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Equipping a Combine Harvester with Turbine Technology Increases the Recovery of Residual Biomass from Cereal Crops via the Collection of Chaff

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Abstract: In cereal crops, chaff is a valuable lignocellulosic by-product that accounts for more than 50 Mt y^{-1} in Europe and is suitable for bioenergy purposes. Chaff is usually not collected due to the lack of combine harvesters that have the capability to handle it properly. The present two years experimental study investigated the hypothesis that the overall biomass collected in wheat crop can be increased by equipping the combine harvester with an aftermarket device. Chaff, discharged from the combine harvester-cleaning system, is collected by the turbine that delivers it either on the swath or on a lateral trailer towed by a tractor. The performance of all machines involved in the harvesting (combine harvester, tractor, baler, and trailer) were assessed. The chaff was collected in bales with the straw (A mode) and separately on a trailer (C mode). Comparisons with non-collected treatment (B mode) were performed in order to estimate the total chaff collected and the biomass losses. The results showed that 1.79 t FM ha^{-1} per year of chaff could be collected when baled with the straw, whereas 1.27 t FM ha^{-1} were collected separately on a trailer. Both field and material capacity were not negatively affected by the chaff collection. Therefore, our study confirmed the hypothesis that turbine technology is a valid solution for increasing the total residual biomass collected in cereal cropping for energy purposes.

Keywords: wheat; straw; weed seed; biocommodity; threshing; bioenergy

1. Introduction

The development of the bioeconomy in the last years has increased the biomass demand, not only for energy purposes but also for chemicals and material applications [1]. The European policy for energy encourages the utilization of agroforestry residues, limiting the energy crops plantations [2]. Moreover, traditional sources for bioenergy production would not be enough to meet the future energy needs and to respond to the new targets of EU 2030 framework for climate and energy policies [3,4]. In this scenario, it is crucial to exploit biomass resources that are currently unexploited, such as agricultural residues [5].

Among the agricultural residues, cereal chaff has gained interest due to its availability and properties. Chaff is commonly defined as the by-product of cereal harvest comprehensive of glumes, hulls, short straw, damaged kernels, and weed seeds. During threshing, the chaff fraction sieved by the cleaning shoe underneath the straw walkers is blown to the rear of the combine harvester [6].

This material is normally either left to fall on the ground below the straw swath or is spread. In both cases, the chaff cannot be collected by the straw baling press pick-up, in the following baling operation.

According to the statistical office of the European Union EUROSTAT, about 295 Mt of cereal grains are harvested yearly in EU28 [7]. Considering a mean value of chaff-to-grain ratio of 0.17 [8], more than 50 Mt yr^{-1} of chaff is available and harvestable in Europe. However, such a resource is generally left on the ground after cereal threshing and is lost.

Nevertheless, chaff could be a valuable source for an energetic utilization, either when baled with straw [9] or when pelleted after being separated from the straw [10]. Moreover chaff can be a valuable feedstock in a second generation bioethanol process [11].

Although cereal straw and chaff have low nutritive value they could be used as substantial feed resource for beef cows [8] or as a hay substitute in winter feeding [12]. The main use of straw in animal farming is for littering but since the use of combine harvesters has taken over manual trashing, the chaff is no longer included into the straw, as before. The lack of absorbent capacity provided by chaff has dictated the reduction in straw usage as a natural bedding for feedstock. In fact, unless specific equipment is used, the chaff is usually not collected by combines in the field and is incorporated into the soil during the preparation of the field for following year crop [13]. However, the incorporation of residual organic matter, particularly the chaff, is also reported to be correlated to root diseases and *Pythium* spp. populations that result in root system damages in the new seedlings [14].

On the other hand, agronomic advantages are also experienced when the chaff is removed. In fact, the collection of the chaff during cereal harvesting can reduce the weed seed stock in the soil by removing weed seeds before they are returned to the field [15]. The recognition that during grain harvest, the seeds of important crop weeds are intact and attached to the upright plant and can be "harvested", led to the introduction of Harvest Weed Seed Control (HWSC) systems in Australia [16]. The most widely adopted system is the narrow windrow burning. It consists of a grain harvester, mounted chute, to concentrate all the exiting chaff and straw residues into a narrower windrow that is subsequently burnt. In order to avoid in-situ burning, other methods are currently used. (i) The chaff cart method, which consists of a wagon towed by the combine that collects the chaff exiting the trashing system and temporarily accumulates it in the bin for discharge, when full. (ii) Bale direct systems (BDS), which are large square balers that are directly attached to the harvester that makes bales from the chaff and straw residues exiting the grain harvester. (iii) The Harrington seed destructor (HSD), which uses a cage mill mounted on a trailer to crush the weed seed carried by the chaff flow [17,18].

