

Article

Fruits Traits of Carob (*Ceratonia siliqua* L.) Influence Their Detachment Force: A First Step Towards Semi-Mechanical Harvesting

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Abstract

The carob tree (*Ceratonia siliqua* L.) is a typical tree of the arid Mediterranean, and its cultivation contributes to the sustainability of local agroecosystems. In recent years, the economic and environmental importance of the carob tree has grown due to its use as a raw material in the food, pharmaceutical, and cosmetic industries. It also plays an ecological role in conserving biodiversity and promoting sustainable agricultural systems by improving cultivation and mechanization strategies. Currently, national carob groves are facing competition from other more profitable crops such as olive, citrus, almond and horticultural systems. This has led to the marginalization of carob cultivation in several Mediterranean rural areas and increased the need to modernize and mechanize harvesting to enhance the potential of carob and its derived products. This study aimed to investigate the physical characteristics of the fruit (weight, length, width and fruit detachment force) in relation to the degree of ripeness, with the objective of providing useful information on the optimal harvesting period and introducing semi-mechanical harvesting systems.

Keywords: *Ceratonia siliqua* L.; harvesting method; sustainable mechanization; physical variables; size; statistical processing



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1. Introduction

The carob tree (*Ceratonia siliqua* L.) is believed to have originated in the eastern Mediterranean and the Middle East [1]. It has since spread throughout the Mediterranean basin via multiple domestication and diffusion events, resulting in the differentiation of the current genotypes in the western Mediterranean. The carob tree plays an important role in the Mediterranean vegetation due to its environmental, agricultural and economic significance [2–5]. Its ecological resilience and tolerance to variable environmental and weather factors (such as irregular temperatures and precipitations, drought, arid and rocky soils, and the impact of human activity) make the carob tree a strategically important species with high ecological value. The presence of carob helps to combat soil erosion and

promote sustainable agriculture, biodiversity conservation and ecosystem stability. The species has a potential role in agroforestry planning and regenerative agriculture strategies aimed at restoring degraded land in marginal mediterranean environments [1,6–8]. Carob cultivation is mainly concentrated in Mediterranean countries such as Spain, Portugal, Morocco, Italy, and Turkey, which together account for over 84% of the total cultivated carob area worldwide and have a global annual production of 100,000 tonnes [9–11]. Despite carob's wide geographical distribution, its productivity varies considerably among producing countries due to differences in orchard management, varietal selection, soil conditions, and mechanization levels. Although carob cultivation has relatively low agronomic requirements compared with other fruit tree species, improvements in cultivation practices and resource management are still needed to increase productivity and sustainability. This is particularly important considering the growing demand for carob-derived products in the food, feed, biofuel, pharmaceutical, and cosmetic sectors [12]. The presence of minerals, proteins, lipids, phenols, flavonoids, vitamins, carbohydrates and polyphenols makes pods and seeds extremely valuable for market application [2,12–16].

