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Equipment Performance, Costs and Constraints of Packaging and Transporting Rice Straw for Alternative Uses to Burning in the “Parc Natural l’Albufera de València” (Spain)

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Abstract: Rice straw is a residue that causes significant environmental problems, as burning it causes CO₂ and ash emissions, while buried waste can cause issues associated with eutrophication. The extraction of straw from fields for alternative uses may contribute to solving these problems, but research into its economic viability is necessary. The straw can be used for crop mulching, bio-fuel, bedding for livestock, and so on. In this study, we analyse the work carried out by straw harvesting machines (rakes, balers, bundlers, and loaders) and calculate the costs of packing, road-siding, and transportation of the straw from the rice fields to stockage points in the producer area, as well as to locations outside of the rice production area, in order to assess the viability. The costs of all elemental operations were calculated. The costs of all the operations included between raking and unloading in the producer area stocking point ranged between 28.1 and 51 EUR t⁻¹. These costs were compared with the price of rain-fed cereal straw (wheat and barley), which is the most abundant, noting that the years in which rain-fed cereal straw reached high prices, rice straw could serve as a competitive product; however, in years when the former is cheap, it would be necessary to subsidise the harvesting of rice straw.

Keywords: straw; rice; baler; transport; economy; mechanisation

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1. Introduction

The Parque Natural de L’Albufera de València (Spain) is one of the most important wetlands in Southern Europe. It is characterised by the lake and rice fields that surround it, the flooded lands of which serve as a refuge for a multitude of birds. Its management and preservation depend on various authorities: at the European level, it is part of the Natura 2000 network of European protected areas, as well as having been granted a number of LIFE projects. The legal jurisdiction affecting the conservation of l’Albufera de València is distributed among various authorities, meaning that it is sometimes difficult to know which one of them is in charge of each of the numerous aspects involved in the conservation of such an area. This fact provides an added difficulty when developing certain kinds of proposals [1].

Rice, as a crop, has a long history in the area, and is the most important in the Natural Park, with a production of 116,925 t and an area of 15,087 ha [2]. The traditional way of eliminating straw after harvesting was burning it, as this method has many advantages. It is a cheap system and has other positive effects, such as eliminating weed seeds and reducing the presence of other pathogens. However, the somewhat uncontrolled burning on days with prevailing winds meant that smoke was carried towards neighbouring cities, leading many citizens to complain about the presence of smoke and ash in the air.

This confrontation, combined with the current heightened awareness of climate change, has led authorities to prohibit or limit this practice in Spain [3,4], as well as in other occidental countries such as the USA [5].

There are no easy alternatives to burning. Burying straw leads to problems with water eutrophication, the possible spread of some herbicide-resistant weeds, and pests and diseases becoming more difficult to control [3–6].

An alternative to burning or burying is the extraction of the straw from the fields, in order to put it to other uses, such as energy and biofuels, pulp and paper [5], construction materials [7], compost [8], livestock [9], mulch to prevent soil erosion [10], to reduce water losses [11], crop yields [11], weeds [12], and so on [13]. However, all these alternatives have a significant common cost, which is the packaging and subsequent transportation of the straw to the points of use, including biofuel industries, buildings, compost plants, animal farms, or agricultural fields for mulching [9–13].

In this study, a quantification of the magnitude of these costs was carried out, as well as monitoring the packing and loading of machines, analysing the possible routes based on the orography of the production area, and estimating the transport costs from the production site to destinations located within a 200 km radius [14,15].

The following phases are involved in the analysis of straw management:

- (a) Regulation of the combine to produce long straw and windrows;
- (b) Straw raking to improve the work of the balers;
- (c) Baling;
- (d) Road-siding;
- (e) Loading and transportation to storage areas in the straw-producing area;
- (f) Stockpiling in the production area;
- (g) Loading in the production area and transportation to the destination;
- (h) Stockpiling at the destination; and
- (i) Final use of the straw.

