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Seed quality and efficiency of mechanical harvest of castor crop at commercial scale

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ABSTRACT

Mechanization of the harvest is the main challenge for increasing the production of castor in the world (*Ricinus communis*). This study evaluated the header JLS Kascavel, which was designed specifically for harvesting castor, with fingers that vibrate and rotate to remove castor fruits, and a threshing unit adapted as the grain elevator. In this harvesting equipment, the castor plant is not cropped, and only the fruits enter in the combine harvester to be cleaned. The device was tested for two years (2023 and 2024) under operation in the harvest of castor field at commercial scale. The highest seed loss occurred in the header (152 – 216 kg/ha), while there was low rate of not-harvested fruits (6 – 26 kg/ha). The cleaning shoe was very effective, the seed loss was negligible in this step of the process, and it did not vary along the day. The harvest efficiency was 88.8 % in 2023 and 83.5 % in 2024. The harvested product had from 91.9 % to 92.2 % (by weight) of normal seeds (excluding broken and empty seeds, fruit husk, and other impurities). Along the day, the rate of broken seeds was the lowest around noon. The resistance to break of castor fruit peduncle was strongly associated with the relative air humidity.

1. Introduction

Castor (*Ricinus communis*) is an industrial oilseed with potential to supply a versatile oil that has many uses in the chemical industry and for bioenergy. The main regions of castor seed production are located in countries (India, China, Brazil, and Mozambique) and regions where, in the past, labor was available at low cost for hand-picking the crop; however, the manual harvest is becoming impracticable because of increasing labor cost. The worldwide growing demand for castor oil will not be met if the production continues depending on manual harvest. For that reason, mechanization of the harvest is the main challenge for increasing the production of castor in the world (Kong et al., 2024; Pari et al., 2020; Severino et al., 2012; Stefanoni et al., 2022; Zhao and Zhang, 2019).

There is scarce scientific literature on castor mechanical harvest. Stefanoni et al. (2022) reported field tests made in Greece with a sunflower and a cereal header attached to a regular combine harvester. It was found that the equipment was able to harvest and thresh the seeds, but the seed loss was high and the seed was not cleaned to an adequate level to be stored and processed in the industry. A large portion of the problems were related to the thick stem of castor plants that needed to be cut, and to the volume of biomass to be processed inside the combine harvester.

Two studies performed in China also reported modelling simulations of cutting disks for harvesting castor, considering also the option to cut the whole plant to be processed inside the harvester (Hou et al., 2018; Kong et al., 2024). Removing the fruits by vibration was an alternative harvesting method proposed by Zhao and Zhang (2019) aiming to avoid the high volume of biomass to be processed. The study by Latterini et al. (2022) demonstrated that adequate desiccation of the crop is fundamental for an efficient mechanical harvest. Harvesting the crop with high moisture content resulted in high loss, poor cleaning, and reduced seed quality.

Mechanization of castor harvest has been developed and studied in Brazil since 2013, when the first prototype of the header that was designed specifically for castor was produced by the company *Jorge Máquinas* (Rondonopolis, MT, Brazil) (Severino et al., 2016). In 2014 and 2015, the header for harvesting 10 rows (model M10) was tested at commercial scale, and it allowed that the fruit picking and threshing operations occurred at the same time. The mechanism on that header was rotating cylinders with nylon bristles that removed the fruits without cutting the castor plant. Only the fruits were taken into the

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combine harvester, what reduced the volume of biomass to be processed. The rotor inside the combine harvester was covered with rubber. The main concern at that time was the high seed loss in the header, which was between 15 % and 25 % of the seed yield (Severino et al., 2016), while farmers reported seed loss in excess of 30 %. Castor producers also complained that the harvest operation was delayed because of excessive pauses for maintenance of defective parts and to remove weed biomass that accumulated in the header.

Another prototype of header specific for castor was developed by the company *JLS Máquinas* (Matão, SP, Brazil) and tested at field conditions for the first time in 2020. The equipment continued under development, with improvements implemented after each harvesting season, and this study reports the evaluations made at field conditions in commercial castor fields in 2023 and 2024 using the model JLS Kascavel with six rows.

Besides the development of headers, it is noteworthy the parallel development of castor varieties that are suitable for mechanical harvest, and the collective experience accumulated by farmers regarding the crop management. After several years planting those varieties at commercial scale, they learned relevant aspects such as the choice of the varieties, planting time, weed and disease management, irrigation, and preparation of the crop to harvest, among many other relevant practices (Almeida et al., 2018; Costa et al., 2018, 2021; Latterini et al., 2022; Oswalt et al., 2014).

The objective of this study was to evaluate a header for mechanical harvest of castor operating at field conditions, aiming to quantify the seed loss, to measure the seed quality, to test a method for evaluation in the field of the harvesting conditions of the fruits, and to report observations on the improvements needed for optimization of the harvesting process.

2. Material and methods

2.1. Experimental site and crop management

The field experiments were conducted for two years (2023 and 2024) in the farm *Agropecuária Água Azul*, located in Campo Novo do Parecis, State of Mato Grosso, Brazil (14° 0' S, 57° 57' W), altitude of 620 m. Castor was sowed in 8-Mar-2023 and 26-Feb-2024. The harvest was performed from 20-Jul to 22-Jul-2023 and from 24-Jul to 1-Aug-2024. The field had more than 200 ha continually planted with castor, and the evaluations were made along the farm's regular harvesting operation.

The area was previously cultivated with soybean (November through February), and castor was planted a few days after harvesting the previous crop in a no-tillage system. The variety 'RS Otto 01' was sown in the spacing of 1 m between rows, and 0.33 m between plants in the row (plant population of 30,000 pl/ha). The crop was fertilized with 106 kg/ha of N, 40 kg/ha of P, 40 kg/ha of K, and 10 kg/ha of S. From sowing to harvest, the average temperature was 25 °C, and the total precipitation of approximately 600 mm, concentrated in the first two months (65 % in March and 25 % in April). Weed, pests, and diseases were managed with the regular protocols for the region. The crop was not managed with plant growth regulator for control of height, and it was terminated with a spray of 300 g/L of diquat (Reglone®) at least one week before the harvesting operation (the time may vary because it was a large field that was harvested for several days). At harvest, the plants were completely dry, and very few green leaves or fruits could be found (Fig. 1). The plants had very low rate of fruit dehiscence and few lateral branches, as required for appropriate mechanical harvest. Data was not taken on plant height, but very few plants were taller than 180 cm, and it was assumed that the harvest efficiency was not influenced by the occurrence of excessively tall castor plants.