Fully mature carob pods, which are composed of approximately 90% pulp pericarp and mesocarp, and 10% seeds, are characterized by low moisture content and a pulp-rich structure. This influences the efficiency of harvesting and post-harvest processing, as well as mechanical separation technologies [12]. The reduction in cultivated areas is primarily due to low levels of mechanization levels, high labor requirements, and the conversion of traditional orchards into more profitable intensive crops [16,17]. The annual yield of carob pods depends on the variety, climatic conditions and farming systems used. Understanding how environmental factors interact and influence phenological development could provide useful insights into management strategies for stabilizing yield without affecting production cycle regularity [2,15,18–20]. The valorization of carob groves requires the adoption of sustainable agricultural practices from soil management to canopy evaluation. To this end, morpho-physiological studies must be conducted, and innovative technologies for mechanizing harvesting and post-harvest management, such as conservation and transformation systems, must be investigated [21]. The carob harvesting process is often characterized by some malpractices related to seasonality, such as early harvesting followed by inadequate storage methods [22]. In manual harvesting, workers usually estimate the ripeness stage by evaluating the hardness of the pods, the presence of brown spots (partial browning) and the rate of complete browning, but the exact timing remains challenging. Ideally, pods should be collected when they are fully mature, which is indicated by uniform darkening of the pod and pedicel (the pedicel turning brown, just prior to abscission), and by reduced internal moisture (12–18%). Harvesting too early results in lower sugar content and poorer quality, while harvesting too late increases the risk of losses due to molds or pests. Therefore, defining objective maturity indices is essential to identify quality standards and optimize operational phases to improve harvesting accuracy. In Sicily, for instance, harvesting usually occurs from late August to early September, when the pods exhibit an intense reddish-brown hue and are considered ripe. A common method of harvesting carob pods, particularly in orchards where full mechanization is impractical, is to use poles or rods to shake the branches so that the pods fall onto nets or cloths laid beneath the trees. Although data on harvest time per tree (minutes per tree) using poles and netting are scarce, professionals report that harvesting is very laborious and requires labor time and costs that represent 30–35% of the total production cost [23,24]. In general, mechanized harvesting would reduce time and costs, as well as improve work safety, but its success depends on the cultivation system, the machinery, and the characteristics of the orchard [25]. Moreover, the size and shape of the harvested product are strongly linked to the technology adopted. Some studies have

in fact highlighted the correlation between the fruit detachment force and the efficiency of mechanical harvesting [26–31]. Others emphasized how information about machine performance can improve their design and help develop new harvesting technology [32,33], as well as how the characteristics of the fruit itself can influence the process based on different operating parameters [34–38]. The transition from a manual to mechanical or semi-mechanical harvesting of carob pods will reduce the risks for the operators and will improve the profitability of carob cultivation. As with other supply chains studied by CREA, technological development in specific cultivation phases, such as for energy crops, can be achieved through radical innovations [36,37] or by adapting solutions that are already on the market for other purposes [38]. As studies investigating the influence of the physical properties of the carob pods are lacking, this study aimed to examine the relationship between the ripening stage of the pods, their biometric characteristics, and fruit detachment force (FDF) in carob fruits, in order to provide preliminary information that could be useful for developing sustainable semi-mechanical harvesting systems.

2. Materials and Methods

2.1. Characterization of the Carob Orchard

The first part of this study concerned the characterization of carob fruits, their position in the canopy and the force required to detach them. The fruits analyzed in this study were collected from trees belonging to the ‘Latinissima’ cultivar, which is among the most widely traditional carob varieties cultivated in Sicily. The survey was carried out in August 2024. The carob orchard was located in Noto (SR), Sicily, (37°02′36.1″ N, 15°02′46.2″ E). The planting spacing was 10 × 10 m, with a globe training system (Figure 1a). The orchard was managed under traditional practices and climatic conditions of Sicily. The 11-year-old plants were 4–6 m high, with a crown width varying between 5 and 7 m.



Figure 1. Example of carob manual harvesting (a); carob silques collected after harvesting, ready for storage and transport (b); complete ripeness (CR) stage (c).

Three stages of fruit ripening were selected:

1. Green (GR), green peduncle and pod or partially browned pod;
2. Medium ripeness (MR), peduncle and pods with 50% of brown coloration;
3. Complete ripeness (CR), peduncle and pods fully and uniformly brown.

Six different trees were randomly selected, and 4–5 fruits were collected from each tree at each ripening stage. A total of 91 fruits were analyzed, comprising 24 fruits at the green ripening stage (GR), 35 at the mature ripening stage (MR), and 32 at the fully ripe stage (CR). Although the number of fruits and trees sampled was relative to the specific site of the case