Additionally, there are other, no less important factors which must be considered, such as the control of irrigation water, avoiding any crop burning that may spread to the areas where straw is being baled and, most importantly, how the collection and transportation is organised. The time period available is very short, as the fields must be flooded for environmental reasons and, moreover, keeping the fields dry implies energy costs due to the use of bilge pumps in the lower areas.

The handling of the combine harvester for straw baling is similar to that which would be employed for burning; that is, the cut should not be too low, in order to facilitate the subsequent drying of the straw. The machine does not chop the straw or spread it, thus facilitating its subsequent collection [5].

The straw remains can be collected directly with the balers but, if they are laid out with a windrowing machine, the subsequent work of the balers is made easier [5].

The baling can be done with small prismatic bales, which must later be grouped to facilitate mechanical handling. It can also be carried out with cylindrical bales or with large prismatic bales [16].

Road-siding is usually carried out by tractors equipped with fork loaders [5].

Transportation from the plot to the storage area at the origin is usually carried out by small trucks or tractors and trailers, due to the limited dimensions of the roads in the production area [5].

Unloading and stacking in the stockpile at the production area is usually carried out by dumping and/or manipulation with loaders coupled to a tractor, or with telehandlers. The stacking height is not usually excessive, as a long storage period is not foreseen. In addition, the straw is usually very humid, which can lead to problems with spontaneous combustion due to the high temperatures which can be reached inside the piles, if the stowage densities are too high [15].

The transportation of the straw from the production areas to the final destination is usually carried out with trucks. Tractors with loaders can be used, provided that the trucks are not excessively large or, whenever possible, they can be loaded from the sides. However, if they are large and have closed boxes, it is necessary to use telescopic handlers.

This study takes the measurements of the following aspects into consideration: the size of the straw and of the uncut remains left by the rice harvesters, the moisture of the straw, the working capacities of the rakes, prismatic balers of various sizes, the use of straw bale wrappers, the transportation of the straw, and its subsequent loading from the bed to the loading point at the foot of the plot. Transportation to the main stockpile in the production area and the working capacities of telescopic loaders in loading trucks for long-distance transport were also studied.

The transport of the straw to the final destination has a high influence on the total cost [17,18]; therefore, the main transport routes within the production area were evaluated and the costs of transportation by road from the production storage areas to possible destinations were estimated, taking the transport equipment used, the distance covered, and the bale density into consideration.

With all the above information, estimates were made for the cost of handling rice straw in L'Albufera de València, with a view to considering its economic viability for alternative uses, thus leading to an improvement in the environmental conditions of a place with such exceptional ecological value.

2. Materials and Methods

2.1. Straw Production Area and Transport Distances between the Fields and the Storage Point

The rice-producing area was divided into 13 zones. The plots are all accessed by paths which are parallel to the ditches, making transverse movements difficult. In addition, seven possible storage points were identified within the production area. These areas of harvesting and storage points were used as a reference for calculating the distances to be covered during transportation in the production area. The delimitation of these zones was carried out by direct observation of the transport routes and intermediate obstacles in Google Earth (Figure 1).



Figure 1. Image of rice crop area in the P.N. Albufera de València and the actuation zones into which it was divided (Image source: Google Earth. Modified by J.M. Giner).

Furthermore, the plot size was analysed using land register data. [19].

The centre of gravity (CG) of each zone was calculated and the shortest distance from that point to the closest road was measured (D_{CG}). The distance between the last point and the storage point was also calculated with Google Earth (D_{pa}). The full distance (D_p) between each production area and each storage point was calculated as the sum of the two previous values:

$$D = D_{CG} + D_p. \quad (1)$$

2.2. Straw Characterisation

Being the most abundant in the area, the biomass of the ‘J. Sendra’ rice variety was used.

To typify stubble, five 1×1 m squares were selected randomly in four fields, and the heights were measured. The stubble was cut at ground level and the samples were transferred to the laboratory, where they were weighed and dried.

To measure the amount of straw deposited by the combine harvester, four strips equivalent to the machine’s cutting width (6 m) and 1 m in length were collected and weighed.