Recently, with the aim to fight the herbicide-resistant weeds, Klaus Jakobsen and Christoph Glasner et al. (2019) [19,20] investigated if hot exhaust gas from a combine harvester could be used to reduce germination or kill weed seeds during the harvesting process, in order to develop an integrated system in the combine harvester.

On the contrary, the growing interest in the exploitation of these residues for industrial uses has pushed some constructors to develop systems for the recovery of the chaff. Nowadays, several solutions for chaff harvesting are available on the market, and others are still at a prototype stage [21].

Conceptually, they are based on two management methods—collection of chaff together with straw and collection of chaff separately from the straw. In the first case, chaff is discharged either on top or inside of the straw swath then baled together with the straw. In the separate collection method, the chaff is delivered to dedicated collection systems, such as trailers towed by a tractor or by the combine itself, or integrated containers in the back of the combine, or non-stop baling systems. These management methods implement different chaff delivery systems, including augers, blowers, and conveyor belts. The combination of management methods and delivery systems determine different mechanical solutions that can be summarized as follows—windrowing systems, turbine systems, dedicated back container systems, one pass harvest and baling systems, and modified chaff spreader systems.

The interest in chaff collection is a recent phenomenon, as a result, there is a limited number of agricultural machine constructors that offer mechanical solutions for the recovery of the chaff.

In general, the solutions provided for the discharge on the swath (windrowing system or turbine system) or inside the swath (modified chaff spreader) have a limited investment cost, and they are easily adaptable to all types of combine harvester without the influence of the harvesting performance (working time).

On the contrary, a separate collection would allow a wider range of possible uses of chaff and straw and possible higher market prices as well. However, chaff recovery systems like turbine systems with trailer and chaff-cart or one pass harvest and baling systems could have negative effects on the maneuverability of the machines, with possible increase in the working time and, therefore, a reduction of the harvesting performance. Additionally, these solutions imply higher purchasing costs [21].

Due to a lack of scientific data about the chaff collection feasibility, performance, and quality of the work carried out by the machine available in the market, during the H2020 AGROinLOG project [22], Research Centre for Engineering and Agro-Food Processing (CREA) carried out straw and wheat chaff harvesting tests in Le Faulx (Pannecè, France), using a combine harvester equipped with the turbine system, named "Turbopaille", developed by the French company Thievin. The wheat residue harvesting tests were carried out in July 2018 and July 2019, which aimed to quantify the amount of residue that can potentially be collected (chaff and straw), the machines performance, fuel consumption of all machines involved in the harvesting chain, as well as the potential yield of seeds, straw, and chaff, and the losses in the two-years experiment.

2. Materials and Methods

2.1. Field Test and Crop Characteristics

Both two-years tests were carried out on the same field in Le Flaux (Pannecè, France) (47°29′16.4″N 1°13′26.1″W) (Figure 1). The sowing of wheat took place in the 43rd week in both years at a density of 225 kg ha^{-1}, a 50% blend of the two cultivars was used—Absalon and Syllon. In both years, the same regime of fertilization and pest control was followed. The harvest in 2018 was performed during the 29th week, while in 2019 it was performed in the 30th week. During the week before the harvest, a homogeneous area of about 6 ha was selected and delimited to perform the tests.