Fig. 1. Castor field cv. 'RS Otto 01' just before the mechanical harvesting operation in 2023.

2.2. Header and combine harvesting

Mechanical harvest of castor was performed with a combine harvester Case 7230 attached with a header JLS Kascavel with 6 rows (Fig. 2A). The header was equipped with a system of rubber fingers attached to a vertical axis that rotates and remove the castor fruits from the plant (Fig. 2B). The branches and stems of castor plants are not cut allowing to reduce the amount of biomass to be threshed inside the combine harvester. The header's internal floor has movable overlapping plastic plates (Fig. 2C) that hold the shattered fruits and allow the movement of the header without cutting the castor plant stem. The header has a forced-air system that blows in the tip of the platform (Fig. 2D) to prevent the accumulation of fruits. The shattered castor fruits are transported by a system of spiral blades to the feeder (entrance) of the crop elevator.

The threshing operation (breaking the fruit to release the seeds) occurs in the crop elevator, the device that attaches the header to the combine harvester. The elevator has a rotor (cylinder covered with rubber) (Fig. 2E), rotating inside a concave (another cylinder covered in rubber). The castor fruits pass in the gap between the cylinders and the concave, and the friction breaks the fruit capsules. At that point, the capsules are broken, but the material containing seeds and chaff remains mixed. This study evaluated two crop elevators (threshing mechanism). The test in 2023 was made with the crop elevator developed by the company *Jorge Maquinas* (Rondonópolis, MT, Brazil) (Fig. 2F), and in 2024, with the elevator developed by JLS Maquinas (Matão, SP, Brazil) (Fig. 2G). Both devices have similar working mechanisms, but the one tested in 2024 was designed to a higher processing capacity and has some additional functionalities, such as adjusting the rotor speed and the gap directly in the dashboard of the combine harvester, allowing easy regulation along the day.

After threshing, the material is carried into the combine harvester. The internal threshing system of the harvester was turned off, and only the cleaning system (shaking sieves and forced-air) was used to separate the seed from the chaff. After separation, the chaff is ejected in the back of the harvester, and the clean seed is transported by the elevator (grain auger) to the seed tank on the top of the harvester.

The combine harvester speed was not strictly controlled along the day because it was following the operator decision as the normal practice in the farm. The target velocity was 4 km/h in 2023 and 6 km/h in 2024. The higher speed in 2024 occurred because of the greater processing capacity of the thresher unit evaluated in that year.