In addition, the straw baled in nine plots was estimated by counting the number of bales formed and, consequently, calculating the average weight of each bale.

Small bales (<25 kg) were weighed with an Alpha Tools scale with a capacity of 50 kg and a resolution of 10 g. The large prismatic bales were weighed with a PCE Ibérica dynamometer (<http://www.pce-instrument.com>, accessed on 10 October 2019) model PCE-PFG 10 K of 10 kN capacity and with a resolution of 0.5 N.

To measure the straw moisture, samples were dried in an oven at 60 °C for 48 h. The moisture, on a dry matter basis, was calculated as in Equation (2):

$$M_d = 100 (W - DM) DM^{-1}, \quad (2)$$

where M_d is the percentage of moisture, W is the weight of a wet sample, and DM is the weight of the dry sample.

2.3. Equipment

The field capacity of the following equipment was measured using video records, GPS records, and posterior time analysis. The main specifications of the equipment analysed are detailed in Table 1.

Table 1. Equipment used for packaging and transporting in the production area.

Code	Description	Tractor	Implement	Activity
E1	Tractor 81 kW + Rake	New Holland T6 120	MUR, 6 m withd	Raking
E2	Tractor 70 kW + small baler	Landini REX 95 F	Welger AP 400	Baling small bales
E3	Tractor 75 kW + bale bundler	New Holland TN 95FA	Arcusin Multipack A14	Bundling small bales
E4	Tractor 125 kW + large baler	New Holland G170	NJ BB 940	Baling large bales
E5	Tractor 75 kW + Front loader	New Holland TN 95FA	Tenias S-100-2697	Road-siding
E6	Tractor 110 kW + front loader	Fendt 415 Vario	Fendt front loader	Small truck loading
E7	Small truck 28 big bales			Transport into the rice area

E8	Telehandler	JCB 535	Large truck loading
E9	Articulated large truck 64 big bales		Long distance transport

2.3.1. Raking

The straw was windrowed with a MUR rake. It has two vertical windlasses with a working width of 6 m. The rake was hitched to a New Holland T6 120, 88 kW tractor.

2.3.2. Baling and Bundling

The following balers were analysed:

- Small rectangular baler: Welger AP 400; and
- Big rectangular baler: NJ BB 940.

The small rectangular bales were packaged into groups of 12 bales using an Arcusin Multipack A14 bundler.

2.3.3. Road-Siding

The work of a New Holland TN 95FA tractor with a Tenias S-100-2697 front loader was measured when transporting the bales from the field to the road near the field.

2.3.4. Transport Equipment in the Production Zone

The most commonly used vehicles when transporting bales from the field to the storage area were small lorries. The field capacity of a truck able to transport seven rows of four large bales or bundles (28 in total) was measured using a GPS and video records.

2.3.5. Long-Distance Transport Equipment

Articulated trucks were used for long-distance transportation. The field capacity of the JCB 535 telehandler, used to load an articulated dump truck with a capacity of 68 large bales, was measured.

2.4. Equipment Costs

The estimation of the equipment cost was calculated according to the ASABE method [20,21].

2.5. Long-Distance Transportation Costs

The costs of transportation from the production area to the final destination were estimated using the data published by the 'Ministerio de Fomento' (Ministry of Development) [22].

2.6. Total Costs

To calculate the costs of straw handling and transport, the operations were divided into three steps (Figure 2). Step I included raking, baling, and road-siding. Step II included loading a small lorry or tractor trailer and transportation within the production area to a storage point and then being unloaded. Step III included loading to a large lorry for transportation to the final destination.