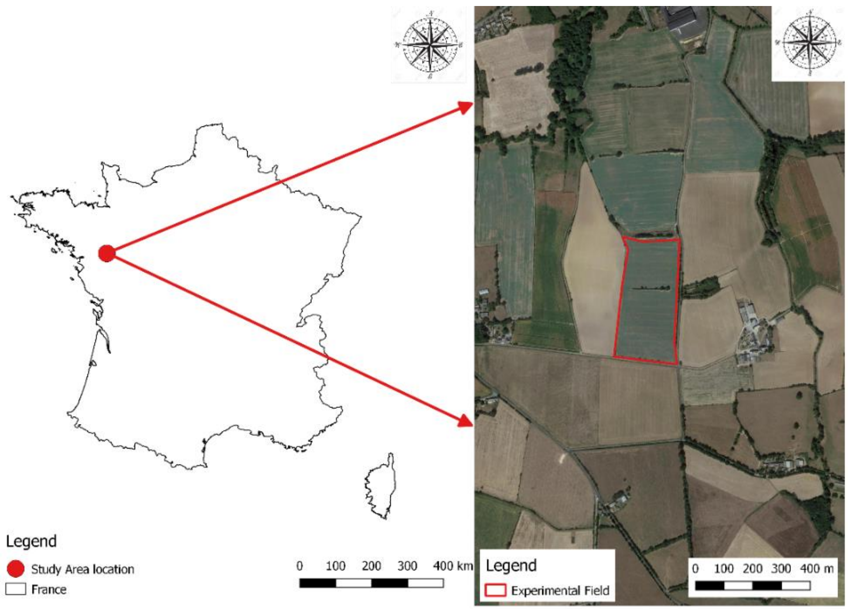
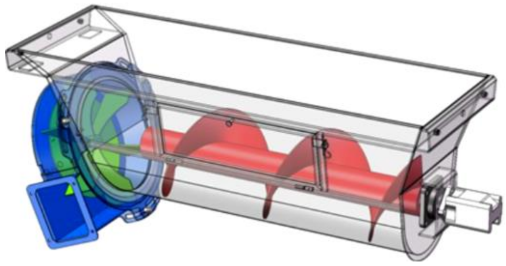


Figure 1. Study area location and field test.

2.2. Thievin System Description

The Thievin system for the chaff recovery, named "Turbopaille" [23], was mounted in the rear part of the combine harvester. It had a dedicated tank provided with an endless screw, which pushed the chaff in the inlet of a turbine. Here, the turbine increased the pressure of the air and the chaff was forced out through a pipe (Figure 2).

(**a**)



(**b**)

Figure 2. (**a**) Thievin system "Turbopaille" for chaff collection and (**b**) schematic representation.

The Thievin system can work in three different arrangements—discharging of the chaff over the straw swath (A Mode); spreading of the chaff by applying a V-shaped spreader (B Mode); chaff discharging by PVP pipes on a trailer towed by a tractor alongside the combine harvester (C Mode) (Figure 3).

(**a**)

(**b**)

Figure 3. *Cont.*

(c)

Figure 3. The Thievin system working arrangements—unloading of the chaff on the straw swath (**a**); chaff spreading mode (**b**); and unloading of the chaff on a trailer (**c**).

In 2018, only the A mode (chaff on the swath) and the B Mode (chaff spreading) were tested, while in 2019 the C Mode (discharge on trailer) was also analyzed. In the two-years experiment, all machines were the same except the combine. However, the setting and the drivers were the same in all machines (Table 1).

Table 1. Equipment used during the tests.

Harvesting Phase	2018	2019
Seed threshing	Combine: New Holland CX840 Thievin system: A and B mode	Combine: New Holland CX8.70 Thievin system: A, B and C mode
Biomass baling	Tractor: Deutz-Fahr Agrotron M620 Baler: Deutz-Fahr Varimaster 690	Tractor: Deutz-Fahr Agrotron M620 Baler: Deutz-Fahr Varimaster 690
Separate chaff collection	Not performed	Tractor: John Deere 8270R Trailer: Thievin Cortal 240

According to the working arrangements, the biomass discharged on the windrow and baled afterward, was made of straw and chaff in the A mode, and only straw in both B and C modes. Therefore, the amount of chaff baled was calculated as difference between the total weight of biomass baled with system A and system B, while the amount of chaff collected separately in C mode was weighted in the local farm scale.

2.3. Experimental Design and Pre-Harvest Sampling

In both years of testing, split plot experimental designs were used. Before harvesting, the experimental field was divided into three blocks in order to have three replicates per treatment (2 treatments in 2018—A and B modes; and 3 treatments in 2019: A, B, and C modes) (Table 2). The width of each experimental unit (plot) was 4 times the combine header width, in order to assess the combine performance in four adjacent passes per plot (3 turning times). Total surface was about 4.2 ha (0.7 ha each plot) in 2018 and about 3.6 ha (0.4 ha on average each plot).

The first pass of the combine in each side of the experimental field was not considered in order to avoid possible edge effects on the crop. One day before the combine harvesting, the whole plants of 10 sample areas of 1 m^2, each randomly chosen, were hand harvested from the ground level. Stems and ears were weighed separately. Successively, all ears and a representative sample of stems were put in sealed bags and shipped to the laboratory of CREA for further measurements, as theoretical yield of grain and chaff, dry weight, and humidity content.

Table 2. Experimental design (2 treatments in 2018: A and B modes; and 3 treatments in 2019: A, B, and C modes).