study, the study conducted was conceived as an initial exploratory evaluation. The aim was to provide a preliminary quantitative assessment of the detachment strength of carob pod in relation to their ripening stage in traditional Mediterranean orchard conditions. These conditions were representative of many realistic carob-growing areas in Sicily. The fruit detachment force (FDF) of each fruit was measured using a digital hand dynamometer (SAUTER model FK 100, KERN & SOHN GmbH, Balingen, Germany) with a measuring range of 100 N and a division of 0.05 N. When measuring the FDF, care was taken to avoid torsional or lateral stresses to minimize the potential influence of external factors, which could have altered the results. Finally, the fruits were characterized by length, width, thickness, and volume once they had been collected (Figure 1b,c). The weight of each fruit was determined using a Mettler-Toledo balance (mod. PB 1502-S, Mettler-Toledo, Columbus, OH, USA). All dimensional measurements were performed immediately after sampling to minimize potential variations due to post-harvest moisture loss or tissue dehydration, which could influence morphometric accuracy.

2.2. Statistical Analysis

The data were checked for normality using the Shapiro–Wilk test, after which they were analyzed using one-way analysis of variance with the PAST software [39] (version 3.22, <https://www.nhm.uio.no/english/research/resources/past/>, accessed on 9 November 2025).

Significantly different means were separated using Tukey’s HSD test. For data that deviated from normality, the Kruskal–Wallis test for non-parametric ANOVA and Dunn’s test for mean separation were used. A correlation analysis was performed in PAST to determine the Pearson’s r coefficient for each degree of ripeness. The comparisons analyzed were:

- The correlation between fruit weight (FW) and fruit length, width, thickness, and volume;
- The correlation between fruit detachment force (FDF) and fruit biometric parameters, including weight, length, width, thickness, and volume.

Principal component analysis (PCA) [40] was performed using the same software to analyze the separation of the ripeness stages considering the dimensional traits of pods and the FDF.

2.3. Modeling

A K-Nearest Neighbors (KNN) regression model was implemented to predict the force required for carob pod detachment using a set of morphological features. The dataset included input variables such as ripening stage, weight, length, width, and thickness, with “force” as the target variable. The ripening stage was included in the model as the categorical variable “Maturation” was based on the visual classification of pod maturity into three stages: green ripeness (GR), medium ripeness (MR), and complete ripeness (CR), according to pod color and external appearance. The categorical variable “Maturation” was encoded using a Label Encoder, while all features and the target variable were normalized using Min-Max scaling to ensure comparability, improve model performance and enhance algorithm stability in predictions. All modeling and analysis steps were carried out in Python (version 3.11.13). Given the relatively small dataset and the need for exhaustive testing, a Leave-P-Out cross-validation strategy with $p = 2$ was employed to rigorously evaluate the model. For each split, the model was trained using five nearest neighbors with distance-based weighting and Euclidean distance as the metric. Predictions were scaled back to the original range using the inverse transform of the target scaler. Model performance was assessed using Root Mean Square Error (RMSE) and the coefficient of determination (R^2) metrics. A permutation-based feature importance analysis was

performed to evaluate the relative contribution of each predictor to the model's output. This analysis used 10 random shuffles per feature and parallel computation to enhance the efficiency and performance of the KNN regression model. The importance of each feature was estimated by randomly permuting the values of one variable at a time and measuring the corresponding decrease in model performance (R^2). Variables causing a greater reduction in predictive accuracy were considered to be more influential for the model.

3. Results

3.1. Fruit Characterization

In general, the values of fruit traits declined progressively as the ripening process progressed (Table 1). Notably, fruit weight decreased from 24.8 g in GR fruits to 18.9 g in CR fruits, and fruit length decreased from 150.3 mm to 133.5 mm. The difference between the GR/MR and the CR stages was always significant, except for fruit width and specific weight. Therefore, as the fruit completed its ripening, it lost weight, reducing its volume and size. This led to a significant reduction in FDF (Figure 2). Considering the ratio of FDF to fruit weight (Figure 3), this value decreased significantly as the fruit ripened ($r = -0.804$, $p < 0.0001$). Such behavior suggests that the loss of moisture and the process of tissue senescence are closely associated with a decrease in mechanical resistance at the peduncle–branch interface. When the fruit was still green, the pod adhesion was very high, thus requiring the highest detachment force. At the CR stage, the adhesion was very weak, and the detachment force was close to zero, indicating the lowest level of resistance. Although the average FDF values at the CR stage were generally low, a residual variability among fruits was still observed. In some cases, pods with higher weight and volume showed slightly higher detachment resistance, suggesting that biometric traits may still influence the residual detachment behavior even at complete ripeness.

