneous discharging of grain and chaff, avoiding extra unloading time [26]. For that reason, the unproductive times needed were much lower. Similar tests performed by INRA (Institut National de la Recherche Agronomique) in the frame of the project «Systèmes de Cultures Innovants» and CUMA (Federation Nationale des Cooperatives d'Achat et d' Utilisation de Materiel Agricole) in 2011 and 2012 demodays with similar turbine systems, provided higher results in terms of quantity of chaff collected: respectively, 1.5 t·ha^{-1} and 1.15 t·ha^{-1} [43,44].

3.3. Performance of the Baler

Regarding the baling stage, the EFC that includes accessories' times (e.g., turning time and unloading time) was lower in CoS, since a higher quantity of biomass in the swath was to be processed (Table 5). That implied more stops for the discharge of the bales and it also forced the tractor to reduce the speed, in order to avoid overloading of the baler's chamber. In fact, the amount of biomass that the baler could process per unit of time was not statistically different. No significant differences were found regarding TFC. The fuel consumption of the tractor was also recorded and referred to the unit of biomass baled. On average, 1.27 (±0.17) l of diesel fuel was required for each ton of straw baled, regardless of the presence or the absence of the chaff in the bales.

Table 5. Comparison of the performance of the baler within the two treatments. MC is calculated taking into account the overall quantity of residual biomass produced: straw and chaff together (TFC = Theoretical Field Capacity, EFC = Effective Field Capacity, FE = Field Efficiency, MC = Material Capacity). No statistical differences were found between treatments.

Treatment	TFC [ha·h^{-1}]	EFC [ha·h^{-1}]	FE [%]	MC [t·h^{-1}] ⸸
CoT	2.86 ± 0.43	1.92 ±0.09	68 ± 7	7.47 ± 0.85
CoS	2.21 ± 0.25	1.57 ± 0.15	71 ± 2	7.37 ± 0.38
ANOVA	ns	*	ns	ns

Note: (⸸) Material Capacity refers to tons of fresh residues. (ns) Not significant; (*) Significant at $p < 0.05$.

Similar tests were performed by Suardi et al. in France in 2018 and 2019 [24], on baling the straw with chaff. The authors reported higher values for TFC, EFC and MC, respectively: 5.23 (±0.65) ha·h^{-1}, 3.46 (±0.28) ha·h^{-1} and 20.79 (±0.7) t·h^{-1} in 2018; whereas 4.64 (±0.31) ha·h^{-1}, 3.09 (±0.13) ha·h^{-1} and 20.20 (±2.0) t·h^{-1} in 2019. When chaff was not included in the bales, the performance of the baler was not statistically different. The fuel consumption ranged between 0.77 (±0.15) l·t^{-1} and 0.94 (±0.12) l·t^{-1} in the case of straw and chaff baling, while it ranged from 1.01 (±0.13) l·t^{-1} and 0.64 (±0.23) l·t^{-1}, when the chaff was dispersed on the ground. In similar experiment, the TFC and EFC of straw baling operation resulted on average 3.96 ha·h^{-1} and 2.01 ha·h^{-1}, with a mean FE of 51 % [19].

3.4. Losses of Biomass during the Baling Stage

The theoretical availability of straw, in the present study, was estimated in 8.02 t·ha^{-1}; in line with other studies such as Suardi et al. [24], where the theoretical straw availability was estimated at 7.39 (±0.73) t·ha^{-1} and 8.33 (±0.75) t·ha^{-1}, in 2018 and 2019 tests, respectively. Nevertheless, during the present study, the amount of residues baled was on average 3.88 t·ha^{-1} and 4.68 t·ha^{-1} with CoT and CoS treatments, respectively (Table 6). Therefore, the remarkable differences in the residue harvesting performance can be imputed exclusively to the suitability of the machine chosen by the contractor, to carry on the baling stage. The round baler John Deere mod. 550 used during the test was equipped with a pick-up 1.41 m wide, whereas the straw swath produced by the combine harvester measured 1.74 m in width, on average. Hence, 0.33 m of straw swath could not be collected by the baler's pick-up system in each pass, due to reduced width of the its pickup system (Figure 5). At the end of the baling phase, a large quantity of product was still not harvested in the field (Figure 3).

Table 6. Differences in fresh biomass outputs from wheat crop, due to the use of a twin-stage Turbine for chaff collection.

