Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 11, 967-985
2025
Publisher: Learning Gate
DOI: 10.55214/2576-8484.v9i11.11047

Optimizing pomegranate harvest via maturity detection and mechanized settings to improve quality and reduce losses

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Abstract: Pomegranate, *Punica granatum* L., undergoes significant physiological and structural changes during maturation, reflected in its color, total soluble solids, and stem strength. Identifying the optimal maturity stage is essential to maintain fruit quality and minimize postharvest losses. This study evaluated key maturity indices under varying neck moisture levels and developed a low-cost harvesting machine based on those indices. Laboratory tests were performed at 22%, 26%, 36%, and 46% neck moisture to measure shear force, color parameters including L*, a*, b*, chroma, and hue angle, and total soluble solids. The optimal maturity stage was found at 26% moisture, where color development and soluble solids were highest. Field experiments assessed the machine's performance at four disc speeds ranging from 1100 to 1320 rpm and tilt angles of 0°, 12°, 21°, and 32°. The best results were achieved at 1250 rpm and a 21° tilt, yielding 2520 fruits per hour, 1.71% fruit damage, 0.020 kWh/Mg specific energy, and a harvesting cost of 6.86 US$/Mg criterion cost. The developed harvester provides a simple and efficient solution for selective pomegranate harvesting, particularly for small to mid-sized farms.

Keywords: *Color analysis, Fruit quality, Harvesting efficiency, Pomegranate maturity, Selective harvesting, Total soluble solids.*

1. Introduction

Pomegranate (Punica granatum L.) is a commercially valuable fruit crop cultivated in arid and semi-arid regions due to its adaptability, high nutritional content, and therapeutic potential. It is rich in bioactive compounds such as ellagic acid, anthocyanins, punicalagin, flavonoids, and tannins, which contribute to its strong antioxidant and anti-inflammatory properties. As consumer demand for functional foods continues to rise, pomegranate production has expanded significantly, not only for fresh consumption but also for processing into juices, extracts, and nutraceuticals [1, 2].

Achieving optimal postharvest quality and storability requires that pomegranate fruit be harvested at the correct stage of maturity. Although peel color is commonly used by growers as an external indicator, it does not always correlate with internal quality parameters such as total soluble solids (TSS), acidity, or aril development. More reliable harvest criteria include a combination of colorimetric parameters (L*, a*, b*, chroma, and hue angle), shear force, and neck moisture content, which provide a more comprehensive assessment of fruit maturity [3-5].

In many pomegranate-producing regions, including Egypt, harvesting is still performed manually using scissors or by hand. This traditional approach is labor-intensive, time-consuming, and prone to inconsistent results. Manual harvesting often causes mechanical injuries such as bruising or cracking, which reduce market value and accelerate postharvest deterioration. Moreover, rising labor costs and seasonal labor shortages further highlight the need for selective and affordable mechanical harvesting alternatives suitable for small and medium-scale farms.

Previous attempts to mechanize fruit harvesting have focused mainly on mango, citrus, and stone fruits. Gambella et al. [6] developed mechanical aids, including disc cutters and electric scissors for

History: Received: 16 September 2025; Revised: 21 October 2025; Accepted: 24 October 2025; Published: 17 November 2025
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mango harvesting, reporting variable injury rates depending on the tool type. Torregrosa et al. [7] and Zhou et al. [8] demonstrated that modifying the catching surface tilt angle and disc speed significantly influenced bruising and energy efficiency in cherry and citrus harvesting systems. El-Termezy et al. [9] designed a toothed-disc harvester for pomegranate but did not incorporate physiological maturity indices or optimize machine settings for quality retention. More recently, AL-Gezawe [10] integrated basic sensors into a citrus harvesting tool, yet it was not adaptable to the pomegranate's structure and maturity stages.

Although previous studies have contributed to fruit harvesting mechanization, most have not incorporated physiological maturity indicators such as neck moisture content, color kinetics, or internal sugar levels. Additionally, existing devices are often energy-intensive, cause significant fruit damage, or are too complex and expensive for use in small and medium-sized orchards.

This study presents a novel pomegranate harvesting machine that integrates validated maturity indices to improve harvest accuracy. Targeting fruit at the optimal stage (26% neck moisture), the machine was tested under various disc speeds and tilt angles to optimize performance. Built from low-cost, commercially available components, the system offers a scalable and efficient solution that minimizes fruit injury, reduces energy use, and improves economic feasibility for growers.

2. Materials and Methods

All experiments were conducted at a private orchard affiliated with the El Basatin Agricultural Association, located in Abu Shalabi village, Faqous district, in Sharkia Governorate, northeastern Egypt (30.7328° N, 31.8031° E). This region is characterized by a semi-arid Mediterranean climate, fertile alluvial soils, and abundant agricultural activity, making it well-suited for fruit cultivation, including pomegranates.

The study was conducted over two growing seasons from 2022 to 2023. The experimental protocol was designed to evaluate variations in fruit maturity indices across different developmental stages to determine the optimal harvest time for peak fruit quality. Mechanical harvesting trials were subsequently carried out between October 1 and 30, 2023, corresponding to 90 to 120 days after full flowering, using the fabricated pomegranate harvesting machine under field conditions typical of the region.

2.1. Materials

2.1.1. Pomegranate Trees

The study was conducted on two commercially important cultivars of pomegranate (*Punica granatum* L.): *Wonderful* and *Manfaluti*. These varieties are widely cultivated in Egypt due to their high yield potential and consumer appeal. *Wonderful* is preferred for its consistent size, color, and sweetness, while *Manfaluti* is prized for its vivid red peel and juice quality.

The experimental orchard was arranged with a tree spacing of 3 meters within rows and 4 meters between rows, with an average yield of 150–200 fruits per tree. To assess their mechanical harvestability, representative fruit samples (n = 20) from each cultivar were analyzed for key physical and mechanical properties. These include dimensions, mass, density, peel firmness, and neck shear force parameters that directly influence machine-tool interaction, grip stability, and cutting efficiency.

Table 1 summarizes the physical and mechanical properties of *Wonderful* and *Manfaluti* pomegranates used in this study. As shown, the two cultivars exhibited similar average sizes and mass, with slight variations in peel firmness and neck shear force, which are critical for minimizing fruit damage during mechanical harvesting.

Table 1.
Physical and mechanical properties of Wonderful and Manfaluti pomegranate fruits (n = 20)

Property	**Unit**	**Wonderful (Mean ± SD)**	**Manfaluti (Mean ± SD)**
Fruit height	mm	79.20 ± 8.52	78.26 ± 7.10
Fruit width	mm	85.82 ± 7.98	84.09 ± 7.12
Fruit diameter	mm	86.93 ± 7.98	85.12 ± 7.04
Geometric diameter	mm	141.54	138.03
Fruit mass	g	380.26 ± 27.60	367.71 ± 22.92
Volume	mm^3	1,364,109 ± 411,077	1,284,492 ± 331,595
Surface area	mm^2	104,019 ± 19,535	99,785 ± 16,572
Sphericity	%	90.35 ± 1.90	89.60 ± 1.70
Fruit density	g/cm^3	1.12 ± 0.04	1.10 ± 0.03
Peel thickness	mm	3.2 ± 0.5	3.0 ± 0.4
Peel firmness	N	9.8 ± 1.2	8.7 ± 1.1
Moisture content	% (w.b.)	78.5 ± 2.1	80.1 ± 1.9
Neck diameter	mm	13.5 ± 1.0	12.8 ± 0.9

2.1.2. Description of Pomegranate Harvesting Machine

A lightweight, low-cost mechanical harvesting machine was developed using locally available materials to address challenges related to manual harvesting and the high energy and cost demands of imported systems. The machine was fabricated in a private agricultural engineering workshop in Sharkia Governorate, Egypt. It was designed specifically to access pomegranates located in high canopy regions, reduce fruit damage, and optimize the stem-cutting process through improved ergonomics and mechanical precision. A schematic of the machine and its core components is presented in Figure 1.