Year	Block 1				Block 2			Block 3	
	Plot A1 chaff on swath	Plot B1 chaff spreading	Plot C1 chaff on trailer	Plot C2 chaff on trailer	Plot B2 chaff spreading	Plot A2 chaff on swath	Plot B3 chaff spreading	Plot A3 chaff on swath	Plot C3 chaff on trailer
2019	Y	Y	Y	Y	Y	Y	Y	Y	Y
2018	Y	Y	N	N	Y	Y	Y	Y	N

Y: test performed; N: test not performed.

2.4. Harvesting Tests

The harvesting tests concerned the threshing and the baling steps performed in each experimental unit (plot). Machines performance was measured in terms of working times (h ha^{-1}) and fuel consumption (l h^{-1}), grain and residues yield (t ha^{-1}), moisture content (%), and bulk density of biomass (kg m^{-3}). Moreover, after harvesting, the average cutting height (cm) and the losses (t ha^{-1}) were assessed.

2.4.1. Machines Performance

Working time study was performed according to the standards ASAE S496.2 [24]. This allowed to determine the effective field capacity (EFC) (ha h^{-1}), which is the rate at which it performs its primary function and the theoretical field capacity (TFC) (ha h^{-1}), which is the maximum possible field capacity without the accessory times.

The material capacity (MC), i.e. the quantity of grain or wheat residues harvested per time unit (t h^{-1}), was also assessed.

Fuel consumption of all machines involved (combine and tractors) was calculated by refilling the tank at the end of each plot. A graduated cylinder was used for the measurements of the volume of the fuel needed per single operation.

2.4.2. Biomass Yield and Characterization

The total yield of grains, straw, and chaff (collected separately in C Mode) per plot was measured using the farm scale. After the harvesting, three samples of grain and residues were collected from all treatments, for moisture content determination. Chaff bulk density was assessed in-situ, according to the technical standard ISO 17828:2015 [25]. Briefly, a 0.05 m^3 metal basket was filled with chaff, then jolted three times vertically and filled again. The extra chaff was removed by swinging a small scantling over the container, then the basket was weighted. The measurement was repeated 5 times per plot. The net weight of the basket was previously recorded. Per treatment, five bales were randomly chosen and measured in weight and volume, for the determination of the mean bulk density.

2.5. Post-Harvest Measurements

The average cutting height value of the combine header (height of the stubbles) was derived by averaging 100 measurements, randomly taken in a diagonal transect selected on-field. The amount of biomass not harvested was assessed by cutting and weighing the stubbles from 10 sample areas (1 m^2 each) that were randomly chosen. Among them, five samples were collected for moisture content.

In the laboratory, the kernels were first separated in a stationary thresher (Cicoria mod. Plot 2375) from the rest of the ears (rachis, lemma, glumes, and palea). In addition to the residual material previously assessed in laboratory, the turbine technology allowed for collection of other kinds of light-weighted residuals produced by the cleaning mechanisms of the combine, such as short straw, damaged seeds, and weed seeds. On-field samples of the residuals produced by the Thievin system were further investigated in order to estimate the contribution of the light-weighted residuals to the total extra biomass collected. Dry weight and the humidity content of stems, kernels, and chaff were assessed according to the standard EN ISO 18134-2:2017 [26]. Briefly, three samples per plot were weighted for fresh weight and then dried in a ventilated oven at 105 °C ± 2 °C, until constant weight. Afterwards, the dried weight was recorded.

Seed, chaff, and straw losses in each plot were assessed as difference between the theoretical yield of biomass was estimated with the pre-harvest plots and the effective amount harvested.

2.6. Statistical Analysis

A statistical analysis was performed in order to discriminate the differences among the treatments of the same year; while the comparison of the same treatment in the two years was not taken into account.

All data were subjected to the analysis of variance (ANOVA), using the R 3.6.1 software to separate statistically different means ($P \leq 0.05$) [27]. Tukey's HSD post-hoc test was performed to calculate the statistical differences between the means [28].

3. Results and Discussion

3.1. Combine Performance

Apart from the MC (that was affected by different yield in the two years), the performance of all machines involved in the treatments in both years were similar (Table 3). In fact, the combine performance was not influenced by the working arrangements, contrary to the hypothesis speculated by Unger and Glasner (2019) [29]. The performance was not affected in the C mode either, where the combine harvester and tractor with the trailer had to work side-by-side. In fact, no statistical differences were found among the treatments.

Table 3. Combine performance in 2018 and 2019 according to the working arrangements (treatments).