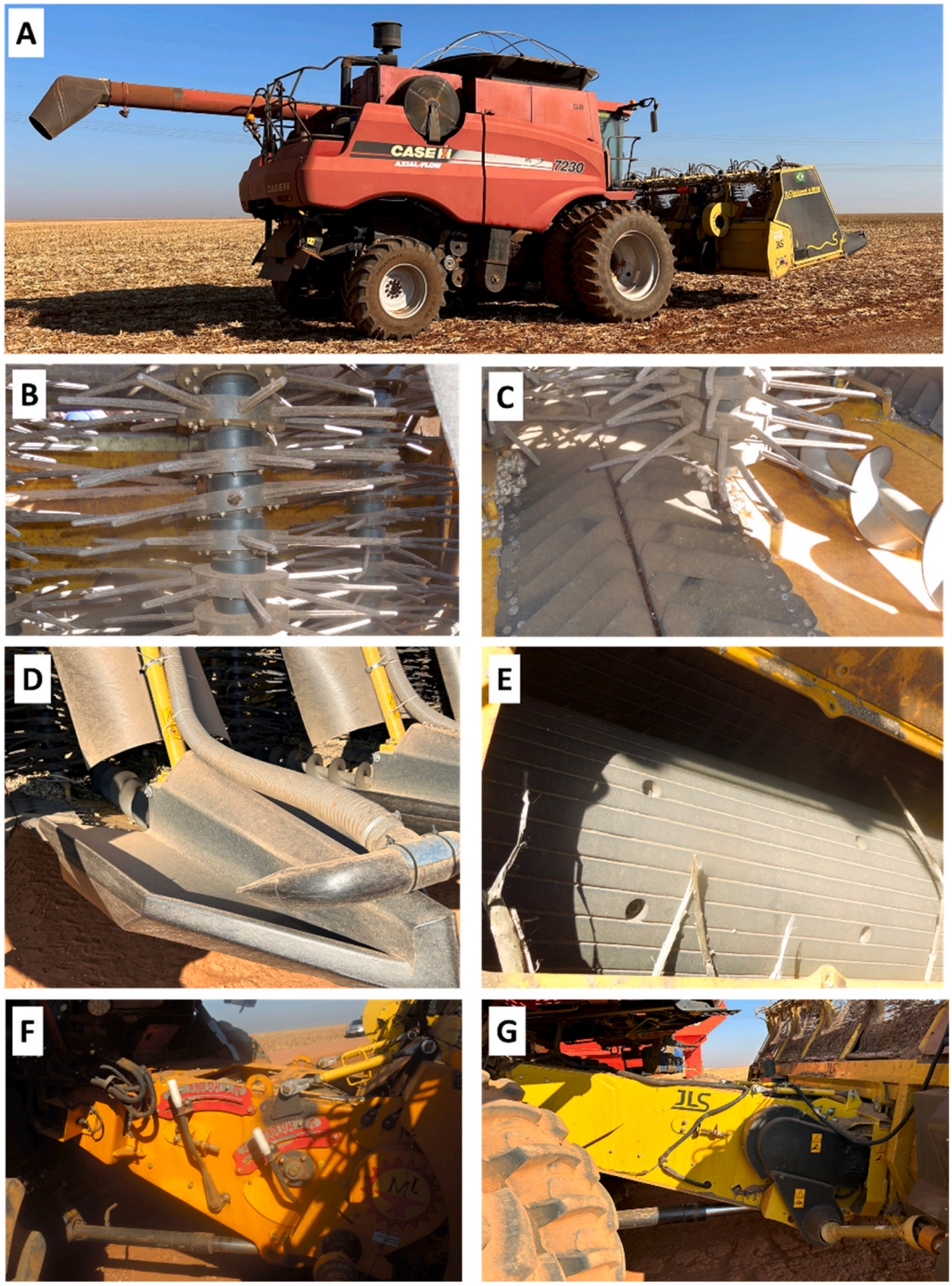

Fig. 2. Details of the header JLS Kascavel for mechanical harvest of castor. A: header with a Case 7230 combine harvester; B: rotating fingers that vibrate to remove castor fruits from the plant; C: movable overlapping plastic plates and auger to move castor fruits; D: forced-air system to prevent accumulation of castor fruits in the tip of the header; E: rotor covered in rubber into the threshing unit; F: threshing unit evaluated in 2023; G: threshing unit evaluated in 2024.

2.3. Measurements of seed yield and shattered fruits

The seed yield of the field was estimated before the harvesting operation. In 2023, twenty plots of 2 rows x 10 m and, in 2024, ten plots 1 row x 10 m were randomly chosen inside the field, and all the fruits were harvested by hand and weighed. Sub-samples (approximately 50 g) of fruits were taken to the laboratory, weighed, threshed by hand, and the clean seed was weighed. Seed yield (kg/ha) was calculated considering the fruit weight, the proportion of seed to fruit weight, and the harvested area.

The fruits shattered by natural factors (dehiscence, wind, machinery transit, animals etc) were measured (only in 2024). All the fruits on the ground before the harvesting operation were handpicked in fifteen plots of 7 rows x 1 m, taken to the laboratory, manually threshed , and the clean seed was weighed. The shattering was not measured in 2023 because it was considered negligible by visual inspection.

2.4. Seed lost in the mechanical harvest

The castor seed loss caused by the harvesting operation was measured using collecting structures placed on the ground prior to the harvest. The structures consisted in frames made of iron bars (0.9 $\times$0.6 m), covered with a plastic bag. The frames were previously tested to confirm that they would not be damaged by the tires of the combine harvester. For each sampling, six frames were placed on the ground across six rows of castor plants being harvested. The combine harvester passed over the frames, the dropped fruits and the seeds were retained in the structures, and they were collected after the harvester passed. Each sampling was equivalent to the harvested area of 3.6 m^2 (6 frames x 0.6 m^2). The sampling process was repeated six times in 2023 and 12 times in 2024. The sampling in 2024 was made separately for each row to check if the seed loss was evenly distributed. All the material collected in the frames was taken to the lab, and the seed was cleaned by hand and weighed. The loss of seeds by the mechanical harvest was calculated as the weight of clean seed in the material collected on each frame, divided by the harvested area. The seed loss measured in the frames was subtracted from the amount of seeds estimated as loss by the cleaning shoe (Section 2.6), and the result was the seed loss in the header. The seed loss from each individual row was subjected to analysis of variance and test of Tukey ($p < 0.05$) to evaluate the distribution of seed loss among the rows.

2.5. Fruits not harvested

The fruits that were left on the plant after the mechanical harvest were collected and weighed. This sampling was made in four plots of 6 rows x 5 m in 2023 and in six plots of 2 rows x 10 m in 2024. The fruits weight was converted to seed weight using the same conversion factor estimated for seed yield (Section 2.3). The amount of fruits that were not harvested was calculated in kg/ha dividing the seed weight by the sampling area.

2.6. Seed loss in the cleaning shoe of the combine harvester

The castor seed lost in the internal mechanisms of the combine harvester were estimated. In 2023, the twin rotating disks (spreaders) were removed from the back of the harvester, a big bag was placed on the exit of the harvester, and all the chaff expelled was collected while the harvest was made along approximately 100 m. In the chaff retained in the bag, 12 samples of approximately 200 g were collected for analysis. In 2024, the spreaders were not removed, and the chaff was collected holding a bucket on the back of the harvester, while it harvested the field for approximately 50 m (the chaff collected was just a sample of the expelled material). This sampling process was repeated 21 times along the day (only in 2024), and the time of each sampling was registered aiming to monitor changes in the rate of seed loss along the day (from 8:50 through 17:45). The average amount of chaff collected in each sampling was 700 g. In both years, the chaff was taken to the laboratory, and all the clean seeds were carefully picked, separated in normal and broken seeds, and weighed. Seeds inside the fruits that were not properly threshed were separated from the husk, and classified as normal or broken. Empty seeds were not weighed.

The weight of seeds found in the chaff was converted to kg/ha with the equation that follows:

$$\textit{Seed loss}(kg/ha) = \frac{W_s \times S_y \times (1 - F_c)}{W_a - W_s}, \text{ in which :}$$

Seed loss (kg/ha) is the amount of seed lost by the internal mechanisms of the combine harvester and expelled with the chaff

W_s is the weight of clean seeds found in the sample (kg)

S_y is the castor seed yield (kg/ha)

F_c is the conversion factor of fruit to seed weight

W_a is the weight of the chaff sample (kg)

The data of normal, broken, and total seed lost in the chaff along the day was subjected to analysis of regression using the quadratic model, and the data was plotted in function of the time of the day. The regression was presented with a solid line when the model was significant ($p < 0.10$) or with a dashed line when it was not significant.