Treatment	Machine	Yield Grain [t·ha^{-1}]	 Residue [t·ha^{-1}]	Bale Weight [kg]	Bale Density [kg·m^{-3}]	Chaff Bulk Density [kg·m^{-3}]
CoT	Combine	9.83 ± 1.26	0.84 ± 0.12	-	-	41.75 ± 3.30
	Baling	-	3.88 ± 0.06	184.6 ± 4.41	76.78 ± 1.83	-
CoS	Combine	9.48 ± 0.45	-	-	-	-
	Baling	-	4.68 ± 0.23	198.4 ± 3.14	82.22 ± 1.33	-
ANOVA		ns	ns ⸸	*	*	

Note: (⸸) In treatment CoT the mean residue value takes into account also the chaff, (-) not performed; (ns) non-significant; (*) Significant at $p < 0.05$.

Figure 5. The narrow pick-p of the round baler (**left**) caused high loss of straw (**right**) along the swath (areas of the swath not reached by the baler's pickup system are highlighted in red).

The estimated average loss of residue after baling was 4.75 t·ha^{-1} (4.68 t·ha^{-1} for CoS, and 4.72 t·ha^{-1} for CoT), corresponding to a loss of biomass of 50% on average, without statistical difference between the two treatments.

Bergonzoli et al. [26] reported a similar value when a combine harvester mounting Harcob system (developed for Maize cob harvesting) was modified and used for collecting the chaff in wheat crops, even if the results were ascribed to the cleaning system of the combine harvester.

Such a level of product losses recorded during the tests exceed the sustainable removal rate of 33% proposed by Unger and Glasner (2019) [23]. For this reason, it could be considered positive from the point of view of soil fertility, even if the economic sustainability is closely linked to the amount of recoverable biomass. Therefore, low collection efficiencies may render the operation of recovering residual biomass economically unviable.

However, the scenarios herein proposed provided differences in both the quantity and quality of residuals biomass collectable from wheat cropping, without affecting the grain yield. Such an aspect is very important; in fact harvesting, along with storage, is the most responsible factor for loss of grains throughout the wheat supply chain [45]. The presence of the chaff included in the bales increased both weight and density of the bales by 7.45% and 7.09% respectively, in comparison with bales free of chaff (Table 6). Increases of 18.0% in bale bulk density, due to the inclusion of chaff, was reported by Suardi et al. [24], when a similar turbine technology for chaff recovery was used. On the other hand, Suardi et al. reported a non-significant increase in the case of chaff admixing performed with a combi system (manifactured by Rekordverken Sweden AB, Kvänum, Sweden) [19].

The different methods studied, allowed to harvest 4.68 t·ha^{-1} and 4.72 t·ha^{-1} of wheat residues by baling chaff and straw together, or by harvesting chaff in the trailer and straw baling, respectively (Table 6), with no statistical differences.

3.5. Cost Analysis

In the analysis of the unitary costs, the running cost of each machinery involved in the supply chain is related to the market price [€·t^{-1}] of each product and by-product obtained. The performance of the machines contributed to the final calculation of the costs. For instance, the reduction in EFC, FE and MC of the combine harvester (Table 4) found that, when the combine towed the wagon (CoT), it increased the hourly harvesting cost by 3.41%, the cost per hectare by 73.35%, and the cost per ton of biomass processed by 67.73% (Tables 7 and 8), in comparison with CoS. Here, the combine harvester did not waste time to continually stop and unload the wagon.

Table 7. Costs for unit of time, surface and ton of biomass processed in CoS harvesting system, considering the productivity and the market price of each product.

		Unit	Grain	Straw	Chaff	Total Harvesting Costs
	Market price	[€·t^{-1}]	198.5	50	50	
	Yield	[t·ha^{-1}]	9.83	3.88	0.84	
Harvesting	Cost allocation	[%]	89%	9%	2%	100%
	Combine harvester + Twin stage turbine + Wagon	[€·h^{-1}]	123.01	12.23	2.65	137.89
		[€·ha^{-1}]	120.6	11.99	2.6	135.18
		[€·t^{-1}]	12.27	3.09	3.09	18.45
Baling	Cost allocation	[%]	0%	100%	0%	100%
	Tractor + Baler	[€·h^{-1}]		116.85		116.85
		[€·ha^{-1}]		60.86		60.86
		[€·t^{-1}]		15.69		15.69
Total cost of the harvesting system		[€·h^{-1}]	123.01	129.08	2.65	254.74
		[€·ha^{-1}]	120.6	72.85	2.6	196.04
		[€·t^{-1}]	12.27	18.78	3.09	

Table 8. Costs for unit of time, surface and ton of biomass processed in CoT harvesting system considering the productivity and the market price of each product.