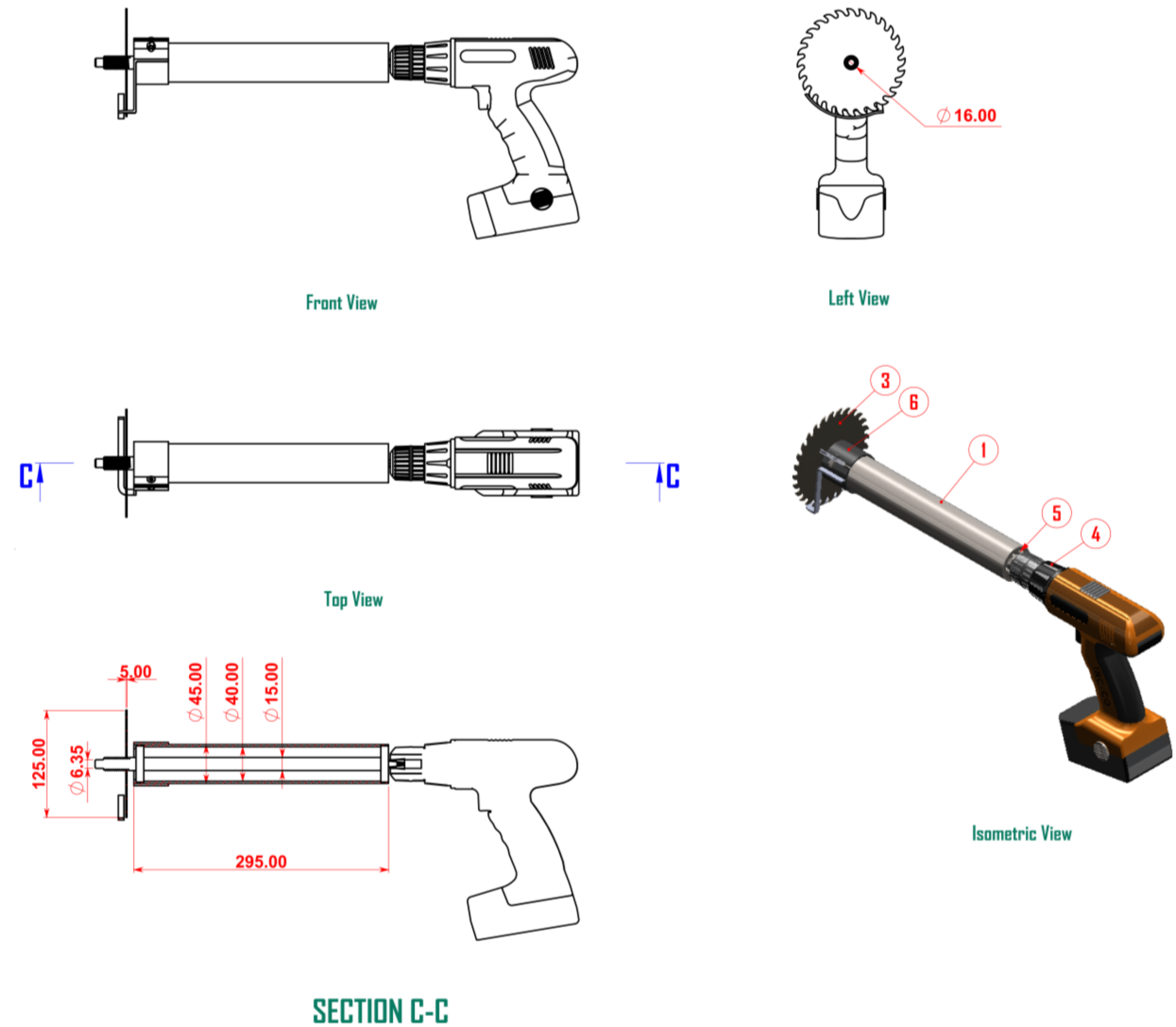

Figure 1.
Schematic diagram of the fabricated pomegranate harvesting machine showing the major components: (1) tube, (2) shaft, (3) disc, (4) drill, and (6) bush. All dimensions are in mm.

2.1.2.1. Cutting Assembly

The primary harvesting element is a toothed circular cutting disc, manufactured from alloy steel with a diameter of 125 mm and a thickness of 1 mm. The disc is mounted onto a steel shaft using a sealed ball bearing assembly, which is positioned at the upper end of the telescopic transmission shaft for stable rotation (Fig. 2). A protective metal cover shields 80% of the disc's circumference, leaving a 50 mm segment exposed to enable precise stem cutting. This design ensures safe operation while minimizing unintentional contact with nearby foliage or fruit.

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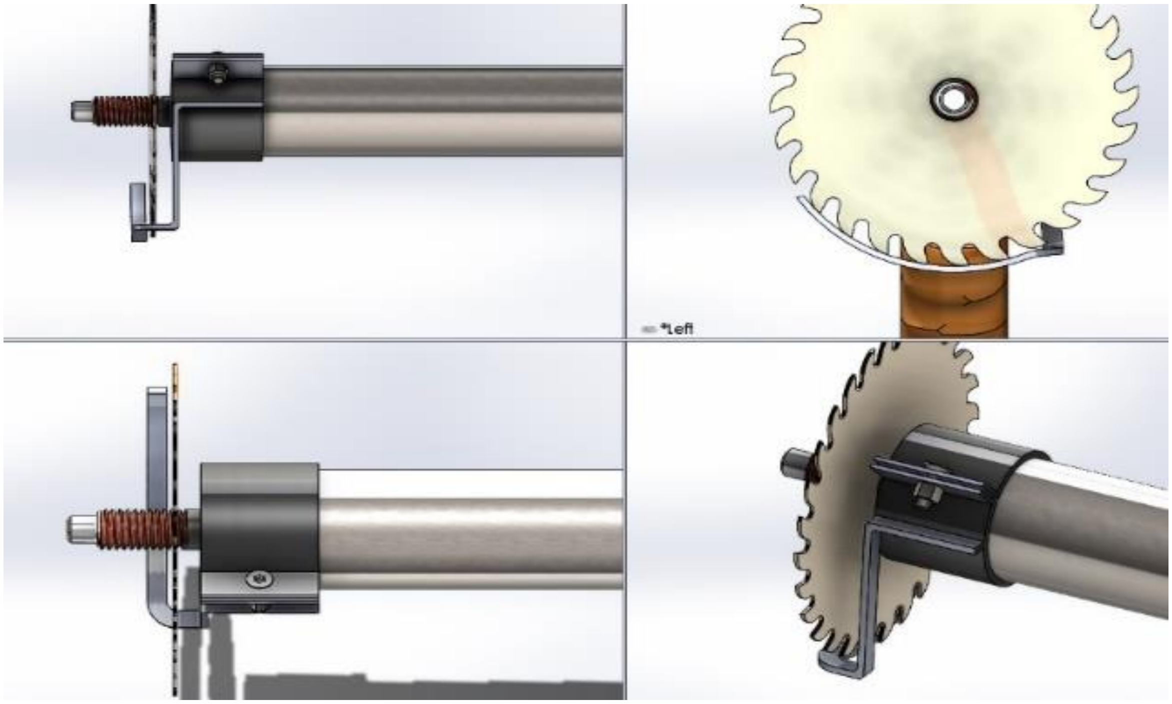

Figure. 2.
Detailed view of the alloy-steel toothed cutting disc mounted on a shaft with a protective housing.