2.7. Harvest efficiency

All the variables related to castor seed loss were integrated into the harvest efficiency with the equation that follows and calculated separately for each year:

$$\textit{Harvest efficiency}(\%) = 100 \times \frac{S_y - L_b - L_h - L_c - L_n}{S_y}, \text{ in which :}$$

Harvest efficiency (%) is the fraction of the castor seed that was collected

S_y is the castor seed yield (kg/ha)

L_b is the castor seed shattered before harvest (kg/ha)

L_h is the castor seed lost from the header (kg/ha)

L_c is the castor seed lost in the cleaning shoe (kg/ha)

L_n is the castor seed that was not picked by the header (kg/ha)

2.8. Quality of the harvested seed

Seed samples were collected in the seed tank of the combine harvester for measurements of quality characteristics. In 2023, 16 samples of 0.5 kg (on average) were collected along the day. The samples were taken to the laboratory and separated in the classes (i) normal seeds, (ii) broken seeds, and (iii) fruit husks and other impurities. Seeds that were inside the capsules were separated in fruit husks and seeds and were classified accordingly. A sample of 100 normal seeds was counted and weighed to measure the mean seed weight.

In 2024, 21 seed samples of 1.8 kg (on average) were collected in the tank, and the time of harvesting was registered. The samples for seed quality assessment were collected at the same time as described for the seed loss in the internal mechanisms (Section 2.6). The samples were evaluated with the same procedures and for the same quality aspects considered in 2023, adding the class of empty seeds and classifying fruit husks separate from other impurities. The data was subjected to analysis of regression using the quadratic model, and the data was plotted in function of the time of the day. The regression was presented with a solid line when the model was significant ($p < 0.10$) or with a dashed line when the effect was not significant.

2.9. Seed damage in the grain auger

After castor seed was harvested, it passed five times through grain augers: (i) inside the combine harvester to transfer the seed from the cleaning shoe to the tank (this step has two sequential augers), (ii) from the tank to a transporting wagon, (iii) from the wagon to a stationary tank in the farm's barn, and (iv) from the stationary wagon to a funnel used to fill big bags (1.5 Mg).

Five seed samples (2 kg each) were collected before the seed entered the big bag aiming to measure the potential damage of the sequential transportation through grain augers on the quality of the seed. This sampling was made in only one time in the day, it does not reflect the fluctuations along the day, and these seed samples could not be correlated with the time of harvest. When the seed was collected in the tank (Section 2.8), it had already passed twice through grain augers, and some of the broken seeds were probably caused the first passing through the grain auger. These samples were evaluated with the same procedures and seed quality indicators described in the Section 2.8. This measurement was made only in 2024. The quality characteristics before and after the transfer through auger were compared by t test ($p < 0.05$).

2.10. Flexibility of the castor fruit peduncle influenced by air humidity

The flexibility of castor fruit peduncle was monitored along the day as an indicator of the crop readiness for mechanical harvest. The test was made 26 times from 7:16 in the morning through 18:14 in the evening. One castor fruit was randomly chosen in 50 sequential plants in a row (one fruit per plant). The fruit was rotated approximately 90 ° to bend the peduncle in the region close to the fruit (1–5 mm from the insertion) (Fig. 3). The fruit was not pulled, but the test was only on the peduncle's resistance to the bending movement. The broken peduncles were counted, and the percentage was calculated.

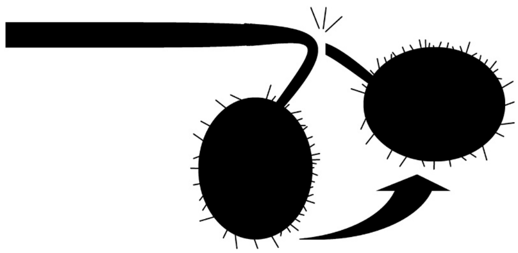

Fig. 3. Test of the flexibility of castor fruit peduncle. The fruit is rotated by hand to bend the peduncle close to the fruit insertion.

Data on the relative air moisture was collected from a meteorological station located about 100 km from the farm (coordinates 14.65 S, 57.43 W, altitude 440 m), assuming that the weather characteristics were similar to the study site. As the data on air moisture was available at one-hour intervals, the data was weighted to estimate a value for each time of the test made on the peduncle.

The data on relative air humidity and the rate of peduncle break were plotted in function of the time of the day. The data on the rate of peduncle break was subjected to a regression analysis with the sigmoidal model aiming just to plot a smooth line as the relation between those variables. The association between the rate of peduncle break and the relative air humidity was tested with a stepwise linear regression. Each segment of the regression line was tested for significance ($p < 0.10$).

3. Results and discussion

3.1. Castor seed yield and loss in the mechanical harvest

The proportion of fruit to seed weight was measured as 0.662 in 2023 and 0.608 in 2024. Based on this conversion factor, castor seed yield was estimated in 1730 kg/ha for the crop in 2023 and 1627 kg/ha in 2024 (Fig. 4). At field conditions, castor seed yield has very high spatial variability, and the conversion factor from fruit to seed weight is an additional source of variability. For that reason, estimations of castor seed yield are not precise measurements, but an estimation with high implicit variability.

The shattering prior to the harvest was assumed as negligible in 2023 because at a visual inspection very few shattered castor fruits could be found. In 2024, the seed loss because of shattered fruits was estimated as 45 kg/ha (2.8 % of the seed yield) (Fig. 4). Shattering has multiple causes. It is directly dependent on the characteristics of the variety, particularly on the frequency of dehiscent plants and on the resistance of the peduncle that sometimes is too fragile. It can also be favored by environmental conditions, particularly by winds and low air moisture. Crop management adds some seed loss by shattering, for example, with excessive transit of machinery or too early preparation of the crop to harvest (desiccation).

The correct timing for some interventions is extremely important for the optimization of the mechanical harvest (Cavalaris et al., 2022; Oswalt et al., 2014; Pari et al., 2020). The racemes of castor plant reach maturity at different times. If the preparation for harvest is too delayed, the racemes with dry fruits stay longer under risk of shattering. The crop desiccation should be planned aiming to reach the ideal condition for harvest approximately at the same time that the combine harvester will be available (and all the supporting logistics required). If those operations are mismatched, early desiccation can expose the crop to shattering, while late desiccation will require harvesting with excessive rate of green or moist fruits, what affects the seed quality (Cavalaris et al., 2022; Costa et al., 2018).