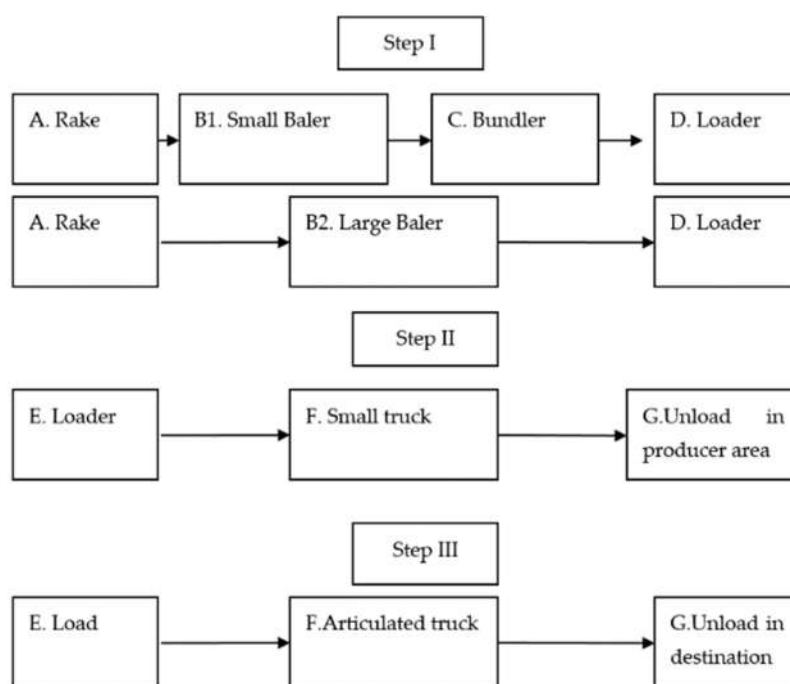


Figure 2. Diagram of operations.

The costs (EUR ha⁻¹) were calculated according to the following equation (3):

$$C = C1 + C2 + C3, \quad (3)$$

where C is the total cost and C1, C2, and C3 are the costs of steps I, II, and III, respectively.

3. Results

3.1. Analysis of the Straw Production Area

According to the land registry data [23], in the P.N. there were 9354 registered plots, with a total area of 13,358 ha of rice crops, with an average surface of 1.43 ha/plot and a median of 0.94 ha plot⁻¹. Moreover, there are sometimes small channels and ridges between plots that make manoeuvring equipment difficult.

The vast majority of roads that the vehicles have to travel on are narrow, with single-lane traffic, making it necessary to use sidings when two vehicles need to cross on the same road. Fortunately, traffic is light, and these situations occur infrequently.

In Table 2, the surface, distances, and transport time from the harvesting zones to the storage points in the production zones are summarised. The average distance between the centre of gravity of the production area and the closest road (D_{CG}) was 1.19 km (sd ± 0.63 km), the average distance between zones to the storage point (D_{pa}) was 3.27 km (sd ± 1.42), and the average total distance from the road-siding to the storage point was 4.46 km (sd ± 1.36).

Table 2. Surfaces and transport distances into/within the straw production zone.

Harvesting Zone	Storage Point	Production Surface, ha	D _{CG} , km	D _{pa} , km	D, km
1	A1	370	1.53	4.60	6.13
2	A1	187	0.41	2.60	3.01
3	A1	720	1.79	3.10	4.89
4	A2	152	1.07	2.30	3.37

5	A2	897	1.87	2.10	3.97
6	A3	640	1.09	1.40	2.49
7	A5	1304	1.08	2.60	3.68
8	A5	2682	1.05	5.85	6.90
9	A4	666	2.65	1.90	4.55
10	A6	1476	0.73	5.90	6.63
11	A6	954	0.79	3.25	4.04
12	A6	1053	0.44	3.50	3.94
13	A7	1188	0.95	3.45	4.40
Average			1.19	3.27	4.46
Standard deviation			0.63	1.42	1.36

3.2. Straw and Stubble Characterisation

The straw and stubble were characterised (Table 3). The mean stubble height was 21 cm (sd \pm 0.32), the mean wet weight was 373 g m⁻² (sd \pm 57), and the moisture on a dry basis was 89% (sd \pm 49). Straw had a length of 30 cm (sd \pm 4), a weight of 737 g m⁻² (sd \pm 130), and moisture on a dry basis of 78% (sd \pm 37).

As can be seen, the straw has to be packed while it still has a high degree of moisture, a factor which can cause problems in its storage.