Treatment	Theoretical Field Capacity (ha h^{-1})		Effective Field Capacity (ha h^{-1})		Material Capacity (t FM h^{-1})	
	2018	2019	2018	2019	2018	2019
A mode	2.57 ± 0.13	2.56 ± 0.01	2.24 ± 0.11	1.98 ± 0.02	13.98 ± 0.13	17.27 ± 0.56
B mode	2.71 ± 0.09	2.61 ± 0.06	2.41 ± 0.10	2.04 ± 0.06	14.39 ± 0.13	17.25 ± 1.13
C mode	np	2.69 ± 0.12	np	2.03 ± 0.11	np	17.10 ± 0.77

np: not performed.

Combine harvester fuel consumption, measured only in 2019, was on average 21.63 l h^{-1} (46.7 l ha^{-1}), with no significant differences among treatments.

3.2. Baler Performance

Considering the baling phase, statistically significant differences were found in the EFC (which included accessories times, such as the turning time and unloading time) and the MC between the A and B modes in both years. Baling the swaths with a higher biomass content (A mode: straw and chaff) was significantly slower than baling the swaths with less biomass (B mode: only straw) (Table 4). Contrary to the expectations, no differences were found when the chaff was collected separately on the trailer (C mode). This may have been caused by an efficiency of the turbine system that is used for loose chaff recovery, as further explained in paragraph 3.3.1. In 2019, the TFC, EFC, and MC were lower than that in 2018, due to a higher biomass yield.

Table 4. Baler performance in 2018 and 2019 according to the treatments (common letters within columns denote the absence of significant difference ($p < 0.05$)).

Treatment	Theoretical Field Capacity (ha h^{-1})		Effective Field Capacity (ha h^{-1})		Material Capacity (t FM h^{-1})	
	2018	2019	2018	2019	2018	2019
A mode	5.23 ± 0.65	4.64 ± 0.31	3.46 ± 0.28 b	3.09 ± 0.13 b	20.79 ± 0.7 a	20.20 ± 2.0 a
B mode	5.99 ± 0.16	4.82 ± 0.09	4.05 ± 0.16 a	3.45 ± 0.10 a	18.73 ± 0.7 b	15.09 ± 0.7 b
C mode	np	4.93 ± 0.13	np	3.33 ± 0.09 ab	np	19.16 ± 2.5 ab

np: not performed

In 2018, the fuel consumption during baling was not affected by the treatments. On the contrary, the tests in 2019 showed a higher fuel consumption during the baling in treatment A (Table 5). It was about double when analyzed in relation to the surface (l ha^{-1}) and the time (l h^{-1}). Considering the biomass baled (l t^{-1}), such results were found only in comparison to treatment C, while no statistical differences were observed in treatment B (Table 5).

Table 5. Baler fuel consumption in 2018 and 2019 according to treatments (common letters within columns denote the absence of significant differences ($p < 0.05$)).

Treatment	Fuel Consumption (l ha^{-1})		Fuel Consumption (l h^{-1})		Fuel Consumption (l t^{-1})	
	2018	2019	2018	2019	2018	2019
A mode	4.65 ± 0.91	6.21 ± 1.5 a	16.09 ± 3.36	19.13 ± 4.33 a	0.77 ± 0.15	0.94 ± 0.12 a
B mode	4.66 ± 0.11	2.81 ± 0.64 b	19.02 ± 1.44	9.68 ± 3.87 b	1.01 ± 0.13	0.64 ± 0.23 ab
C mode	np	2.43 ± 0.94 b	np	8.04 ± 2.90 b	np	0.41 ± 0.09 b

np: test not performed

3.3. Biomass Assessment

3.3.1. Yield

Productivity in 2019 was higher than in 2018. The total biomass estimated in pre-harvest plots was about 1.9 t ha^{-1} higher in 2019. The wheat ears were 56% of the total biomass (44% straw) in both years, with the same ratio in the ears of the seeds (about 78%) and the chaff (22%), as showed by the laboratory threshing (Table 6).

Table 6. Theoretical biomass in the wheat field assessed in 2018 and 2019.