The most relevant castor seed loss occurred in the header during the mechanical harvest operation. The seed loss was estimated to be 152 kg/ha (8.8 % of the seed yield) in 2023 and 216 kg/ha (13.3 % of the seed yield) in 2024. Some fruits were thrown out of the header with the impact of the equipment on the plant or by the fast-rotating fingers, some fruits and seeds fell in gaps in front of the header or when the stems passed in the moveable plastic plates (Fig. 2C). The forced-air system (Fig. 4D) implemented to prevent accumulation of fruit on the tip of the header was effective, and no fruit was stuck on that place along the day. Many other details in the header for castor seed harvest were designed to reduce the seed loss, but this step remains as the most relevant source of inefficiency in the process.

Castor seed loss in the header was the highest in the central rows, and it was the lowest on the two rows in the left (Fig. 5). A hypothetical reason for the seed loss in the central row is that the fruits harvested from all rows are moved by the augers to the center of the header to enter the elevator (threshing unit). On that point, fruits accumulate, and may leak when the castor stems pass by the moveable plastic plates

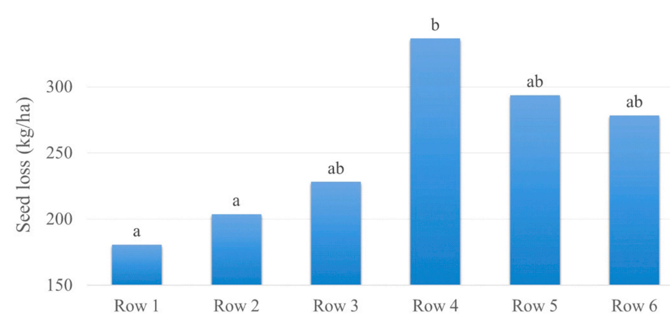

Fig. 5. Castor seed loss in the mechanical harvest operation according to the row of header.

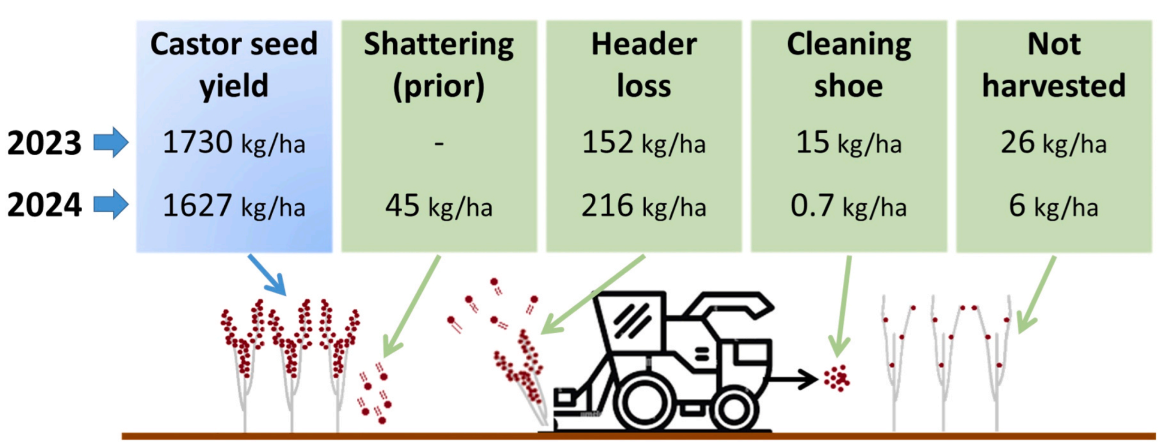

Fig. 4. Castor seed yield and the seed loss in the mechanical harvest in 2023 and 2024.

(Fig. 2C). A possible reason for the difference between left and right rows is that the operator cannot align the header looking to all the rows at the same time. It seems that the operator had attention concentrated in the row on the left, favoring the reduced seed loss on that side.

The internal mechanisms of the combine harvester caused the seed loss of 15 kg/ha (0.9 % of the seed yield) in 2023 and 1.2 kg/ha (0.07 % of the seed yield) in 2024. The discrepancy between years is largely explained by the improvements in the threshing unit introduced in 2024, but it should also be considered the better crop preparation for harvest and equipment operation (accumulated experience). The type of castor seed lost in the cleaning shoe was 0.6 kg/ha of normal seeds and 0.6 kg/ha of broken seeds (this classification was made only in 2024). Mechanical harvest of castor is very recent, and the farmers are still accumulating experience on how to prepare the crop for harvest and how to regulate and operate the harvesting equipment.

The seed loss related to fruits that were not harvested was estimated as 26 kg/ha (1.5 % of the seed yield) in 2023 and 6 kg/ha (0.4 % of the seed yield) in 2024. This result demonstrates that the header was very efficient for harvesting modern castor varieties with characteristics for mechanical harvest and fields properly prepared. Nevertheless, it was observed at field conditions that in a few spots many fruits were not harvested. In general, this problem was not related to the equipment, but to the operation or problems in the plants. For example, the header can occasionally lose alignment with the rows or the field may have some spots with very short plants (waterlogging, weed infestation, soil compaction), in which the header passes over the racemes. The planter used for sowing the castor field must have a number of rows that is multiple of the number of lines in the header to keep the rows aligned in the harvesting operation.

Accounting all the sources of seed losses, the harvest efficiency was 88.8 % in 2023 and 83.5 % in 2024, and most of the seed loss occurred in the header. Improving the harvest efficiency requires improvements in the equipment, in the selection of varieties with better characteristics for mechanical harvest, and adequate crop management. For comparison, the seed loss in the mechanical harvest of some oilseed row-crops can be as low as 2 % in sunflower (*Heliantus annuus*), 3 % in crambe (*Crambe abyssinica*), and 3.2 % in safflower (*Carthamus tinctorious*), while in canola (*Brassica napus*) the seed loss of 10 % is regarded as acceptable (Pari et al., 2020). Equipment for corn mechanical harvest is likely the most advanced available, but the grain losses at field conditions are still as high as 309 kg/ha (Shauck and Smeda, 2011).