Table 3. Straw and stubble characteristics.

Place	Stubble				Straw			
	Height cm	Wet Mass g m ⁻²	Moisture on Dry Basis, %	Length, cm	Wet Mass, g m ⁻²	Mois- ture Dry Basis, %	kg ha ⁻¹ Wet	kg ha ⁻¹ , Dry
Catarroja	21.5	451	95	25	732	91	7320	3832
Albal	20.9	375	60	35	481	55	4810	3103
Romaní 1	21.6	320	45	30	459	43	4590	3210
Romaní II	21.2	348	155	28	475	125	4750	2111
Average	21.3	373	89	30	537	78	5370	3017
Standard deviation	0.32	57	49	4	130	37	1300	949

3.3. Straw Production

In the fields where the straw collected was measured, the results were highly variable, ranging from 1652 to 4456 kg ha⁻¹ of wet straw. These values were lower than the total amount of straw produced by the fields, which have been estimated at around 6 t ha⁻¹ of wet straw [3]. These differences were fundamentally due to the collection system. The balers only harvest a fraction of the deposited straw, as the farmers want a clean product without any mud. In fact, some samples of the straw that remained on the ground after packing were collected, and values to the order of 200 g m⁻² (2 t ha⁻¹) of wet straw were found. No comprehensive measurements were made.

For subsequent machine cost calculations, an average production of 4.4 t ha⁻¹ of harvested wet straw was considered.

3.4. Equipment Field Capacity

The field capacities were measured in relation to the machines used, as well as in comparison to the general capacities of similar equipment working with other winter cereals and in other countries. The terminology used was that recommended by ASABE [20].

3.4.1. Rake

The travel speed of the rake was 9.0 km h^{-1} and the working width was 6 m, giving a theoretical field capacity of 5.4 ha h^{-1} . However, as the plot dimensions are small, the field efficiency was low (estimated at 0.6), giving an effective working capacity of 3.2 ha h^{-1} .

3.4.2. Small Rectangular Baler

The baler produced 10.7 kg bales ($\text{sd} \pm 0.7$) with dimensions $40 \times 30 \times 90 \text{ cm}$. The stubble was measured randomly to be 20 cm long. The straw was in ties. The amount of wet straw harvested was 1652 kg ha^{-1} ; these values indicate low-density bales (99 kg m^{-3}), as well as a low amount of straw harvested.

The machine advanced at 2.3 km h^{-1} and the windrows were distanced at 6 m; therefore, the theoretical field capacity was 1.4 ha h^{-1} ; however, frequent holdups due to problems with the tie rope led to an effective field capacity of 0.6 ha h^{-1} . Therefore, the field efficiency was as low as 42%.

The effective field capacity was similar to that reported by authors such as Márquez [23], but the field efficiency was much lower than that reported by other authors [24,25].

3.4.3. Small Bale Bundler

The small bales were grouped and packaged in the field with a bale bundler. The machine produced bundles of 12 bales, measuring $180 \times 100 \times 70 \text{ cm}$. The average speed was 3.3 km h^{-1} , the distance between bale lines was 6 m, and a field efficiency of 76% was measured; therefore, the effective field capacity was 1.5 ha h^{-1} .

3.4.4. Large Rectangular Baler

Speeds of 3.1 and 6.0 km h^{-1} were measured in 2019 and 2020, respectively. Straw lines were spaced at 7 m apart; therefore, considering an average speed of 4.5 km h^{-1} , the theoretical working capacity was 3.15 ha h^{-1} . Considering a field efficiency of 75%, the effective field capacity was 2.4 ha h^{-1} . The bales were $220 \times 90 \times 80 \text{ cm}$, with a volume of 1.58 m^3 .

3.5. Road-Siding

The average distance for road-siding was 85 m ($\text{sd} \pm 21$). In each trip, the loaders carried two large bales or bundles, and the duration of a full cycle was 3.0 min ($\text{sd} \pm 0.3$); therefore, the theoretical field capacity was 40 bale h^{-1} ($\text{sd} \pm 4$). If a field efficiency of 75% is assumed, the effective field capacity was 30 bale h^{-1} . At a weight of 300 kg bale^{-1} , this means 9000 kg h^{-1} , therefore, at 4.4 t ha^{-1} , the effective field efficiency will be 2.05 ha h^{-1} . Calculations were carried out with large bales.