Year	Theoretical Biomass (FM)	
	2018	2019
Total biomass (t ha^{-1})	16.76 ± 1.44	18.69 ± 1.77
Straw (t ha^{-1})	7.39 ± 0.73	8.33 ± 0.75
Wheat ears (t ha^{-1})	9.37 ± 0.77	10.36 ± 1.34
Seeds (t ha^{-1})	7.32 ± 0.60	8.18 ± 1.06
Chaff (t ha^{-1})	2.04 ± 0.17	2.18 ± 0.28

Although the agricultural protocol (see paragraph 2.1) was the same in both years, differences in the biomass yield were recorded. Consistent with the theoretical yield, in 2019, the seeds harvested were on average 1.8 t FM ha^{-1} higher than that in 2018. In both years, there were no statistically significant differences in seed yield, among treatments (Table 7).

Table 7. Seed harvested according to the treatments in 2018 and 2019.

Treatment	Seed Harvested (t ha^{-1} FM)	
	2018	**2019**
A mode	6.26 ± 0.19	8.15 ± 0.32
B mode	6.04 ± 0.06	7.85 ± 0.40
C mode	np	7.87 ± 0.10
Mean	6.17 ± 0.21	7.96 ± 0.30

np: not performed

With regards to the biomass collected, there were statistically significant differences between treatment A (bales made of straw and chaff) and B (only straw), confirming the contribution of chaff as additional biomass, raising the total weight of biomass harvested. In fact, the difference between the biomass baled in the two treatments allowed to assess the chaff baled, respectively, 1.39 t FM ha^{-1} (30% extra biomass) in 2018 and 2.19 t FM ha^{-1} (50% extra biomass) in 2019 (Figure 4). Similar tests performed by the Institut National de la Recherche Agronomique (INRA) as part of the local project 'Systèmes de Cultures Innovants' and the Federation Nationale des Cooperatives d'Achat et d' Utilisation de Materiel Agricole (CUMA), in 2011 and 2012, with turbine systems, provided lower means, respectively 1.5 t FM ha^{-1} and 1.15 t FM ha^{-1} [30,31].

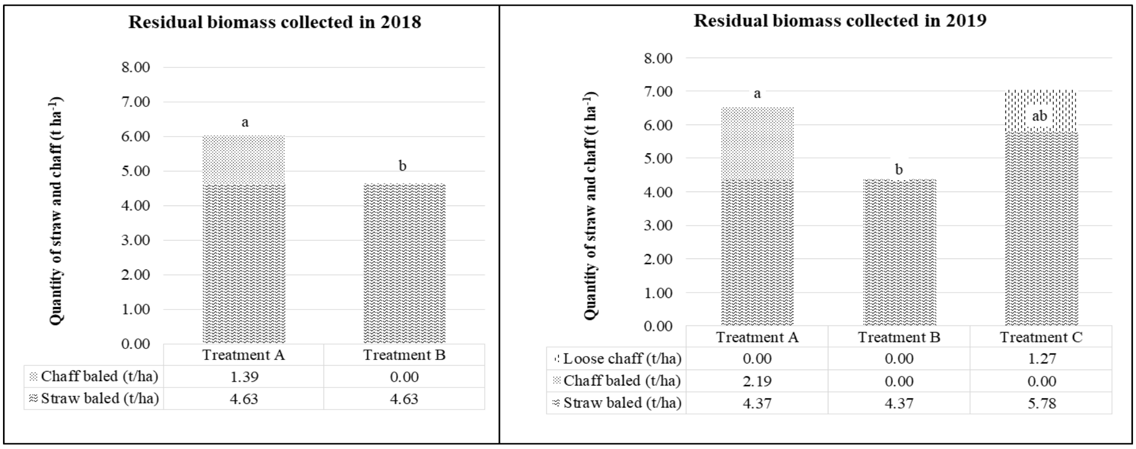


Figure 4. Biomass collected (in FM) per treatments during the tests carried out in 2018 and 2019. Treatment A—straw and chaff baling; treatment B—only straw baling (chaff spreading on the ground); and treatment C—straw baling and separate chaff collection on trailer. By including the chaff in the bales, 1.39 t FM ha-1 and 2.19 t FM ha-1 could be collected in 2018 and 2019, respectively. On the other hand, only 1.27 t ha-1 of loose chaff could be collected in the 2019 test. Different letters in the graph denote the presence of significant differences ($p < 0.05$) in the quantity of straw and chaff collected among treatments.

Trials performed by Rönnbäck and Lundin with a different technology [9] showed a 14% extra biomass by admixing chaff into the straw swath, representing about half of the available chaff that was harvested.

Although the biomass baled in A was 0.78 t FM ha^{-1} higher than the biomass baled in C, contrary to what was expected, there were no significant differences in the baled biomass between treatment A and C (chaff on trailer tested only in 2019).