Table 1. Mean values of the fruit traits measured at each ripening stage analyzed. For each row, values with different letters differ according to Tukey's HSD test at $p \leq 0.01$ (uppercase letter).

Trait	Stage *		
	GR	MR	CR
Fruit weight (g)	24.8 ^A	23.4 ^A	18.9 ^B
Fruit length (mm)	150.3 ^A	145.5 ^A	133.5 ^B
Fruit width (mm)	23.8	28.9	23.0
Fruit thickness (mm) **	10.2 ^A	9.9 ^A	8.9 ^B
Volume (cm ³)	36.52 ^A	41.91 ^A	27.57 ^B
Specific weight (g cm ^{−3})	0.69	0.67	0.70

* GR, green fruit; MR, medium ripeness; CR, complete ripeness. ** Significant difference after analysis with Kruskal–Wallis test for non-parametric data and Dunn's test (HSD) for $p < 0.01$ for the separation of means.

PCA analysis showed how the ripeness stages could be separated based on the morphological and physiological traits of fruit (Figure 4). The first two PCA components explained 69.6% of the observed variability, thus providing a good description of the differences among the ripening stages. The spatial distribution of the data reflects the progressive transition towards mechanical fragility in response to complete ripening conditions. Data relating to the GR stage were positively associated with detachment force, fruit weight, fruit length, and the FDF/FW ratio. At the MR stage, the observations showed a higher dispersion in relation to the fruit characteristics, which were distributed along both components. Finally, the CR area was shifted towards the opposite quadrant with respect to the dimensional variables. This separation confirms that the stage of fruit ripening strongly influences both biometric characteristics and mechanical detachment behavior.

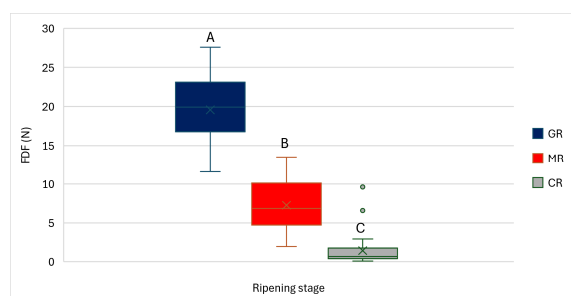


Figure 2. Mean of the fruit detachment force (N) at different ripening stage. Different letters above the boxes indicate significant differences after analysis with Kruskal–Wallis test for non-parametric data and Dunn’s test (HSD) for $p < 0.01$ for the separation of means. The bars of each box indicate the minimum and maximum values, while the x represents the average value.