3.6. Loading and Transporting Equipment in the Production Zone

The average transport speed observed for several rigid trucks and tractors with trailers in the production area, transporting rice between the fields and the factories, was 31 km h^{-1} ($\text{sd} \pm 4.3 \text{ km h}^{-1}$). The straw transport speed can be considered similar to that of these same vehicles transporting grain on the same roads.

3.7. Equipment Hourly Costs

In order to calculate the costs of each operation, the hourly costs of each machine were calculated beforehand, using the ASABE methodology [19]. The results are summarised in Table 4.

Table 4. Hourly costs (EUR h⁻¹) of the used equipment.

Code	Description	EUR h ⁻¹
E1	Raking	39.2
E2	Small bale baling	43.9
E3	Bundling	79.0
E4	Large baler	116.6
E5	Road-siding	33.1
E6	Small truck loading	35.1
E7	Small truck, 7 × 4 big bales	45.0
E8	Telehandler	40.1
E9	Articulated truck, 16 × 4 big bales	EUR km ⁻¹

3.8. Total Costs

3.8.1. Step I Costs

This step involved all the operations carried out, from raking to stacking at the road-side, including:

Raking (A);

Baling (B), field capacities of small (B1) and large (B2) rectangular balers;

Bundling small bales (C);

Road-siding with tractor equipped with front loader (D).

The registered effective field capacities are summarised in Table 5.

Table 5. Effective field capacity of each operation.

Task	Effective Field Capacity, ha h ⁻¹	Equipment Hourly Costs, EUR h ⁻¹	Equipment Costs, EUR ha ⁻¹	Cords, EUR ha ⁻¹	Total, EUR ha ⁻¹
A. Raking	3.2	39.2	12.3	0	12.3
B1. Packing small bales	0.6	43.9	73.2	23.7	96.9
B2. Packing large bales	2.4	116.6	48.6	11.1	59.7
C. Grouping small bales	1.5	79.0	52.7	11.1	63.8
D. Road-siding	2.1	33.1	16.1	0	16.1

The cost (EUR ha⁻¹) of this step is

$$C1 = C_A + C_{B1} + C_C + C_D. \quad (4)$$

Baling (B) was done with two types of machines. The costs for each type (B1, small baler, and B2, large baler), including the costs of the cords, are given in Table 6.

Managing small bales is considerably more expensive than managing large bales, due to the lower field capacity and the additional cost of making blocks of bales to facilitate mechanical managing.

Table 6. Step I costs (EUR ha⁻¹ and EUR t⁻¹).

Operations	A (EUR ha ⁻¹)	B _i (EUR ha ⁻¹)	C (EUR ha ⁻¹)	D (EUR ha ⁻¹)	C1 (EUR ha ⁻¹)	C1 (EUR t ⁻¹) *
A + B ₁ + C + D	12.3	96.9	63.8	16.1	189.1	43
A + B ₂ + D	12.3	59.7	0	16.1	88.1	20

* Assuming 4.4 t ha⁻¹.

3.8.2. Step II Costs

This step includes: (E) small truck loading, (F) transportation to storage in the production area and return, and (G) unloading.

Loading (E) was carried out with stacks four bales high. The average time to load one stack was 1.8 min (1.10–2.50 min stack⁻¹) but, as there were interruptions, the effective loading time can be estimated as 50% more (2.7 min stack⁻¹). Assuming the use of a two-axle truck or a trailer with a capacity of seven rows, the loading time would be 0.32 h.

If unloading (G) is done with a loader, it would take a similar amount of time to that of loading; therefore, we used the same value. Self-unloading trailers or lorries are not common in this area.