		Unit	Grain	Straw	Chaff	Total Harvesting Costs
	Market price	[€·t^{-1}]	198.5	50	50	
	Yield	[t·ha^{-1}]	9.48	3.88	0.8	
Harvesting	Cost allocation	[%]	89%	9%	2%	100%
	Combine harvester + Twin stage turbine	[€·h^{-1}]	118.59	12.23	2.52	133.34
		[€·ha^{-1}]	69.35	7.15	1.47	77.98
		[€·t^{-1}]	7.32	1.84	1.84	11
Baling	Cost allocation	[%]		83%	17%	100%
	Tractor + Baler	[€·h^{-1}]		96.47	19.89	116.36
		[€·ha^{-1}]		61.45	12.67	74.12
		[€·t^{-1}]		15.84	15.84	31.67
Total cost of the harvesting system		[€·h^{-1}]	118.59	108.7	22.41	249.7
		[€·ha^{-1}]	69.35	68.6	14.14	152.09
		[€·t^{-1}]	7.32	17.68	17.68	

On the other hand, when the chaff was blown on the swath, the baler had much more biomass (straw and chaff) to process. In fact, the baler's EFC (Table 5) dropped by 18.23% and the costs per hectare and per ton of biomass processed increased by 21.79% and 101.85%, respectively. The hourly cost for baling did not change (Tables 7 and 8).

The choice to apply CoS over CoT harvesting method affected both the performance and running cost of the machines. According to Table 9, the harvesting cost per hectare increased by 28.90% (from 152.03 €·ha^{-1} to 196.05 €·ha^{-1}), when the chaff was collected as loose material (CoT).

Table 9. Economic calculation cost, revenue and the net gain obtained from the collection of grains, straw and chaff when harvested with the two different methods: CoS and CoT.

Treatment	Product	Yield [t·ha^{-1}]	Market Price [€·t^{-1}]	Revenue [€·ha^{-1}]	Harvesting Costs [€·ha^{-1}]	Net Gain [€·ha^{-1}]
CoT	Seed	9.83	198.50	1951.26	120.60	1830.66
	Straw	3.88	50.00	194.00	72.85	121.15
	Chaff	0.84	50.00	42.00	2.60	39.40
	Total	14.55	-	2187.26	196.05	1991.21
CoS	Seed	9.48	198.50	1881.78	69.35	1812.43
	Straw	3.88	50.00	194.00	68.60	125.40
	Chaff	0.80	50.00	40.00	14.14	25.86
	Total	14.16		2115.78	152.09	1963.69

The same results were obtained by Unger and Glasner in 2019, where the separate chaff collection and supply led to higher costs [23]. However, the overall capacity of CoT system permitted one to collect more biomass per hectare (0.38 t and 0.04 t of grain and chaff respectively), counterbalancing the higher costs. In fact, if considering just the net gain per hectare, CoS permitted to gain only 27.52 €·ha^{-1}.

Furthermore, in the present study, a market price for chaff of 50 €·t^{-1} was considered. However, Unger and Glasner [23] highlighted that the potential revenue of chaff could vary depending the final use and market price that can range from 81 €·t^{-1} to 200 €·t^{-1}, making chaff separate collection economically viable, and giving the farmer, from year to year, different sales opportunities of the product to more profitable markets.

4. Conclusions

The cultivation of the cereals is an important source of staple food around the world, and it also produces a relevant quantity of ligno-cellulosic biomass, that can be further exploited in order to improve the economic and environmental sustainability of the whole supply chain. In fact, agricultural residues are gaining more and more interest, due to their considerable availability and their potential content of energy, or as raw material for industrial processes. Cereal straw and chaff collected either separately or baled altogether can be a source of food for animals, particularly in case of shortage, or natural bedding for livestock. In poultry farming, farmers reported positive experiences on the use of loose chaff for littering, since it provides wellness to animals and a good adsorbent capacity. However, possible utilization of chaff is to produce bioenergy. Normally, about two tons of chaff per hectare are available, but still not collected, due to three major problems: unawareness of proper mechanical devices available on the market for its collection, uncertainty on the harvesting system to adopt and the development of a specific supply chain for its exploitation. So far, the literature reports few cases of chaff collection with the specific purpose of weed seeds removal, but it still lacks specific experiments on these machines intentionally used for biomass collection. Therefore, the present study aimed to fill that gap and provide deeper understanding in the possibility to enhance the current wheat harvesting method, in order to improve the quantity of biomass collected by including the chaff. This research analyzed the technical and economic feasibility of two different logistic methods for chaff collection: chaff collected as loose product onto a towed trailer (CoT) and baled altogether with the straw (CoS).