2.1.2.2. Power Source

The machine is powered by a dry lithium-ion battery (12 V, 1.5 A), which supplies electricity to a DC motor through a waterproof connection. The battery is housed in a shoulder-suspended pouch for ease of transport and balance during operation. A fast-charging unit supports efficient recharging between field sessions. The motor operates at a nominal speed of 1500 rpm, which is reduced via gearing to an output shaft speed of 300 rpm. Under load, the system delivers a torque of 20 N·m and an output power of 18 W, sufficient to sever pomegranate stems up to 6 mm in diameter (**Figs. 3**).

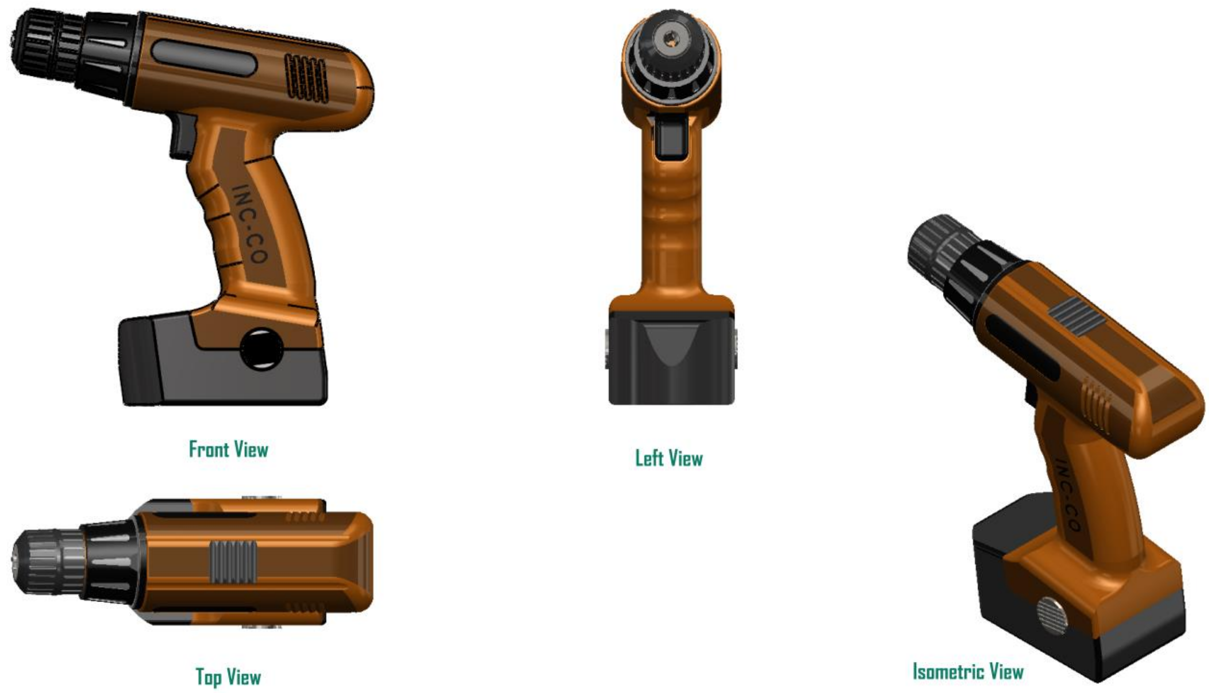

Figure 3.
Electric motor assembly delivering 20 N·m torque at 300 rpm for stem cutting in the harvesting machine.

2.1.2.3. Transmission and Electrical System

Electrical current from the battery to the motor is conducted through insulated cabling routed internally through the telescopic shaft. This enclosed configuration protects the electrical lines from mechanical wear, weather exposure, and field obstacles. The control system consists of a sealed ON/OFF switch mounted near the operator's handle, enabling safe and convenient activation of the cutting disc.

2.2. Methods

Two sequential experiments, laboratory and field-based, were designed to identify the optimal maturity stage of pomegranate fruit based on quality indices and to evaluate the performance of the fabricated harvesting machine under varying operational conditions.

2.2.1. Laboratory Experiment

2.2.1.1. Experimental Setup

The laboratory study was conducted during 2022–2023 using two widely cultivated pomegranate varieties: 'Wonderful' (*P. granatum* cv. *Wonderful*) and 'Manfaluti' (*P. granatum* cv. *Manfaluti*). Ten fruits from each cultivar were randomly selected and categorized based on four fruit neck moisture levels 46%, 36%, 26%, and 22% to represent progressive ripening stages.

2.2.1.2. Color Kinetics Measurement

Fruit color was measured using a CR-10 color difference reader (Konica Minolta, Japan). This handheld device operates in the CIE L*ab** color space and provides on-the-spot data analysis with integrated pass/fail software. The color parameters lightness (L*), redness (a*), and yellowness (b*) were recorded. Based on these values, chroma (C*) and hue angle (H°) were calculated using Eqs (1) and (2), respectively. All color measurements were performed in the specular component included (SCI) mode under standard C-illuminant lighting with a 10° standard observer angle.

$$C^* = \sqrt{a^2 + b^2} \qquad (1)$$

$$H^o = \tan^{-1}\left(\frac{b}{a}\right) \qquad (2)$$

Where a represents the redness/greenness and b represents the yellowness/blueness of the fruit surface. Chroma (C^*) indicates color intensity, and the hue angle (H^o) reflects the dominant wavelength, providing insight into perceived fruit color.

2.2.1.3. Total Soluble Solids (TSS)

Total soluble solids were determined using a digital refractometer (Model PAL-1, Atago, Tokyo, Japan). The device calculates sugar concentration based on the refractive index of the pomegranate juice, providing Brix values at room temperature (25 ± 1 °C).

2.2.1.4. Fruit Neck Shear Force

Shear force measurements were carried out using a Shimpo Series FGE-XY digital force gauge. The device recorded the maximum force needed to sever the fruit neck, reflecting the mechanical resistance of the attachment. Each reading was replicated three times to ensure accuracy.

2.2.2. Field Experiment

2.2.2.1. Experimental Conditions

Field trials were conducted during the 2023 harvesting season using the fabricated harvesting machine on 'Wonderful' pomegranate trees. To evaluate the influence of mechanical parameters on harvesting efficiency and fruit quality, the machine was tested under four cutting disc rotational speeds: 1100, 1180, 1250, and 1320 rpm, which correspond to linear cutting speeds of 7.49, 8.03, 8.51, and 8.98 m/s, respectively. Additionally, four cutting-edge tilt angles 0°, 12°, 21°, and 32° were applied to investigate their effects on fruit detachment and damage. The specific configurations of these tilt angles during the trials are illustrated in Figure 4.

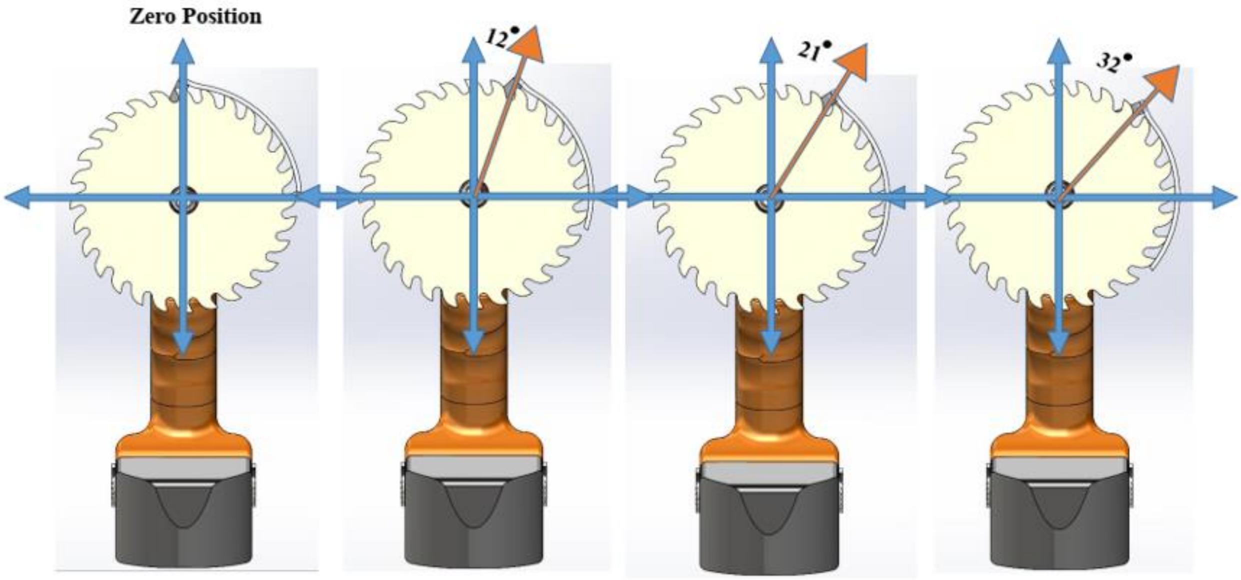

Figure 4.
Cutting-edge tilt angles are used during mechanical harvesting.