Transportation costs depend on the distance travelled. The distances from the geometric centres of the harvesting areas to the storage points in the production area, as well as the surfaces of the harvesting areas, were calculated, in order to estimate their straw production. Travel times were estimated as a function of distance. A travel speed of 25 km h⁻¹ was assumed.

Considering a cost of 45 EUR h⁻¹—which is usual in similar equipment—the cost of this operation was calculated (Table 7). On average, for all areas, it was calculated at 44.9 EUR trip⁻¹ (round trip). If the weight of the bales was 300 kg bale⁻¹, and 28 bales were carried per trip, the cost of this step would be 5.34 EUR t⁻¹ or 1.6 EUR bale⁻¹.

Table 7. Distances, surfaces, straw yield, and transport costs between the fields and the storage points in the production area.

Harvest Zone	Storage Point	Surface, ha	Straw Yield, t	D _{CG} , km	D _{pa} , km	D, km	Time, h Trip ⁻¹	C _F EUR Trip ⁻¹
1	A1	370	2246	1.53	4.60	6.13	1.13	50.9
2	A1	187	1137	0.41	2.60	3.01	0.88	39.6
3	A1	720	4371	1.79	3.10	4.89	1.03	46.4
4	A2	152	923	1.07	2.30	3.37	0.91	40.9
5	A2	897	5448	1.87	2.10	3.97	0.96	43.1
6	A3	640	3885	1.09	1.40	2.49	0.84	37.8
7	A5	1304	7915	1.08	2.60	3.68	0.93	42.0
8	A5	2682	16,283	1.05	5.85	6.90	1.19	53.6
9	A4	666	4041	2.65	1.90	4.55	1.00	45.2
10	A6	1476	8961	0.73	5.90	6.63	1.17	52.7
11	A6	954	5792	0.79	3.25	4.04	0.96	43.3
12	A6	1053	6393	0.44	3.50	3.94	0.96	43.0
13	A7	1188	7213	0.95	3.45	4.40	0.99	44.6
Average				1.19	3.27	4.46	1.00	44.9
Sd				0.63	1.42	1.36	0.11	4.9

The cost (EUR ha⁻¹) of this step was

$$C_2 = C_E + C_{Ft} + C_G = 1.34 + 5.35 + 1.34 = 8.03 \text{ € t}^{-1}, \quad (5)$$

where C₂ is the cost of Step II, C_E is the cost of loading, C_{Ft} is the cost of transporting in the producer area, and C_G is the cost of unloading.

3.8.3. Step III Costs

This step consisted of two parts: lorry loading and transportation to the final destination. The unloading at this point could be carried out by tilting or using the customer's own equipment; therefore, this cost was not included.

Loading can be carried out by tractors with loaders, if the truck is small, or (regardless of size, and if possible) from the sides. There are few trucks of this type in the area, the most common being articulated trucks with a closed-sided box; so, in the case of big trucks, it is usually necessary to use telescopic loaders.

The loading of articulated trucks was recorded on video and the times were analysed. An average time of 0.63 h truck⁻¹ was measured. Hourly loader costs were estimated at 40 EUR h⁻¹, meaning that loading costs were 1.24 EUR t⁻¹, assuming 68 bales weighing 300 kg per truck. The average transport costs are 1.7 EUR km⁻¹ [23].

Therefore, the cost of step III is the sum of loading (J) and transporting (K), the latter depending on the distance:

$$C3 = C_J + C_K = 1.24 + 1.7 \cdot 2 d W^{-1}, \quad (6)$$

where C3 is the total cost [EUR (t km)⁻¹]; C_J is the loading cost (EUR t⁻¹); C_K is the transport cost (EUR km⁻¹), as a function of the one-way distance d (km); W is the truck load (t).

Table 8 shows an estimation of the transport costs for a range of one-way distances (25–150 km) from the stock in the production area to different destinations, calculated with a load of 20.4 t truck⁻¹.