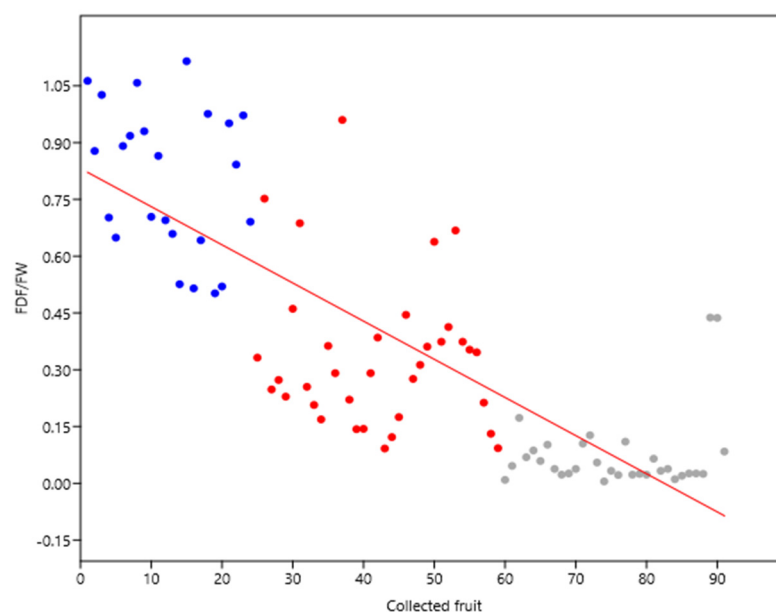


Figure 3. Trend of FDF/FW ratio per each collected fruit at each ripening stages analyzed (blue, GR; red, MR; grey, CR). The red line shows the linear regression fitted to the data.

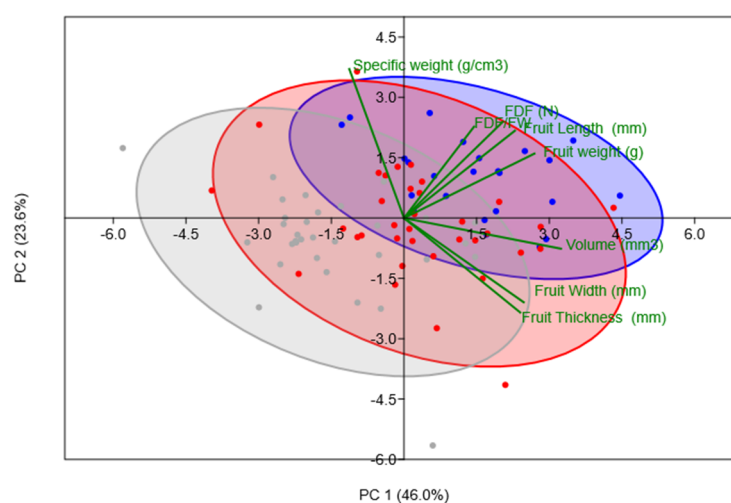


Figure 4. Biplot showing the separation of the three ripening stages analyzed (GR, MR and CR) considering the dimensional characteristics and detachment force (CR, grey points/polygon, MR, orange points/polygon, GR, blue points/polygon).

Fruit weight showed a significant correlation with pod morphology (Table 2). The strongest correlations with fruit weight were observed for volume and fruit. Excluding thickness, the correlation coefficient was always significant for pod length, width, and volume at each ripening stage, with r coefficient ranging from 0.73 to 0.88 for length and volume. However, the relationship between pod dimensions and detachment force was weaker (Table 3). At the level of a single ripening stage, the only significant coefficient observed was that between detachment force and pod volume at the GR stage ($r = 0.41$, $p = 0.046$, $n = 24$). Considering the entire dataset, all the variables (excluding width) were correlated with detachment force, with correlation coefficients ranging from 0.30 for thickness to 0.40 for volume.

Table 2. Correlation analysis (Pearson's r coefficient) between the fruit weight (FW) and the morphological variables of the pod (length, width, thickness, and volume). The coefficient was calculated for each ripening stage and confounding all the stages. The asterisk indicates a significative correlation for $p < 0.05$.

	Length (mm)	Width (mm)	Thickness (mm)	Volume (cm ³)
FW-GR ^a	0.77 *	0.62 *	0.24	0.77 *
FW-MR	0.88 *	0.44 *	0.30	0.73 *
FW-CR	0.77 *	0.51 *	0.20	0.76 *
FW	0.85 *	0.51 *	0.36 *	0.79 *

^a GR, green fruit; MR, medium ripeness; CR, complete ripeness.

Table 3. Correlation analysis (Pearson's r coefficient) between the fruit detachment force (FDF) and the morphological variables of the pod (length, width, thickness, and volume). The coefficient was calculated for each ripening stage and confounding all the stages. The asterisk indicates a significative correlation for $p < 0.05$.