2.2.2.2. Machine Productivity

The productivity of the harvesting machine was calculated as the number of fruits collected per hour of active operation using the following formula:

$$Productivity\ (fruits/h) = \frac{N}{t} \quad (3)$$

Where N is the total number of fruits harvested, and t is the effective harvesting time in hours. This measurement reflects the machine's throughput under different operational settings and provides a basis for comparing the impact of disc speed and tilt angle on harvesting efficiency. The methodology follows the approach outlined by El-Termezy et al. [9] in evaluating harvesting systems based on field capacity and output rate.

2.2.2.3. Fruit Damage Ratio

To assess the mechanical sensitivity of the harvesting system, the fruit damage ratio was determined based on the number of visibly injured fruits resulting from cutting, impact, or bruising during the harvesting process. The approach follows the methodology described by Barth et al. [11], who evaluated bruise occurrence in mechanically harvested apples by analyzing the effects of equipment design and impact conditions.

$$Fruit\ Damage\ Ratio\ (\%) = \left(\frac{D}{T}\right) \times 100 \quad (4)$$

In this expression, D refers to the number of damaged fruits and T denotes the total number of harvested fruits per trial. This ratio provides a direct measure of the extent of physical damage imposed by the machine and is essential for optimizing operational parameters to reduce postharvest losses.

2.2.2.4. Specific Energy Consumption

Specific energy consumption was calculated to evaluate the energy efficiency of the pomegranate harvesting process. This value represents the electrical energy required to harvest one kilogram of fruit and helps determine the suitability of the machine for large-scale or energy-sensitive operations. The method applied in this study is based on the approach by Chancellor [12], who analyzed the power demands of mechanized field activities.

$$Specific\ Energy\ (kWh/kg) = \frac{P}{Q} \qquad (5)$$

In Equation (5), P is the electrical power required to operate the machine in kilowatts, and Q is the machine productivity expressed in kilograms per hour (kg/h).

The electrical power required to operate the harvesting machine (PPP) was calculated using a clamp meter to record voltage and current, applying the following formula:

$$P = \frac{V \times I \times cos\theta}{\eta} \qquad (6)$$

where V represents the potential difference (220 volts), I is the current intensity in amperes, $cos\theta$ is the power factor (assumed to be 0.84), and η is the mechanical efficiency of the system (assumed to be 95%). These values were selected based on standard electrical operating conditions for low-power agricultural machinery.

2.2.2.5. Criterion Cost

The criterion cost serves as a comprehensive metric for evaluating the economic efficiency of the manufactured pomegranate harvesting machine. It accounts for both the machine's operational cost and the economic losses resulting from damaged fruit during the harvesting process. This analysis is particularly important for small- and medium-scale farms seeking affordable and efficient harvesting solutions. The method adopted here aligns with practices recommended by Nothard et al. [13] and previously utilized in fruit harvesting cost assessments by Grisso et al. [14]

$$Criterion\ Cost\ (US\$/kg) = Operational\ Cost + Fruit\ Damage\ Cost \qquad (7)$$

In Equation (7), the criterion cost is expressed in US$/Mg of harvested fruit, summing the operational cost and the monetary value of fruit loss due to damage during harvesting. The operational cost was calculated by dividing the machine's hourly operating cost (C_h) by its productivity (Q):

$$Operational\ Cost\ (US\$/Mg) = \frac{C_h}{Q} \qquad (8)$$

Here, C_h represents the total hourly cost of operating the machine, which includes fixed costs (e.g., depreciation, interest) and variable costs (e.g., energy, maintenance). Q refers to the machine's productivity in kg/h. The cost associated with fruit damage was computed using:

$$Fruit\ Damage\ Cost\ (US\$/Mg) = \frac{M_d \times P_f}{Q} \qquad (9)$$

Where M_d is the total mass of damaged fruit in kg, and P_f is the market price per kg of fresh pomegranates. This dual-component cost analysis ensures that both operational efficiency and product quality are considered in determining optimal harvesting configurations.

2.2.3. Statistical Analysis

A completely randomized design (CRD) was used for both laboratory and field experiments to assess the effects of fruit neck moisture content, cutting disc speed, and tilt angle on quality and operational parameters. Data were analyzed using IBM SPSS Statistics (Version 26.0). One-way ANOVA was conducted to test the significance of treatment effects, and means were compared using Tukey's HSD test at a 5% significance level ($p \leq 0.05$).

3. Results and Discussion

3.1. Results of the Laboratory Experiment

This section presents findings from laboratory analyses aimed at determining the optimal harvest maturity stage for '*Wonderful*' and '*Manfaluti*' pomegranate cultivars based on color kinetics, total soluble solids (TSS), and fruit neck shear force under varying moisture contents (46%, 36%, 26%, and 22%).

3.1.1. Effect of Fruit Neck Moisture Content on Color Kinetics

Color development is one of the most recognizable external indicators of pomegranate fruit maturity. In this study, the influence of neck moisture content (46%, 36%, 26%, and 22%) on color parameters was assessed in *Wonderful* and *Manfaluti* pomegranate cultivars. The color metrics included lightness (L*), redness (a*), yellowness (b*), hue angle (H°), and chroma (C*), as shown in Table 2.

Table 2.
Changes in Color Kinetics of Pomegranate Varieties as Influenced by Neck Moisture Content.

Varieties	Fruit neck moisture content, % w.b	Color Development Degree				
		L*	a*	b*	H°	;C*
Wonderful	**46**	65.17±1.24^{a}	20.87±0.58^{d}	39.16±0.91^{a}	70.42 ± 1.07^{a}	29.22 ± 1.04^{d}
	36	49.13±1.13^{b}	29.11±0.62^{c}	31.16±0.83^{b}	66.41 ± 1.12^{ab}	31.53 ± 0.86^{c}
	26	39.30±0.96^{c}	45.23±0.78^{a}	16.67±0.55^{c}	37.03 ± 0.89^{c}	40.33 ± 1.08^{ab}
	22	29.30±0.87^{d}	34.59±0.64^{b}	14.01±0.48^{c}	21.68 ± 0.85^{d}	49.62 ± 1.15^{a}
Manfluti	**46**	56.47±1.36^{a}	20.64±0.51^{d}	33.88±0.88^{a}	42.05 ± 1.14^{a}	27.30 ± 0.92^{d}
	36	48.13±1.14^{b}	27.85±0.59^{c}	26.9±0.77^{b}	36.47 ± 1.06^{b}	29.41 ± 0.85^{c}
	26	35.60±0.94^{c}	38.29±0.68^{a}	14.87±0.51^{c}	22.67 ± 0.91^{c}	38.20 ± 1.02^{ab}
	22	32.85±0.89^{d}	31.52±0.61^{b}	12.51±0.46^{d}	20.48 ± 0.84^{c}	40.30 ± 1.10^{a}

Note: Values followed by different lowercase letters within each column indicate statistically significant differences at $p < 0.05$ according to Tukey's HSD test (n = 10).