3.2. Seed quality

The average seed weight of castor seed cv. 'RS Otto 01' was 239 mg (2023) and 282 mg (2024).The weight of normal castor seeds in the tank of the combine harvester was 92.2 % in 2023 and 91.9 % in 2024 (Table 1). Broken seeds accounted for 2.2 % (by weight) in the first year and 4.4 % in the second year. Broken seeds are a problem for the castor oil industry because without the protection of the seed coat, the oil deteriorates by acidification and oxidation. As castor seed is stored and processed along the year, high levels of broken seeds are detrimental for the oil quality.

Empty seeds were not measured in 2023, but in 2024, they represented 1.3 % (by weight). Empty seeds are concerned as a quality aspect because they reduce the density of the seed lot and increase logistic cost for storing and transportation. As castor seed is usually transported for long distances between the locations of production and processing, the inflated volume and weight to be transported add a significant cost to the freight. High rates of empty seeds also increase the volume to be stored, adding another cost.

The husks and impurities accounted for 5.6 % of the weight in 2023 (Table 1). In 2024, those classes were separated, and the fruit husks were 1.4 % while the impurities were 0.9 %. Fruit husks cause losses for the castor oil industry for the same reasons presented for empty seeds, but also because they absorb oil and reduce the efficiency of industrial process of oil extraction. The other contaminants were predominantly fibrous materials such as weed seeds, and castor plant fragments (stems, leaves, fruit internal axis), and they affect the seed quality for the same reasons of fruit husks. Inorganic materials such as sand, rocks, plastic, or metals were not detected.

Table 1
Castor seed quality in samples collected in the tank of the combine harvester and after being transferred multiple times through grain augers.

	Normal seeds	Broken seeds	Empty seeds	Fruit husks	Other impurities
2023 (combine harvester)	92.2 %	2.2 %	-	5.6 %	-
2024 (combine harvester)	91.9 %	4.4 %[b]	1.3 %[a]	1.4 %[a]	0.9 %[b]
2024 (after transferred)	83.9 %	5.0 %[a]	0.7 %[b]	1.6 %[a]	8.8 %[a]

Means followed by the same letter in the column are statistically equal by t test ($p < 0.05$).

3.3. Castor seed damaged by the grain auger

The visual inspection of the ducts that transfer castor seed in the combine harvester and in the transportation wagon revealed that a crust was formed with seed fragments on the walls of augers (Fig. 6). Castor seed is prone to create this type of crust because its seed coat is brittle, and its high oil content creates a stick mass that easily adhere to the internal surfaces. After some days of harvest, it was verified that inside the combine harvester there was no sign of broken castor seed (no stickiness points or crust), but the crust was found in all the ducts that transport the seed to the tank. The content of broken seeds in the samples collected after the multiple transfer with grain auger (5.0 %) was significantly higher than on the seed collected in the tank of the combine harvester (4.4 %) (Table 1). Other significant changes detected in the seed samples after transportation were the reduction in the content of empty seeds and the increased impurities. In both cases, the changes occurred because the vibration while the seed was transported separated the contaminants according to the density. The light (empty) seeds moved to the top layer, while a small weed seed (*Sena* sp.), which had an intense contamination on some patches in the castor field and was harvested as contaminant, moved to the bottom. As the samples were collected predominantly from the bottom of the tank, the light empty seeds were diluted, and the dense weed seeds were concentrated. We assume that broken seeds were not influenced by vibration as observed for the empty seeds because the broken castor seed had the same density of a normal seed.

The data collected in this study is not robust enough to conclude that the damage to the castor seed caused by the grain auger is significant. To confirm this effect, the grain augers and ducts should be carefully cleaned before the harvesting operation, and the crust formation should be monitored along the harvesting operation. The seed samples after transportation should be collected in an extended period. Anyway, this anecdotal result was presented aiming to register the signs that the grain auger may damage castor seed, and this transportation process deserves further investigation.

Grain damage by auger transportation has caused seed quality deterioration in some other crops, such as soybean and rice. Although some level of damage is inevitable, it can be minimized with attention to the main factor causing this problem, which are the rotation speed of the auger, the moisture content of the seed, and the inclination angle of the helix to the screw axis (Neves et al., 2016; Sukhanova et al., 2023; Zareiforoush et al., 2010).

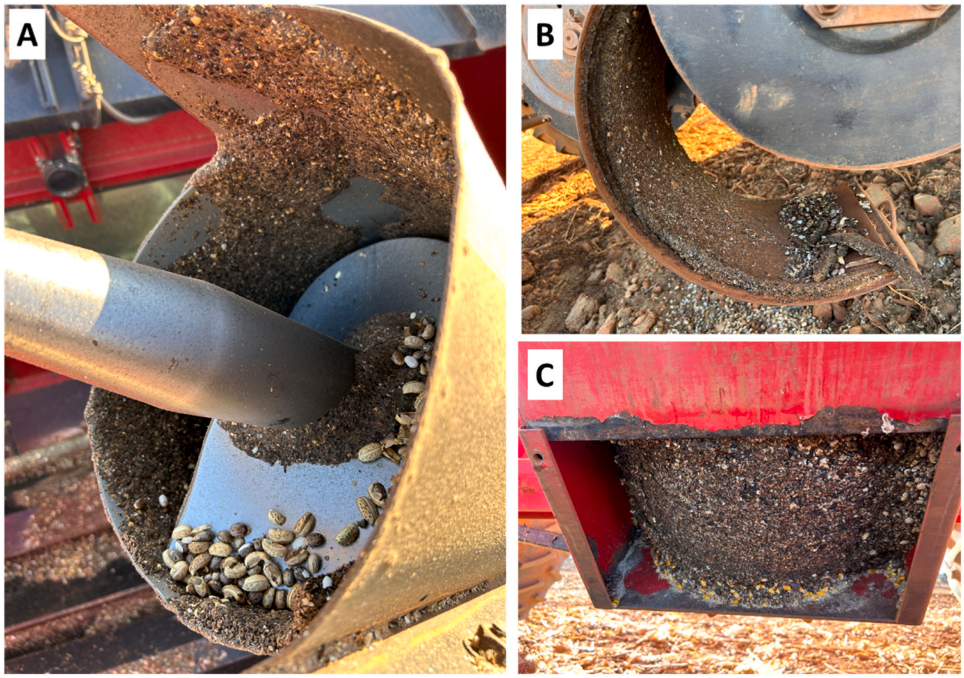

Fig. 6. Crust of seed fragments that formed in the internal surface of the ducts that transport castor seeds: A - grain auger ending in the tank of the combine harvester, B – passage between the cleaning shoe and the tank in the combine harvester, C – passage in the bottom of the transporting wagon.