	Fruit Weight (g)	Length (mm)	Width (mm)	Thickness (mm)	Volume (cm ³)
FDF-GR ^a	0.28	0.15	0.33	0.35	0.41 *
FDF-MR	−0.04	0.15	−0.24	−0.29	−0.11
FDF-CR	0.21	0.32	0.16	0.08	0.30
FDF	0.39 *	0.37 *	0.13	0.30 *	0.40 *

^a GR, green fruit; MR, medium ripeness; CR, complete ripeness.

3.2. Modeling Results

Since ripening stage and biometric variables showed significant relationships with fruit detachment force, a predictive modeling approach was applied to evaluate their combined contribution to FDF estimation. The performance of the K-Nearest Neighbors (KNN) regression model evaluated using Leave-P-Out cross-validation ($p = 2$) yielded a Root Mean Square Error (RMSE) of 0.4094 and a coefficient of determination (R^2) of 0.7448. This indicated a good predictive capability, with approximately 74.5% of the variance in the target variable explained by the model (Figure 5). Among the predictors, the ripening stage showed the highest importance score, confirming its significant influence on FDF variability. Therefore, the relatively high R^2 value further supports the robustness of the predictive framework, despite the intrinsic biological variability of the sampled fruits. The scatter plot of observed versus predicted values showed a strong linear correspondence, as confirmed by Pearson correlation analysis between observed and predicted FDF values ($r = 0.863$, $p < 0.001$), although some dispersion was present at intermediate force. This suggests minor underfitting or variance not captured by the input features. Permutation-based trait importance analysis revealed that the ripeness was the dominant predictor,

contributing the most to model performance. In contrast, the morphological descriptors such as weight, length, width, and thickness exhibited a comparably lower score (Figure 6). The high importance score associated with the ripening stage confirmed that the level of pod maturity represents the main factor influencing FDF variability compared with the analyzed biometric variables. However, the residual variability observed within the CR stage suggests that simplified operational models based exclusively on ripening stage may not fully capture the heterogeneity of fruit detachment behavior under field conditions. This modeling result highlights the important role of physiological ripeness compared to purely physical characteristics in determining the force required for carob pod opening.

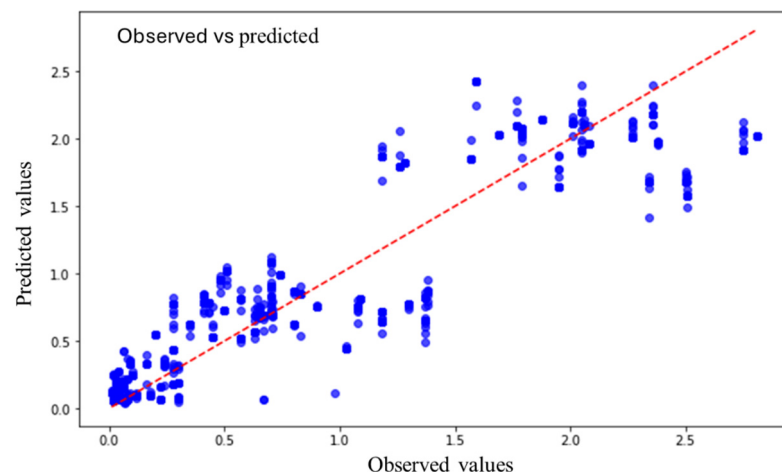


Figure 5. Observed vs. predicted fruit detachment force (FDF) values obtained from the KNN regression model. Blue dots represent individual observations, while the red dashed line represents the 1:1 reference line, indicating perfect agreement between observed and predicted values.