As neck moisture declined, both redness (a*) and chroma (C*) increased significantly. In the '*Wonderful*' variety, peak a* and C* values were 45.23 and 40.33, respectively, at 26% moisture, while the '*Manfaluti*' variety exhibited corresponding values of 38.29 and 38.20. These changes suggest intensified anthocyanin development and stronger color saturation, marking the stage of optimal ripeness. Concurrently, reductions in lightness (L*) and hue angle (H°) indicated a transition toward deeper red tones and diminished yellowness during maturation.

These results are consistent with those reported by Grisso et al. [14], who found that pomegranate skin color (particularly a* and C*) increased significantly (by up to 38%) between the early and full maturity stages. Similarly, Boussaa et al. [4] observed that chroma values increased from approximately 25 to approximately 38 in the late ripening stages of '*Tounsi*' pomegranates. Our findings fall within this range, supporting the use of chroma and a* as maturity indicators. Moreover, Boussaa et al. [4] noted that the hue angle dropped from approximately 60° to approximately 38° as anthocyanins accumulated, which aligns with the observed H° values of 37.03 (*Wonderful*) and 22.67 (*Manfaluti*) at 26% moisture content in this study.

Compared to previous mechanization-focused studies such as El-Termezy et al. [9] the current research provides a physiologically grounded framework by linking maturity detection to internal quality parameters. Unlike tools solely relying on external appearance or mechanical cutting thresholds, this study demonstrates that a neck moisture content of 26% corresponds with optimal color development and can serve as a reliable and measurable indicator for selective mechanical harvesting.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 11: 967-985, 2025
DOI: 10.55214/2576-8484.v9i11.11047

3.1.2. Effect of Fruit Neck Moisture Content on Total Soluble Solids (TSS)

Table 3 illustrates the influence of fruit neck moisture content on the total soluble solids (TSS) in the '*Wonderful*' and '*Manfaluti*' pomegranate varieties. TSS values significantly increased as neck moisture decreased, reaching their highest levels at 26% neck moisture. At this stage, the '*Wonderful*' variety recorded a TSS of 13.05%**,** while the '*Manfaluti*' variety reached 13.63%**.** Both values were statistically higher ($p < 0.05$) than those at other moisture levels. These values reflect a key ripening milestone where sugar accumulation is maximized and organoleptic quality peaks.

Table 3.
Total soluble solids (TSS) of 'Wonderful' and 'Manfaluti' pomegranate fruits at different fruit neck moisture contents.

Fruit Neck Moisture (%)	***Wonderful*** (%)	***Manfaluti*** (%)
46	7.64 ± 0.32 d	9.40 ± 0.35 d
36	8.84 ± 0.41 c	11.18 ± 0.44 c
26	13.05 ± 0.39 a	13.63 ± 0.47 a
22	10.51 ± 0.36 b	11.32 ± 0.39 b

Note: Values are expressed as mean ± standard deviation (n = 10). Different superscript letters in each column indicate significant differences at p < 0.05 using Tukey's HSD test.

This pattern of TSS accumulation corresponds with typical fruit maturation physiology, where dehydration is accompanied by the enzymatic breakdown of complex carbohydrates into simpler sugars, leading to increased sweetness and improved taste quality [15, 16]. The slight decrease in TSS observed at 22% neck moisture may be attributed to over-ripening, during which metabolic activity and moisture loss can degrade sugars or alter the sugar-acid balance, negatively affecting overall quality [17].

These findings align with previous studies. Tehranifar et al. [18] reported similar patterns in pomegranate cultivars, where TSS peaked around physiological maturity and declined thereafter. Kader [15] also emphasized TSS as a key determinant of harvest timing and postharvest quality in commercial fruit production. Thus, a neck moisture content of 26% serves as a reliable indicator for optimal harvest timing, ensuring peak internal quality and market acceptability.

3.1.3. Effect of Fruit Neck Moisture Content on Shear Force

The mechanical resistance of the fruit neck was significantly influenced by moisture content, as shown in Table 4. For both '*Wonderful*' and '*Manfaluti*' pomegranate cultivars, shear force values increased progressively as the fruit neck moisture content decreased from 46% to 22%. The minimum shear force was recorded at the highest moisture level (46%), with values of 1.12 and 1.07 for '*Wonderful*' and '*Manfaluti*', respectively. Conversely, the maximum shear resistance occurred at the lowest moisture content (22%), with values of 4.45 and 4.02**,** respectively.

Table 4.
Effect of fruit neck moisture content on fruit neck shear force.

Fruit Neck Moisture Content (%)	***Wonderful*** (N)	***Manfaluti*** (N)
46	1.12 ± 0.08^{d}	1.07 ± 0.07^{d}
36	1.99 ± 0.10^{c}	1.94 ± 0.11^{c}
26	3.59 ± 0.11^{b}	3.43 ± 0.10^{b}
22	4.45 ± 0.12^{a}	4.02 ± 0.09^{a}

Note: Values with different superscript letters within a column differ significantly ($p < 0.05$) based on Tukey's HSD test.

Importantly, the optimal shear force for efficient mechanical harvesting without compromising fruit integrity was found at 26% moisture content, where the neck shear force measured 3.59 for *Wonderful* and 3.43 for *Manfaluti*. This suggests a maturity threshold at which the pomegranate neck is sufficiently developed to allow clean detachment by mechanical means while maintaining fruit quality.

These results support the hypothesis that as fruit tissues mature, increased lignification and vascular development lead to greater resistance to mechanical severing. This is consistent with findings by Tehranifar et al. [18] and Ampem [19] who reported that maturity progression increases pedicel toughness and shear requirements in pomegranate and other fruit crops. Understanding this relationship is critical for calibrating harvesting tools to deliver appropriate cutting force while minimizing fruit bruising or stem retention. Moreover, high shear force at lower moisture levels (22%) may exceed the design limits of lightweight mechanical harvesters, increasing power consumption and wear. Thus, targeting 26% moisture offers a trade-off between ease of harvest and fruit quality retention.

3.2. Results of the Field Experiment

The field experiment evaluated the performance of the manufactured pomegranate harvesting machine using the *Wonderful* variety. Based on laboratory findings, harvesting was conducted at the optimal fruit neck moisture content of 26%**,** identified as the physiological maturity stage that ensured maximum TSS, optimal color kinetics**,** and appropriate shear force for mechanical detachment.

3.2.1. Effect of Cutting Disc Speed and Cutting-Edge Tilt Angle on Machine Productivity

The productivity of the fabricated pomegranate harvesting machine was significantly influenced by both cutting disc speed and cutting-edge tilt angle, as shown in Fig. 5. The results revealed that increasing the cutting disc speed from 1100 to 1250 rpm led to a marked improvement in machine productivity across all tested tilt angles. At 0°, 12°, 21°, and 32° tilt angles, the productivity values rose from 1080 to 1920 fruits/h, 1119 to 2100 fruits/h, 1440 to 2520 fruits/h, and 720 to 960 fruits/h, respectively, demonstrating the strong positive influence of rotational speed on cutting efficiency. This increase is likely due to improved stem severing dynamics at moderate rotational speeds, which enhances the rate of clean fruit detachment.

However, when the disc speed exceeded 1250 rpm and reached 1320 rpm, a noticeable decline in productivity was observed. At the same respective tilt angles (0°, 12°, 21°, and 32°), productivity dropped to 1440, 1560, 1920, and 840 fruits/h. This reduction is likely attributed to excessive vibration and turbulence caused by the higher disc speed, which disrupts the precise positioning required for effective stem cutting. Rather than facilitating detachment, the increased kinetic energy may result in fruit displacement, missed cuts, or partial detachment, ultimately lowering harvesting efficiency. These findings are in agreement with AL-Gezawe [10], who reported that excessive disc velocity in harvesting systems can lead to instability in fruit-stem interaction, reducing both precision and throughput.