3.4. Seed loss by the internal mechanisms of the combine harvester

The chaff was collected from the back of the combine harvester multiple times from 8:52 through 17:45, at intervals of approximately 25 min. The loss of broken or normal seeds was not influenced by the environmental conditions along the day when the data was subjected to regression analysis with the quadratic model (Fig. 7). In 2023, the seed loss in the internal mechanisms was significant (15 kg/ha, Table 1), and it was a concern. The equipment evaluated in 2024 demonstrated that this problem was potentially solved, and adjustments along the day in the settings of the threshing unit or in the wind speed and sieve shaking inside the harvester are not a primary concern. For further studies, the seed loss along the day should be tested with other castor varieties and at higher speed of the combine harvester.

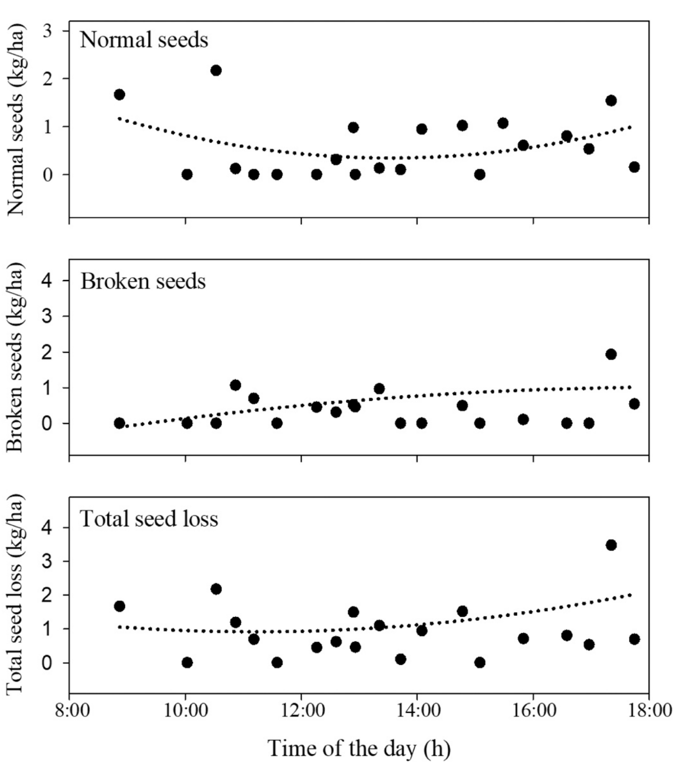

Fig. 7. Loss of normal, broken, and total castor seeds occurring in the internal mechanisms of the combine harvester according to the time of harvest. The dashed line denotes that the quadratic model was not significant at the level of $p < 0.10$.

3.5. Seed quality along the day

The quality of the harvested seed was monitored along one day. The rate of normal seeds was lower in early morning and in the evening (91 %), while it was at the highest (92.5 %) around 13:00 h (Fig. 8). The most relevant change in seed quality was observed in the rate of broken seeds. It was the highest in the beginning and in the end of the day (between 5 % and 6 %), while it was low around noon (4 %). The rate of empty seeds followed a different pattern. It was high in early morning (between 2 % and 3 %), and reduced continually along the day, and stabilizing around 1 % in the afternoon (Fig. 8). The variability on the rate of fruit husks and other impurities was not consistent with the time of the day.

This study did not investigate all the factors that potentially influence the quality of castor seed. In the Section 3.6, air moisture is discussed as one major environmental factor influencing the overall process of mechanical harvest of castor, but a comprehensive explanation require additional experiments, including other variables in the settings of the harvesting equipment, environmental conditions, and characteristics of the varieties and the crop.

3.6. Rate of peduncle brake and relative air humidity

From previous experience, farmers know that castor cannot be properly harvested in the early morning. This occurs because at that time of the day, castor fruit capsules are flexible, and the threshing unit cannot break them, as observed by Latterini et al. (2022). The test of the