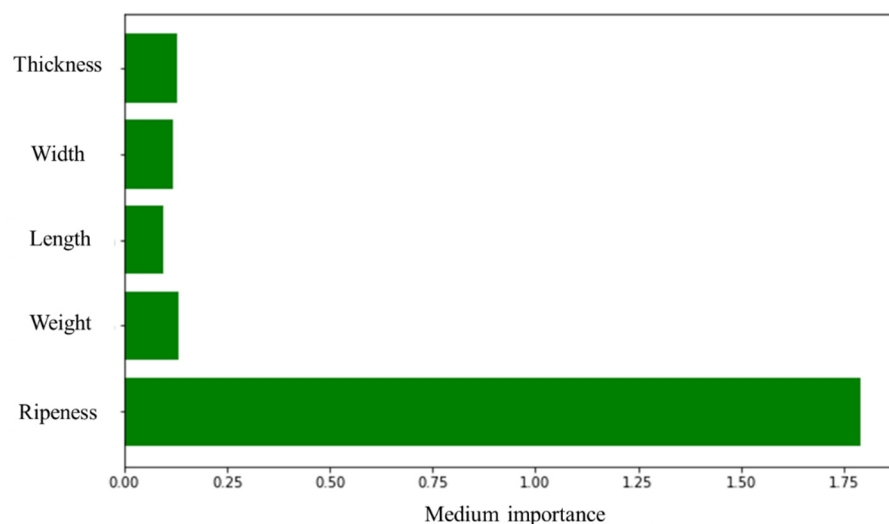


Figure 6. Permutation-based feature importance analysis showing the contribution of ripening stage and fruit biometric traits to the predictive performance of the KNN regression model.

4. Discussion

The study revealed that a decrease in carob pod weight corresponds to a reduction in the fruit detachment force (FDF) at complete ripeness. This progressive reduction may be related to the physiological and structural changes that occur during fruit ripening. These changes include the weakening of the peduncle tissues due to moisture losses and the degradation of cell wall components. Therefore, ripe fruits become more susceptible to

detachment from the plant. Similar trends have also been observed in almond, pistachio, and olive crops, where harvesting efficiency was strongly influenced by fruit size and mechanical properties. The range of fruit detachment forces was approximately 12–10 N for green almonds; 10–40 N for pistachios depending on the harvesting technique and phenological stage [32,41]; and 14.5–11.5 N for jatropha [42]; and could reach 6–10 N for olives at commercial maturity [28,43,44]. However, unlike olives and almonds, carob pods have a leathery pericarp structure that appears to be less susceptible to surface damage during impact. This could facilitate ground-based collection systems. The carob pods analyzed in the present study showed high FDF values during the green ripening phase (19.6 N), when pod mass and volume were the highest. However, at full ripening, these levels were significantly reduced (1.4 N), thereby facilitating abscission. Unlike pistachios, olives, and, even more markedly, almonds, this behavior suggests that the efficiency of carob harvesting depends strongly on accurately identifying the optimal ripening stage, when the progressive weakening of the peduncle–fruit interface maximizes abscission.

As shown in Table 3, the relationship between pod morphology and detachment force was always not significant at any ripening stage, except for pod volume at the GR stage. From a technological point of view, this implies that harvesting systems do not necessarily have to adapt to variability in fruit size; rather, they must adapt to the time window during which the mechanical strength of fruit attachment is minimized. Therefore, the different stages of development and ripening must be considered for their direct impact on detachment efficiency and overall crop performance. In olive harvesting, the FDF/FW ratio has been shown to be linearly related to crop yield. Lower ratios were associated with high efficiency (>85%) when trunk agitators were used, thus highlighting the importance of ripening-related changes in resistance [43]. These findings suggest that the FDF/FW ratio could serve as a valuable mechanical indicator for determining the optimal harvesting time, particularly in systems that use mechanical shaking devices. In other species, such as cashews, FDF has been shown to vary significantly between developmental stages and cultivars, indicating reduced detachment resistance at later ripening stages [45]. Furthermore, early work on olive cultivars found a positive correlation between fruit size and detachment force. This demonstrated that larger fruits with thicker peduncles resist detachment more strongly. This must be considered when designing and programming mechanized harvesting [46].