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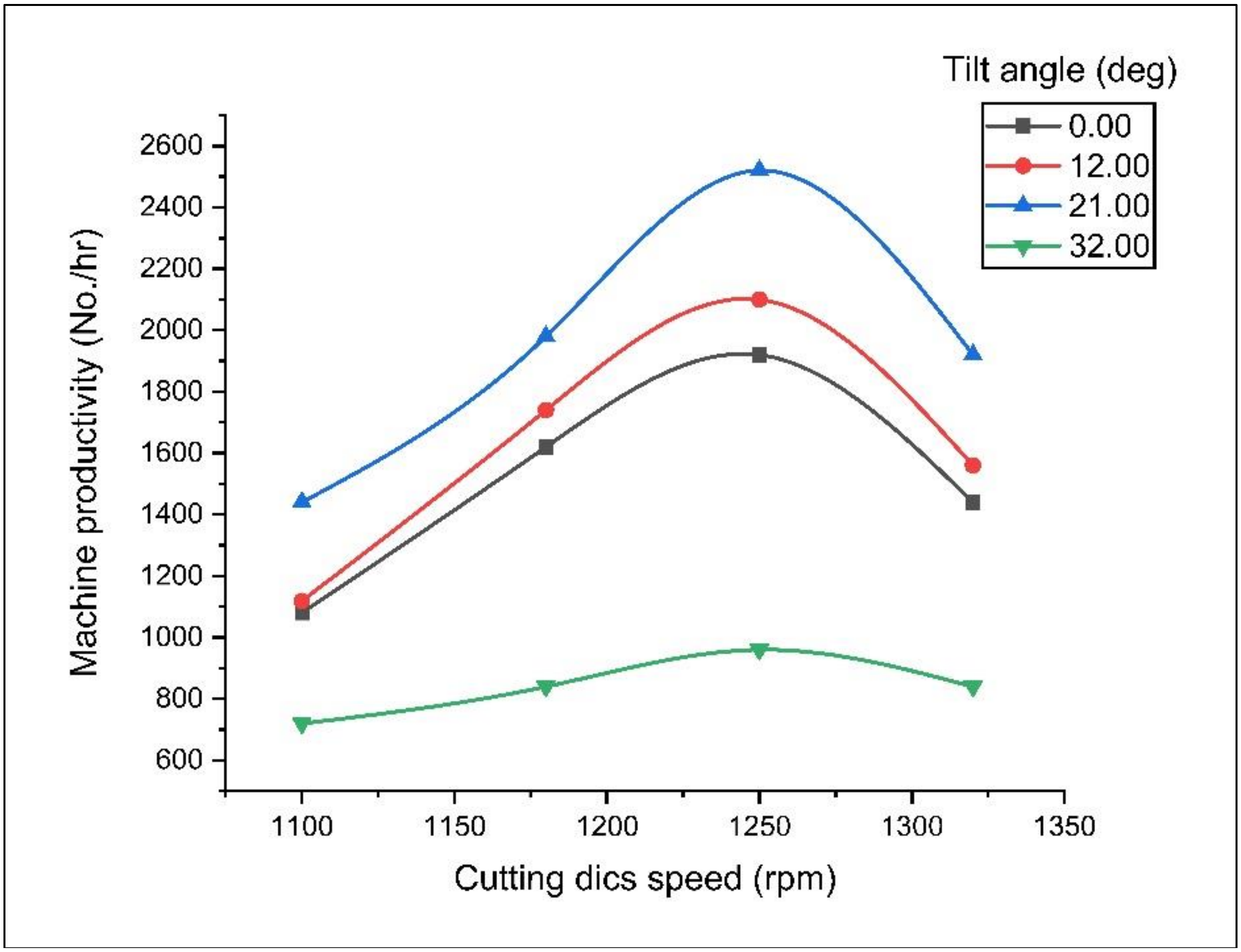

Figure 5.
Effect of cutting disc speed on machine productivity at various cutting-edge tilt angles during pomegranate harvesting trials.

The cutting-edge tilt angle also played a critical role in machine productivity. As the tilt angle increased from 0° to 21°, a significant improvement in harvesting performance was recorded, indicating better blade-to-stem contact and enhanced cutting efficacy. For example, productivity at 1250 rpm increased from 1920 fruits/h at 0° to 2520 fruits/h at 21°. However, a further increase to 32° resulted in a decline in productivity to 1920 fruits/h. This inverted trend was consistently observed at other rotational speeds as well. The reduced productivity at higher tilt angles is likely due to the deviation of the blade path from the optimal cutting plane, which increases the likelihood of incomplete cuts and structural interference with the canopy. These observations support previous research by Zhou et al. [8], who noted that optimal blade tilt can improve tool engagement with the fruit pedicel while over-tilting may misalign the cutting axis and reduce harvest efficiency. Taken together, the interaction between disc speed and tilt angle revealed that the optimum configuration for productivity was 1250 rpm with a 21° cutting-edge tilt. This combination offered a balance between mechanical efficiency and operational stability, maximizing the harvest rate while minimizing fruit loss and mechanical stress.

3.2.2. Effect of Cutting-Edge Tilt Angle and Cutting Disc Speed on Specific Energy

Specific energy consumption (SEC) is a critical indicator of the energy efficiency of mechanical harvesting systems. It reflects the energy required to harvest a unit mass of fruit and is influenced by operational parameters, including cutting disc speed, cutting-edge tilt angle, and machine productivity. Table 5 presents the specific energy values (kWh/Mg) under various combinations of disc speed and tilt angle, including statistical analysis.

The data demonstrate that increasing the cutting disc speed from 1100 rpm to 1250 rpm significantly reduced the specific energy at all tilt angles. For example, at a tilt angle of 21°, specific energy dropped from 0.036 to 0.020 kWh/Mg. However, further increasing the speed to 1320 rpm reversed this trend, with SEC rising to 0.027 kWh/Mg. This increase is attributed to a reduction in machine productivity and a rise in fruit damage at excessive rotational speeds, as the high kinetic energy begins to disrupt clean cutting and causes fruit displacement.

Table 5.
Effect of cutting disc speed and cutting-edge tilt angle on specific energy (kWh/Mg) during mechanical harvesting of pomegranate fruit.

Cutting-edge tilt angle (°)	1100 rpm	1180 rpm	1250 rpm	1320 rpm
0	0.048 ± 0.002^{b}	0.032 ± 0.002^{b}	0.027 ± 0.001^{b}	0.036 ± 0.002^{b}
12	0.046 ± 0.002^{b}	0.030 ± 0.002^{ab}	0.024 ± 0.001^{c}	0.033 ± 0.002^{ab}
21	0.036 ± 0.002^{c}	0.026 ± 0.001^{c}	0.020 ± 0.001^{d}	0.027 ± 0.002^{c}
32	0.071 ± 0.003^{a}	0.061 ± 0.003^{a}	0.054 ± 0.002^{a}	0.061 ± 0.003^{a}

Note: Values followed by different lowercase letters in the same column are significantly different ($p < 0.05$) as determined by one-way ANOVA and Tukey's HSD post hoc test.

Similarly, the tilt angle also played a substantial role. Increasing the tilt angle from 0° to 21° led to a consistent reduction in SEC at all speeds, owing to the enhanced alignment of the cutting force with the fruit neck orientation, thereby facilitating efficient severing. Beyond 21°, the SEC began to increase, likely due to suboptimal contact geometry that reduces cutting efficiency and increases fruit deflection or resistance.