Our results suggest that upgrading a conventional combine harvester with a twin-stage turbine for chaff collection increases the total biomass collected by 0.84 $t{\cdot}ha^{-1}$ without affecting the grain yield. Furthermore, the separation of chaff from the straw is performed simultaneously to the cleaning process of the grain and no additional passes of the machine on the field are needed, and further soil compaction is prevented.

Even if our results reveal that the collection of the loose chaff into a towed wagon is more costly than including it into the bales, the market price of the pure chaff should be higher, to offset the extra costs required by the contractor for the collection and handling. Furthermore, it should be noted that the trailer system could be used also for other crop by-products; for instance, collecting finely chopped roughage after a forage harvester, without the strong modification of the combine, reducing the unitary cost of the investment and increasing the quantity of biomass potentially collectable. In fact, the unproductive time in CoT was 233% higher than in CoS with an increase of 43.94 $€{\cdot}ha^{-1}$ for the harvesting cost. In addition to the higher costs, loss of revenue may take place in case of inappropriate choice of the machine for accomplishing a specific task. Particularly, the round baler chosen by the contractor could not collect all the straw windrowed by the combine harvester. Although the subject is still under discussion, some authors consider that a residue extraction of no more than 33% is sustainable for the soil fertility. On the other hand, however, an amount of uncollected residue, such as that found during the study (50% of harvesting losses), could negatively affect the economic feasibility of the residue collection phase, questioning the investment in specific equipment. In fact, according to 6results from CoT treatment, where the chaff was not included in the straw, only 3.88 $t{\cdot}ha^{-1}$ out of 8.02 $t{\cdot}ha^{-1}$ of straw available on the field were baled. Considering the straw market price of 50 $€{\cdot}t^{-1}$, this can be translated into a loss of income of more than 200 $€{\cdot}ha^{-1}$.

Future studies should be focused on the assessment of the sustainability of the chaff collection, in terms of the effect to the soil fertility, carbon dioxide emissions and soil compaction.