Information on fruit morphology and ripening can contribute to favoring the transition from manual to semi-mechanical harvesting. As a species that is not widely cultivated, carob could benefit from a more detailed characterization of the phenological phases, with the aim of narrowing the harvesting period, reducing the mechanical effort required and increasing profitability. Currently, carob harvesting is performed exclusively by hand, using shaking and subsequent collection of the fallen fruits, like other fruit harvesting (olive, apricots, etc.). Boussioud et al. [47] indicate that several harvesters use browning as an indicator of pod ripeness prior to harvesting. This indication is consistent with the results of the present study, in which the lowest FDF was observed at the latest ripening stage. Additionally, from an operational point of view, integrating visual maturity indicators with biometric thresholds could help to calibrate harvesting machinery. For example, fully mature pods that are brown in color have a lower fruit weight, and reduced FDF values may be more suitable targets for semi-mechanical harvesting operations. A step forward will be the transition from subjective visual observation to objective, sensor-based diagnostics of the ripening stage. An increasing number of studies are exploring the use of automatic image analysis for fruit classification to improve the rapid identification of the degree of ripeness [48].

Previous studies on citrus, olives and jatropha have shown that the efficiency of mechanized or semi-mechanized harvesting depends heavily on optimizing the frequency, amplitude, acceleration and exposure time of vibrations in relation to the characteristics of fruit attachment and canopy architecture [43,49–52]. All of these studies emphasized the need for further research into canopy–machine interaction and susceptibility to bark damage, as well as the mechanical response of branches. Traditional carob orchards generally have low and irregular tree densities, which reduces the efficiency of mechanized operations. The dense canopy architecture and irregular branching pattern, as well as the presence of low scaffolding branches, represent additional structural constraints that may limit the applicability of trunk-shaking systems commonly used in olive or almond groves. Examples of such machinery include vibration-based harvesters, robotic platforms equipped with articulated vibrating arms, and shakers with collection nets that are specifically engineered to conform to the geometry of trunks and branches [35,49,50,53]. Given the low values of the detachment force recorded for carob at full ripeness, excessive vibration intensity could be unnecessary and potentially harmful to the structure of the tree. The relatively low mechanical strength of mature carob pods further suggests that canopy-directed vibration systems or branch agitators with adjustable frequency ranges could be a viable technical solution in traditional orchards with irregular spacing. These shaking systems can be coupled with conveyors that move the fruits directly into dedicated containers or trailers. This type of mechanization reduces structural damage to trees and minimizes fruit loss to the ground, while containing the dispersion of dust and particulate matter. The shaking systems can be integrated with tractors equipped with specialized implements, such as rollers, rotating brushes and suction units, to further enhance the overall performance and sustainability of the harvesting process [54–56]. Identifying the optimal ripeness stage for carob harvesting enables intervention at the point of maximum detachment efficiency, thereby reducing the required force. Furthermore, integrating structural pruning and canopy shaping are essential orchard management and maintenance practices that facilitate mechanical access while preserving tree health and long-term productivity.

5. Conclusions

Although the results are limited to the experimental conditions of the analyzed carob orchard in southern Italy, to the best of our knowledge, this study provides the first quantitative indications of the magnitude of the forces involved in carob pod detachment. The main result suggests that full ripeness is the optimal stage for mechanical or semi-mechanical harvesting, since a reduction in pod weight corresponds to a lower fruit detachment force. Since pod volume was moderately correlated with detachment force, morphological traits that influence fruit volume may also affect detachment dynamics. Narrowing the harvesting window reduces the uncertainty associated with an excessively long collection period. Although traditional manual harvesting remains important, particularly in marginal or structurally complex orchards, the results support a gradual transition towards mechanical or semi-mechanical systems. Further studies should consider factors such as carob cultivars, tree ages, and planting densities, in order to improve, validate, and extend the applicability of predictive models. Additionally, future research should focus on generating precise empirical data on working time per tree or per kilogram of harvested pods, to evaluate operational efficiency and economic viability in various orchard configurations and environmental conditions.

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