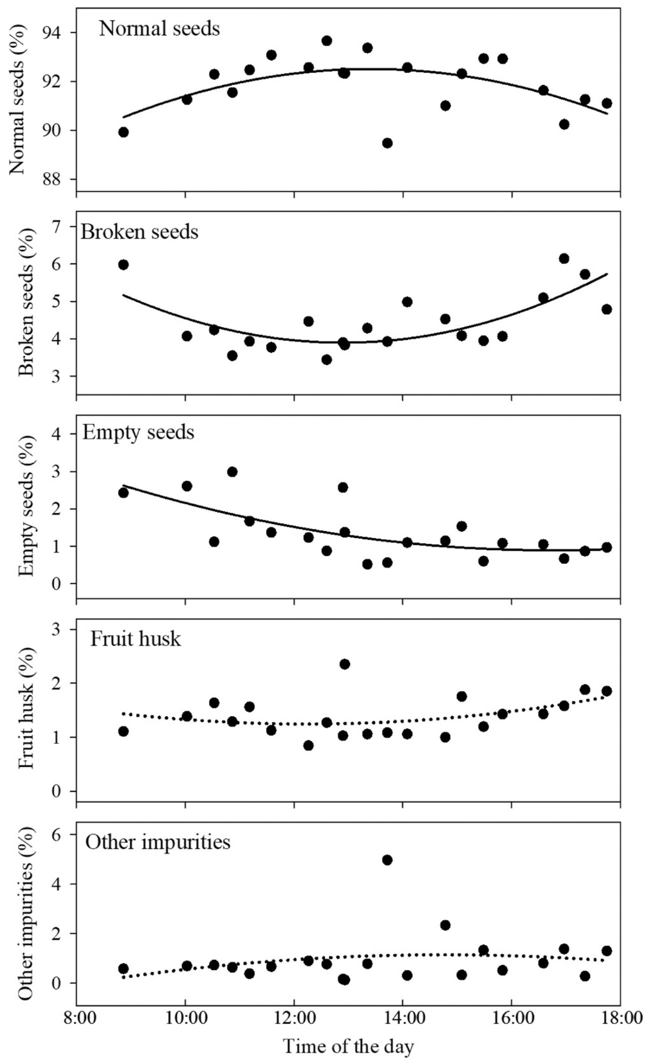

Fig. 8. Aspects of castor seed quality inside the tank of the combine harvester according to the time of harvest.

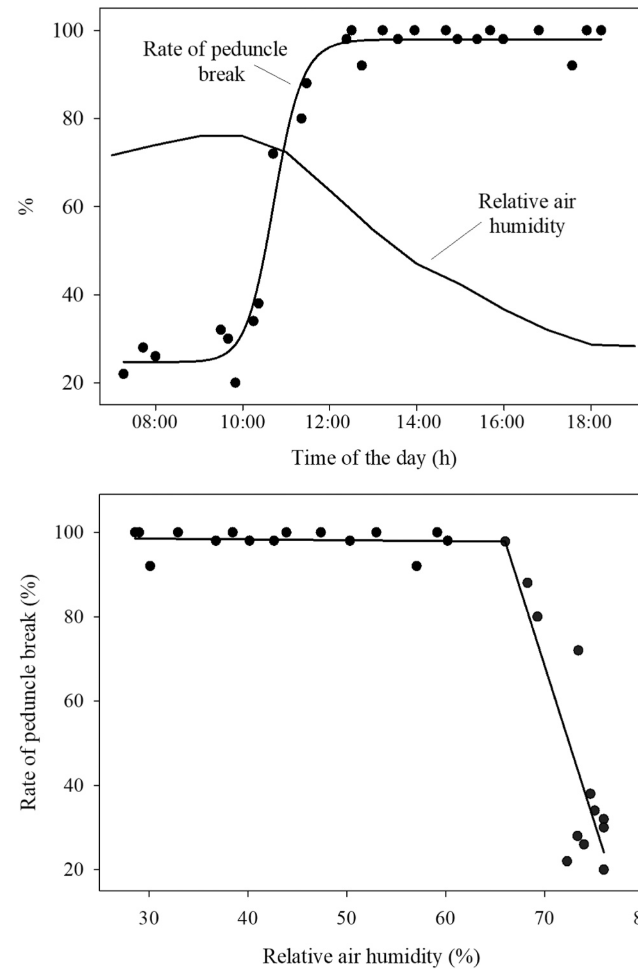

Fig. 9. Rate of castor fruit peduncle break according to the time of the day and in function of the relative air humidity.

peduncle resistance was employed as an objective measurement to estimate at field conditions when the fruit is appropriate for harvest. It considers that the mechanical resistance of the peduncle correlates with the condition of the fruit capsule, and it is easier to measure. It was hypothesized that the crop is in better condition to be harvested when the peduncle has high rate of breakage.

It was confirmed that the peduncle's resistance to bend is drastically changed along the day, and it is directly associated with the relative air humidity (Fig. 9). In the early morning, the rate of peduncle break was stable around 25 %, while the air moisture remained between 70 % and 80 %. After 10:00 h, the rate of peduncle breakage had a sharp increase, coinciding with the drop in relative air humidity. The stepwise regression between the two variables demonstrated that up to 65 % of relative air humidity, the peduncle break remains at the maximum breaking rate. When the air moisture exceeds that threshold, the peduncle turns flexible and do not break with the rotating movement. It should be clarified that this test works only on fruits that are dry and ready for harvest. Green fruits have the peduncle highly flexible and a 0 % breakage would be found regardless of air humidity.

This peduncle test requires deeper investigation. The mechanical harvest evaluated in this study was performed in early morning, despite the indication of low rate of breakage, and it was technically feasible. Further studies should check to what extent the capsule mechanical characteristics are associated with the peduncle resistance to bend, and if the efficiency of mechanical harvest and the quality of the seed are related to the results of this test.

Based on this observation, farmers should consider planning the mechanical harvest according to the air moisture. It is likely that castor seed quality will benefit if harvest operations start later in the morning and continue later in the evening as long as the relative air moisture is adequate. Relative air moisture is directly associated with air temperature. As temperature is easier to measure, it can also be taken in consideration in the decision of the best time for mechanical harvest of castor.

4. Conclusions

The mechanical harvest of castor was effective under field conditions using a combine harvest attached with a header designed specifically for this oilseed. The highest seed loss occurred in the header, while there was low rate of not-harvested fruits. The cleaning shoe was very effective, and the seed loss was negligible in that step of the process. The overall harvest efficiency was 88.8 % in 2023 and 83.5 % in 2024. The harvested product had from 91.9 % to 92.2 % of normal castor seeds. Along the day, the rate of broken seeds was the lowest around noon. The resistance to break of castor fruit peduncle was related to the relative air humidity.

Ethics disclaim

The authors declare that they received no funding or financial

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CRediT authorship contribution statement

Carlos J. Silva: Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Matheus de Oliveira:** Investigation, Data curation. **Liv S. Severino:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Liv S. Severino reports financial support was provided by Terasol Oleos Vegetais. The authors received no financial support from the companies that developed the equipment evaluated in this study. Liv S. Severino had the role of Associate Editor on this journal, but the assignment was terminated one year before the submission of the manuscript. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2025.121787.

Data availability

The research data is available as supplementary file.

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