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References

1. Eise, J.; Foster, K. *How to Feed World*; Island Press Center for Resource Economics: Washington, DC, USA, 2018; pp. 1–250.
2. European Parliament. DIRECTIVE (EU) 2015/1513 of the european parliament and of the council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewabl. *Off. J. Eur. Union* **2015**, *L239/1*, 20–30.
3. EU. A 2030 Framework for Climate and Energy Policies. European Parliament Resolution of 5 February 2014 on a 2030 Framework for Climate and Energy Policies (2013/2135(INI)). 2014. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014IP0094&from=EN (accessed on 18 January 2020).
4. Stelte, W.; Sanadi, A.R.; Shang, L.; Holm, J.K.; Ahrenfeldt, J.; Henriksen, U.B. Recent developments in biomass pelletization—A review. *BioResources* **2012**, *7*, 4451–4490.
5. Paiano, A.; Lagioia, G. Energy potential from residual biomass towards meeting the EU renewable energy and climate targets. The Italian case. *Energy Policy* **2016**, *91*, 161–173. [CrossRef]
6. Mann, M.E.; Cohen, R.D.H.; Kernan, J.A.; Nicholson, H.H.; Christensen, D.A.; Smart, M.E. The feeding value of ammoniated flax straw, wheat straw and wheat chaff for beef cattle. *Anim. Feed Sci. Technol.* **1988**, *21*, 57–66. [CrossRef]
7. Ionel, I.; Cioablă, A.E. Biogas production based on agricultural residues. From history to results and perspectives. *WSEAS Trans. Environ. Dev.* **2010**, *6*, 591–603.
8. Fang, G.; Shen, K. Wheat straw pulping for paper and paperboard production. In *Global Wheat Production*; InTech Open: London, UK, 2018; pp. 223–240.
9. Hýsek, Š.; Čermák, J.; Lexa, M. Influence of lignocellulosic waste pre-treatment on the characteristics of bond rupture. *Sustainability* **2019**, *11*, 4784. [CrossRef]
10. Swain, M.R.; Singh, A.; Sharma, A.K.; Tuli, D.K. Bioethanol production from rice—And wheat straw: An overview. In *Bioethanol Production from Food Crops*; Ray, R.C., Ramachandran, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 213–231, ISBN 978-0-12-813766-6.
11. Yang, Y.; Ma, S.; Zhao, Y.; Jing, M.; Xu, Y.; Chen, J. A field experiment on enhancement of crop yield by rice straw and corn stalk-derived biochar in Northern China. *Sustainability* **2015**, *7*, 13713–13725. [CrossRef]
12. Seglah, P.A.; Wang, Y.; Wang, H.; Bi, Y. Estimation and efficient utilization of straw resources in Ghana. *Sustainability* **2019**, *11*, 4172. [CrossRef]
13. McCartney, D.H.; Block, H.C.; Dubeski, P.L.; Ohama, A.J. Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in western Canada. *Can. J. Anim. Sci.* **2006**, *86*, 443–455. [CrossRef]
14. EU. Eurostat Database, Cereals for the Production of Grain (Including Seed) by Area, Production and Humidity. 2019. Available online: https://ec.europa.eu/eurostat/databrowser/view/tag00027/default/table?lang=en (accessed on 18 January 2020).
15. Rönnbäck, M.; Lundin, G. Simultaneous harvesting of straw and chaff for energy purposes-influence on bale density, yield, field drying process and combustion characteristics. In Proceedings of the XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR) Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB), Québec City, QU, Canada, 13–17 June 2010.
16. Weiß, B.D.; Glasner, C. Evaluation of the process steps of pretreatment, pellet production and combustion for an energetic utilization of wheat chaff. *Front. Environ. Sci.* **2018**, *6*, 1–10. [CrossRef]
17. Zhang, H.; Lopez, P.C.; Holland, C.; Lunde, A.; Ambye-Jensen, M.; Felby, C.; Thomsen, S.T. The multi-feedstock biorefinery—Assessing the compatibility of alternative feedstocks in a 2G wheat straw biorefinery process. *GCB Bioenergy* **2018**, *10*, 946–959. [CrossRef]