In treatment A, the effective additional biomass collected by using the Thievin system totally met the theoretical value of the chaff estimated from the pre-harvest tests. On the other hand, the chaff collected in the trailer was 0.92 t ha^{-1} (42.2%) lower than the theoretical amount of chaff. In this case, the Thievin was required first to collect the chaff into the dedicated tank and then to lift it for discharge into the trailer. Therefore, in order to accomplish the additional second task, the turbine system demands more energy due to the need to push the collected biomass up onto the trailer. The intake rate of the chaff in the dedicated tank of the Thievin system (Figure 2) was probably higher than its capacity to discharge it into the trailer, thus, some chaff remained mixed with straw and then baled. In order to reduce these drawbacks in the case of separate collections of chaff, the following considerations could be taken into account—increase the energy provided to the turbine, increase the diameter of the PVC pipe, and eventually, decrease the biomass intake rate of the combine by either reducing the speed of the combine or using a narrower header. In fact, the last strategy is also reported by the French Company Thiérart that provides a similar Turbine technology for chaff collection. Specifically, Thiérart highlights that its device is suitable for combine headers measuring less than 5.5 m wide [32].

Nevertheless, 1.27 t FM ha^{-1} of chaff collected separately with the C mode is close to the mean value of 1.3 t FM ha^{-1} and 1.5 t FM ha^{-1} reported, respectively, by CUMA and INRA, using a back container system [30,31].

3.3.2. Bulk Density and Humidity

The average bulk density of the round bales (1.8 m in diameter and 1.2 m width) was, respectively, 111 kg FM m^{-3} and 131 kg FM m^{-3} for the A (straw and chaff) and B modes (only straw) in 2018, while in 2019 they were, respectively, 124 kg FM m^{-3}, 121 kg FM m^{-3}, and 131 kg FM m^{-3} for the A, B, and C modes, with no statistical difference among treatments. The average bulk density of the chaff was 62.08 kg FM m^{-3} (measured only in 2019, treatment C), which was in line with the 56 kg FM m^{-3} reported by McCartney et al. (2006) [8]. The moisture content of the different fractions is reported in Table 8.

Table 8. Moisture content in bales and in different fractions of the wheat.

	Moisture Content (%)	
	2018	**2019**
Stems	10.5 ± 0.6	11.9 ± 0.8
Stubbles	np	11.1 ± 1.3
Ears	10.0 ± 0.1	10.8 ± 0.5
Chaff	9.3 ± 0.2	9.2 ± 0.9
Seeds	10.3 ± 0.2	9.1 ± 0.1
Bales	9.78 ± 0.4	11.0 ± 0.7

np: not performed

3.3.3. Biomass Losses

Considering the cutting height of 15.7 ± 2 cm (2018) and 12.2 ± 1.5 cm (2019), the stubbles left on the ground accounted for 1.98 ± 0.15 t FM ha^{-1} and 1.71 ± 0.25 t FM ha^{-1}, respectively. The biomass losses are reported in Table 9.

Table 9. Biomass losses as fresh matter (seed, chaff, and straw) according to the different treatment modes, in 2018 and 2019.

	Seed Losses (t FM ha^{-1})		**Chaff Losses (t FM ha^{-1})**		**Straw Losses (t FM ha^{-1})**	
Treatment	2018	2019	2018	2019	2018	2019
A mode	1.06 ± 0.24	0.04 ± 0.32	0.65 ± 0.59	0.00 ± 0.66	0.78 ± 0.36	2.26 ± 0.22
B mode	1.28 ± 0.06	0.33 ± 0.40	2.04 ± 0.0	2.18 ± 0.0	0.78 ± 0.36	2.25 ± 0.22
C mode	np	0.32 ± 0.10	np	0.90 ± 0.08	np	0.84 ± 0.93

np: not performed

As expected, biomass losses were higher in the case of chaff spreading (treatment "B"), where only 42% of the theoretical total residues (straw and chaff) were baled in 2019 (49% in 2018). In the case of the discharge of the chaff over the swath (treatment "A"), the total losses accounted for only 38% in 2019 (36% in 2018).

By collecting the chaff on the trailer separately from the straw (treatment "C"), the total loss of the residual biomass was 33%. In this case, only 59% of the available theoretical chaff was collected (41% losses). The accurate analysis of the chaff samples revealed that 15.5 ± 0.5% was made of short straw and no weed seeds were found. This was due to the conventional cropping system adopted (chemicals are allowed) that did not permit the assessment of the weed seeds removal capacity of the Thievin technology.