These findings align with those of El-Termezy et al. [9], who reported a similar U-shaped trend in SEC across increasing operational speeds, with an optimal energy minimum occurring at moderate disc speeds. The current results are also consistent with the study of Torregrosa et al. [7], which concluded that both cutting angle and actuation speed strongly influence energy use and operational efficiency in citrus fruit harvesting systems.

Moreover, Zhou et al. [8] noted that misalignment between cutting blades and stem orientation can increase friction and power requirements. The current study confirms that an optimal tilt angle of 21° provides the best compromise between mechanical alignment and energy consumption. The consistent pattern across multiple speeds and tilt angles suggests that 1250 rpm and 21° are optimal for minimizing energy usage without compromising cutting performance or increasing fruit damage. These conditions reflect a synergy between mechanical settings and fruit physiological readiness, particularly at the 26% fruit neck moisture content identified in the lab experiment phase.

3.2.3. Effect of Cutting Disc Speed and Cutting-Edge Tilt Angle on Fruit Damage Ratio

Minimizing fruit damage during mechanical harvesting is crucial to ensuring marketability and reducing postharvest losses, particularly for delicate fruits like pomegranate. The findings in Fig. 6 demonstrate that cutting disc speed and cutting-edge tilt angle significantly affect the fruit damage ratio, which is a key parameter in evaluating harvester performance.

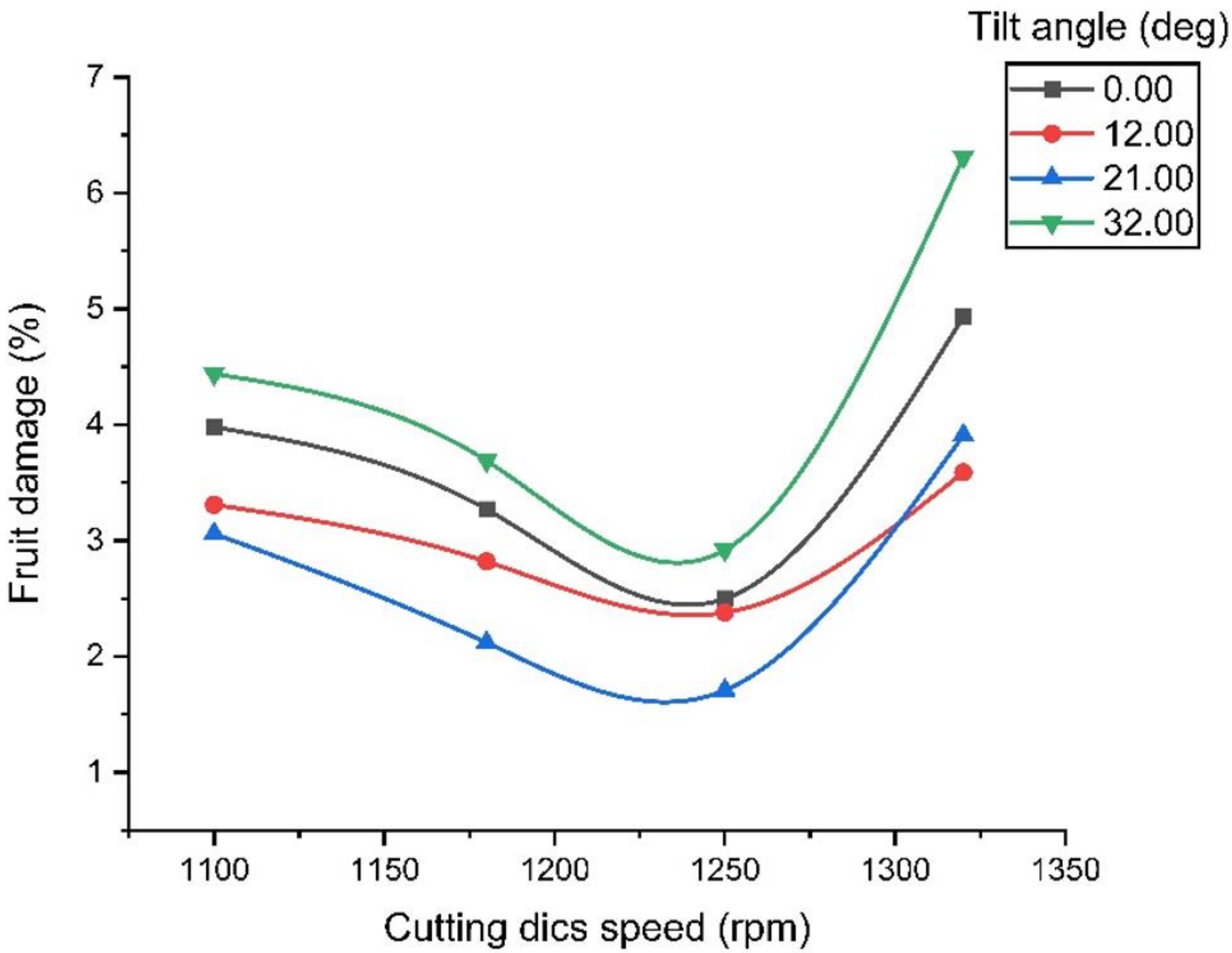

Figure 6.
Effect of cutting disc speed on fruit damage ratio at various cutting-edge tilt angles during mechanical harvesting of pomegranate.

As disc speed increased from 1100 to 1250 rpm, the fruit damage ratio decreased across all tilt angles. At this moderate speed, the blade achieved efficient and cleaner cuts, reducing bruising or tearing. For instance, at 21° tilt, fruit damage dropped to 1.71%, the lowest recorded. This behavior is consistent with the findings of El-Termezy et al. [9], who reported that cutting tools operating at mid-range rotational speeds reduced mechanical trauma in pomegranates due to optimized kinetic energy transfer and improved cutting accuracy.

However, increasing the speed to 1320 rpm led to a sharp increase in fruit damage up to 6.31% at a 32° tilt due to excessive vibration and mechanical interference with fruit-bearing branches. These results align with those of Idama et al. [20], who noted that high-speed harvesters increased the likelihood of fruit impact injuries and unclean stem separation in mechanically harvested peppers. Similarly, Kansiime et al. [21] observed higher fruit losses in papaya harvesters when blade speed exceeded the optimal threshold due to increased inertial forces.

As for the cutting-edge tilt angle, increasing the angle up to 21° significantly reduced the fruit damage ratio, likely due to better alignment with the natural orientation of the fruit neck and improved distribution of cutting forces. However, when the tilt angle exceeded 21°, damage increased again, suggesting a geometric misalignment that compromised cutting precision. This trend supports the results by Miller [22], who found that improper blade inclination in a tomato harvester caused increased mechanical shear and epidermal injury.

Interestingly, while Wang et al. [23] recommended a tilt angle of around 25°–30° for soft citrus harvesting machines to balance cutting efficiency and canopy clearance. The current study identifies 21° as optimal for pomegranates. This discrepancy likely stems from differences in pedicel lignification and neck diameter between citrus and pomegranate fruits. Furthermore, Torregrosa et al. [7] observed that for olive harvesters, the optimal tilt angle was even lower (about 18°) due to the fruit's attachment and canopy structure, highlighting the crop-specific nature of harvester design parameters.

Comparatively, the current study expands upon Fawole and Opara [24], who discussed general mechanical harvesting benefits for pomegranate but did not address fine-tuned parameter optimization. Here, we provide quantitative evidence linking operational settings directly to fruit damage outcomes, bridging a knowledge gap in selective pomegranate harvesting. In summary, these results reinforce the concept that precision tuning of disc speed and blade angle is critical to minimizing fruit injury during mechanical harvesting. The optimal configuration of 1250 rpm and 21° represents a balance between mechanical efficiency and physiological compatibility with the fruit's structure. These insights not only contribute to the development of crop-specific mechanical harvesters but also align with broader trends in smart mechanization and precision agriculture.