Table 8. Transport to final destination cost, according to the one-way distance for a truck with a load of 20.4 t.

km	25	50	100	150
C3 (EUR t ⁻¹)	5	10	18	26

4. Discussion

The field capacities obtained in this study were poor, compared with related studies considering management of the straw of winter cereal crops such as barley or wheat and forage [23,26], included in the bibliography. The main reason for this was the difficulty of working in the small plots of L'Albufera de València, due to the use of traditional irrigation. In addition, the soft ground makes it even more challenging for machines to work well there, thus reducing overall efficiency. This agrees with related studies by other authors from the USA [5,15–17].

When the individual operations were analysed, raking had an effective field capacity of 3.2 ha h⁻¹, which was on the same order as that reported by Jenkins et al. [15], ranging between 2.4 and 4.0 ha h⁻¹.

In the operation of baling with large balers, we measured 2.4 ha h⁻¹, similar to that reported by Jenkins et al. [15], ranging between 2.0 and 3.2 ha h⁻¹. When baling with a small baler, we achieved 0.6 ha h⁻¹, much lower than the values offered in previous studies (in the range of 1.2–2.0 ha h⁻¹). The reason probably relates to the concept of small bales as, in the USA, a small bale has a weight of approximately 40 kg [15] while, in our conditions, a small bale weighed between 15 and 20 kg. Small bale bundling achieved 1.5 ha h⁻¹.

In our conditions, road-siding had a capacity of 2.1 ha h⁻¹; much lower than the values given by Jenkins et al. [15] of 12–22 ha h⁻¹. The only explanation for this is that, in Valencia, small tractors are used and have to do more trips to harvest the same amount of straw.

Step I costs for large bales were 20 EUR t⁻¹, in contrast to 43 EUR t⁻¹ for the small ones. The differences can be explained by the additional operation of bundling necessary to mechanically harvest the small bales. Bundling is expensive, as the machines have a high hourly cost, as well as an extra cord-related cost.

Step II costs were calculated for a bale density of 300 kg m⁻³, resulting in 8.00 EUR t⁻¹. These costs are directly proportional to the bale density as, in any case, the maximum load capacity, in terms of weight of the transport equipment, was reached. These results agree with those of Kadam et al. [5] who, taking a density of 320 kg m⁻³ as reference, obtained a 40% increase in transportation costs when the bale density decreased to 270 kg m⁻³, and a 20% decrease when the density increased to 400 kg m⁻³.

Therefore, if the costs of steps I and II are combined, it is possible to compare them with the price of cereal straw at origin. The total costs of these two steps ranged between 28.1 and 51 EUR t⁻¹, which was in the range of half of the straw prices in 2019, which had an approximate value of 70 EUR t⁻¹ [27]; however, in 2020, the price of cereal straw was about 42 EUR t⁻¹ [28], which was less than the harvesting costs of small bales of rice straw.

Step III, the transport to destination points ranged from 5 EUR t⁻¹ (for short distances of 25 km) to 26 EUR t⁻¹ (for a 150 km one-way trip), using big trucks. Longer distances were not relevant, as the points of straw consumption were always to the West of Valencia, where we found the cereal growing areas, and it would not be possible to compete with either the price of rain-fed cereal or its transportation costs in years with normal straw yields.

5. Conclusions

The collection and packing processes of rice straw in the area of L'Albufera de València were found to not be very efficient, in comparison with the processes carried out for rain-fed cereal. This is due to the structural problems of the plots and the soft soil, which increased the associated costs.

Therefore, in years with low cereal straw prices, the process of collecting rice straw would run at a deficit, meaning that it would require some kind of official subsidy if farmers are to undertake the process; this also happens in other occidental rice producing countries, such as California in the USA, where straw-burning limitations have forced farmers to bale and transport straw, and the relevant authorities are subsidizing these tasks [5].

However, in the years when straw reaches a high price, the costs of collecting rice straw from L'Albufera de València and transporting it to relatively close areas could be seen as a competitive activity. Furthermore, another advantage of rice straw is that, being an irrigated crop, production is regular and reliable, even in times of drought.

The packing and extraction of rice straw could, therefore, be viewed as a way to reduce the environmental impacts of burning or burying rice straw in the natural park.

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