According to findings of Glasner et al. (2019) [20], the percentage of weed seeds that can be removed by bailing could change over time. In fact, once the chaff is discharged on the swath, after one day, only 45% of weed seeds remains on top of it, while 35% is found within the swath and the remaining 20% is already lost in the ground. Hence, if the removal of the weed seeds is the main purpose of turbine technology application, it is very important to consider both the timing and the harvesting chain.

Weed seeds removal is only an additional benefit provided by chaff collection, although it is a valid strategy for weed control. Actually, the turbine technology is meant for the collection of lightweight biomass residuals but the main purpose of using it might change, according to the farmer and the policies used. Nowadays, in Europe, weed seed removal is not the main purpose of chaff collection. More efforts are put in fostering the utilization of such a considerable quantity of residual biomass (50 Mt y^{-1}) that could be used as raw material for industrial or energy purposes.

The collection of chaff separate from the straw (C Mode) implies higher costs due to the tractor and the trailer involvement that can only be compensated, either in the case of organic farming (removing the weed seeds) or in the presence of a dedicated market for chaff (e.g., litter for poultry farming), where the market price of chaff is sufficiently higher than straw. On the other hand, the collection of chaff as a loose product might gain interest in the biogas sector. Such a supply chain is still not completely developed, but the high methanogenic potential of the chaff, which ranges from 200 to 260 Nm^3 t^{-1} [33], paves the way for further developments. Due to the similar methanogenic value of maize-silage, it can be speculated that partial subrogation is possible for cost reduction and lower environmental impact.

On the contrary, the biomass collected in Treatment A (straw and chaff) can have the same market value as the straw for energy. In fact, the net calorific value and the ash melting behavior of admixed straw with chaff do not change significantly, although a 1% increase in ash content is reported [9]. Moreover, Wiwart et al. (2017) [34] reports that spelt chaff has a low heating value (LHV) of 15.1–16.8 MJ kg^{-1} (e.g., wood pellets 16.3 MJ kg^{-1}). Similar LHV for chaff is reported in Pari et al. (2018) [35], but further investigations are needed, specifically in combustion behaviors, in order to reduce the ash content of 9.75 ± 0.14 (w/w), by mixing the chaff with other raw materials.

In addition to combustion, biorefinery industries have a growing interest in lignocellulosic biomass residuals, for the production of 2^{nd} generation bioethanol. Wheat straw and chaff could represent a good source, since they are abundantly produced in Europe and all over the world. Furthermore, both straw and chaff are collected from food crops, like wheat or even from other cereal crops, therefore, no competition for land use occurs.

4. Conclusions

The two-years test aimed to assess if a significant higher quantity of extra-biomass can be retrieved from the field by including the chaff. Chaff is a considerable portion of the by-products of cereal cropping that is usually left on the ground. The system tested in France permitted the collection of chaff in two different ways—either by direct discharge on the swath or on a trailer towed by a tractor alongside the combine harvester.

The potential total biomass assessment in the two-years test resulted in slightly different findings. In 2019, the biomass was found to be higher than that in 2018, by 1.93 t FM ha^{-1}, while no differences among the ratio between stems, spikes, seed, and chaff were found.

Interestingly, in both years, the Thievin did not significantly affect the combine performance. On average, the EFC of A and B modes was 2.12 ha h^{-1}, which was similar to the C mode (2.03 ha h^{-1}). Even the combine fuel consumption (in 2019) was not affected by the treatments; the mean value recorder was 46.7 l ha^{-1}.

Differences among the treatments were found during the phase of baling, particularly in 2019. The EFC was found to be 11.65% higher in treatment B, with respect to treatment A and this was consistent with the total biomass recorded.

In 2019, the EFC in treatment C was not statistically different from the others; while fuel consumption was similar to B but lower than that in A by 57.97%.

The chaff discharged on the swath and baled with straw was 1.39 t FM ha^{-1} in 2018 and 2.19 t FM ha^{-1} in 2019, which accounted for 30% and 50%, respectively, as additional biomass. Regarding the possibility to collect the chaff separately, additional treatment in 2019 was introduced, which yielded 1.27 t FM ha^{-1} more biomass, though, it was lower than the amount of chaff collected in the A mode.

In conclusion, our findings supported the hypothesis that the turbine technology was a valid solution for increasing the total biomass collected in cereal cropping. However, further economic and technical investigations in different conditions and on different cereal species, as well as comparisons with similar technologies available on the market, are strongly encouraged.

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