18. Shirtliffe, S.J.; Entz, M.H. Chaff collection reduces seed dispersal of wild oat (avena fatua) by a combine harvester. *Weed Sci.* **2005**, *53*, 465–470. [CrossRef]
19. Uardi, A.; Saia, S.; Stefanoni, W.; Gunnarsson, C.; Sundberg, M.; Pari, L. Admixing chaff with straw increased the residues collected without compromising machinery efficiencies. *Energie* **2020**, *13*, 1766.
20. Walsh, M.; Newman, P.; Powles, S. Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technol.* **2013**, *27*, 431–436. [CrossRef]
21. Jacobs, A.; Kingwell, R. The harrington seed destructor: Its role and value in farming systems facing the challenge of herbicide-resistant weeds. *Agric. Syst.* **2016**, *142*, 33–40. [CrossRef]
22. Walsh, M.J.; Harrington, R.B.; Powles, S.B. Harrington seed destructor: A new nonchemical weed control tool for global grain crops. *Crop Sci.* **2012**, *52*, 1343–1347. [CrossRef]
23. Unger, J.S.; Glasner, C. Cost analysis of chaff harvesting concepts in Germany. *Agronomy* **2019**, *9*, 579. [CrossRef]
24. Suardi, A.; Stefanoni, W.; Alfano, V.; Bergonzoli, S.; Pari, L. Equipping a combine harvester with turbine technology increases the recovery of residual biomass from cereal crops via the collection of chaff. *Energies* **2020**, *13*, 1572. [CrossRef]
25. Pari, L.; Toscano, G.; Suardi, A.; Bergonzoli, S.; Lopez, E.; Scarfone, A.; Alfano, V. Maize cob and cereal chaff: Feedstocks for energy production. *Eur. Biomass Conf. Exhib. Proc.* **2018**, *2018*, 279–282.
26. Bergonzoli, S.; Suardi, A.; Rezaie, N.; Alfano, V.; Pari, L. An innovative system for maize cob and wheat chaff harvesting: Simultaneous grain and residues collection. *Energies* **2020**, *13*, 1265. [CrossRef]
27. Gerling, M.; Dickey, P.C. Absorbant Animal Bedding. U.S. Patent No 5,878,696, 9 March 1999. Available online: https:/patentimages.storage.googleapis.com/aa/1d/1d/5d9a9f2a556454/US5878696.pdf (accessed on 25 February 2020).
28. Anisuzzaman, M.; Chowdhury, S.D. Use of four types of litter for rearing broilers. *Br. Poult. Sci.* **1996**, *37*, 541–545. [CrossRef] [PubMed]
29. Swain, B.K.; Sundaram, R.N.S. Effect of different types of litter material for rearing broilers. *Br. Poult. Sci.* **2000**, *41*, 261–262. [CrossRef] [PubMed]
30. Shishkin, V.; Shulzhenko, E. The study of soybean chaff pressing process depending on its fractional composition and humidity. *Bull. Sci. Pract.* **2019**, *5*, 160–164. [CrossRef] [PubMed]
31. Trinh Van, Q.; Nagy, S. The influence of temperature on the briquetting of ground post agglomerated spelt chaff. *Mech. Hulladékkezeles* **2019**, *13*, 13–18.
32. EU. Agroinlog—Integrated Biomass Logistic Centres fo the Agro-Industry. Available online: https://ec.europa.eu/eip/agriculture/en/news/agroinlog-integrated-biomass-logistics-centres (accessed on 26 May 2020).
33. Thiérart Etude. Conception et Réalisation de Machines Spéciales. Available online: https://www.thierart.fr/ (accessed on 17 January 2020).
34. NSAI. ISO. ISO 18134-2:2017 Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 2: Total Moisture—Simplified Method 2017. Available online: https://www.iso.org/standard/71536.html (accessed on 6 March 2020).
35. Assirelli, A.; Croce, S.; Acampora, A.; Civitarese, V.; Suardi, A.; Santangelo, E.; Pari, L. An innovative system for conditioning biomass [sorghum bicolo (l.) moench.]. *Am. Soc. Agric. Biol. Eng.* **2013**, *56*, 829–837.
36. ISO 17828:2015 Solid Biofuels—Determination of Bulk Density. 2015. Available online: https://www.iso.org/obp/ui/#iso:std:iso:17828:ed-1:v1:en (accessed on 23 December 2015).
37. American society of agricultural engineers agricultural machinery management. *Agricultural Machinery Management*; American Society of Agricultural Engineers: St. Joseph, MI, USA, 2000; pp. 344–349.
38. Assirelli, A.; Pignedoli, S. Costo di esercizio delle macchine agricole. *Boll. CRPA Not.* **2005**, *5*, 1–10.
39. Banca d'Italia. Banca d'Italia Lending Rate. Available online: https://www.bancaditalia.it/ (accessed on 11 November 2019).
40. Camera di Commercio di Modena (Chamber of Commerce of Modena). Listino dei prezzi all'ingrosso rilevati sul mercato di Modena nella settimana dal 16 luglio al 22 luglio 2019 (List of Wholesale Prices Recorded on the Modena Market in the Week from 16 July to 22 July 2019). 2019. Available online: https://www.mo.camcom.it/tutela-del-mercato/borsamerci/listini/listino-dei-prezzi-allingrosso-rilevati-sul-mercato-di-modena-nella-settimana-dal-16-al-22-luglio-2019 (accessed on 6 March 2020).
41. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2008; ISBN 3-900051-07-0.

42. Glasner, C.; Vieregge, C.; Robert, J.; Fenselau, J.; Bitarafan, Z.; Andreasen, C. Evaluation of new harvesting methods to reduce weeds on arable fields and collect a new feedstock. *Energies* **2019**, *12*, 1688. [CrossRef]
43. INRA. Recuperateur de Menues Pailles «turbo Paille de Thievin». Mignaloux-Beauvoir. 2011. Available online: https://geco.ecophytopic.fr/documents/20182/21720/upload_00011189_pdf (accessed on 6 March 2020).
44. CUMA. Journée Technique: Récuperation des Menues Pailles. 2015. Available online: http://draaf.normandie.agriculture.gouv.fr/IMG/pdf/6_Powerpoint_journee_menues_pailles_FRCUMA_cle0bd622.pdf (accessed on 6 March 2020).
45. Mesterházy, A.; Oláh, J.; Popp, J. Losses in the grain supply chain: Causes and solutions. *Sustainability* **2020**, *12*, 2342. [CrossRef]