3.2.4. Effect of Cutting Disc Speed and Cutting-Edge Tilt Angle on Criterion Cost

A comparative economic assessment was conducted between manual and mechanical pomegranate harvesting methods, focusing on the cost required to harvest one megagram (Mg) of fruit. Manual harvesting employed two skilled workers, while the mechanical operation utilized only one operator.

As shown in Table 6, the mean hourly cost of mechanical harvesting (US$1.18) was 49.7% lower than that of manual harvesting (US$2.35). More importantly, the operating cost per Mg was significantly reduced, dropping from US$6.72 in manual harvesting to US$1.34 in mechanical operation, a reduction of 80**%**. Furthermore, the cost attributed to fruit damage decreased considerably, from US$13.73 (manual) to US$2.41 (mechanical), reflecting a reduction of over 82**%**. Consequently, the total criterion cost, which combines labor, operating, and damage-related costs, declined by 81.65%**,** from US$22.81 to US$4.19.

These findings align with earlier reports. Torregrosa et al. [25] demonstrated that mechanized harvesting substantially reduces labor and operational costs. Similarly, Brotons-Martínez et al. [26] reported up to 75% cost savings in citrus harvesting due to mechanization, while Zhou et al. [8] highlight the role of optimized machine parameters such as blade speed and tilt angle in minimizing fruit loss and associated economic losses.

Table 6.
Comparative economic analysis of manual and mechanical pomegranate harvesting per Mg (all values in US$).

Cost Category	**Manual Harvesting**	**Mechanical Harvesting**	**Reduction (%)**
Hourly Cost (US$/h)	2.35±0.07	1.18±0.05	−49.7%
Operating Cost (US$/Mg)	6.72±0.21	1.34±0.08	−80.0%
Fruit Damage Cost (US$/Mg)	13.73±0.31	2.41±0.09	−82.4%
Criterion Cost (US$/Mg)	22.81±0.38	4.19±0.22	−81.65%

Note: Values represent means ± standard deviations (SD) based on three independent replicates.

Figure 7 illustrates the influence of cutting disc speed and cutting-edge tilt angle on the criterion cost during mechanical harvesting. The data clearly show that operating the machine at 1250 rpm combined with a 21° tilt angle results in the lowest criterion cost. Deviating from these parameters, either by increasing disc speed beyond 1250 rpm or altering the tilt angle, leads to higher costs. This increase is primarily attributed to enhanced fruit damage and decreased harvesting efficiency at suboptimal settings.

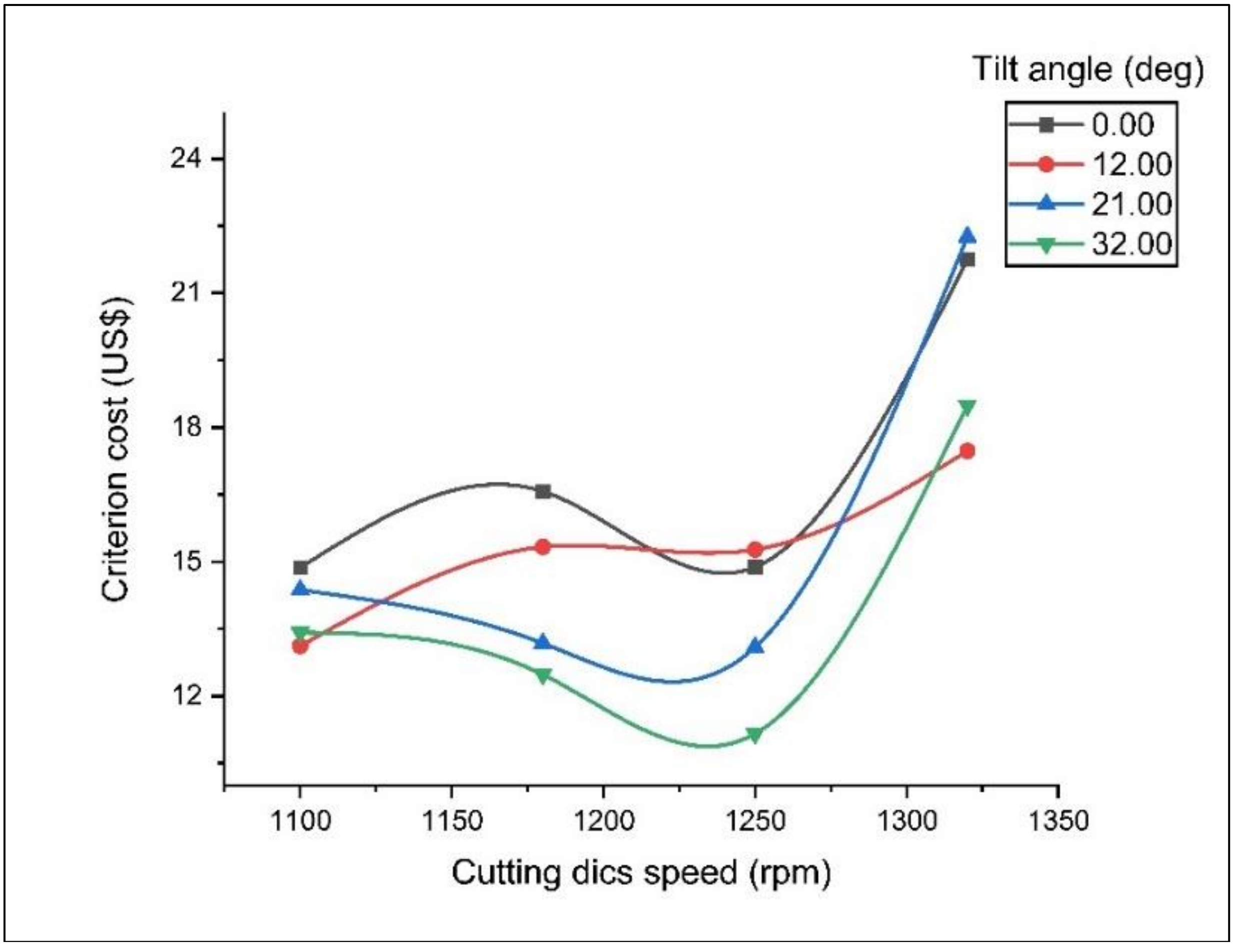

Figure 7.
Effect of cutting disc speed and cutting-edge tilt angle on criterion cost during mechanical harvesting of pomegranate fruits.

These findings are consistent with those reported by Brotons-Martínez et al. [26], who highlighted that excessive machine speeds can lead to mechanical stress and fruit injury, ultimately increasing postharvest losses and economic costs in citrus crops. Similarly, Rashvand et al. [27] demonstrated that optimizing mechanical parameters, such as tool angle and rotational velocity, is critical in minimizing damage and reducing harvesting expenses in olive production. The current study reinforces these outcomes by confirming that precise operational tuning can maximize productivity while preserving fruit quality, leading to a significantly reduced overall criterion cost.

Furthermore, this study echoes the broader consensus in the mechanized harvesting literature, where cost-effectiveness is tightly coupled with both machine calibration and crop-specific characteristics [6, 28]. Given the challenges of labor shortages and increasing wages in many horticultural regions, these results advocate for the scalable adoption of optimized mechanical systems in pomegranate orchards. The demonstrated reduction in labor requirements, damage-related losses, and operational expenditures emphasizes the economic and practical viability of this approach for large-scale and export-oriented growers.

4. Conclusion

This study integrated physiological maturity assessment with mechanized harvesting to optimize pomegranate fruit collection. Laboratory results identified 26% neck moisture content as the optimal harvest point, marked by enhanced skin coloration, peak total soluble solids, and increased shear force, indicating full ripeness and high internal quality. Field trials confirmed that operating the fabricated harvesting machine at a cutting disc speed of 1250 rpm and a cutting-edge tilt angle of 21° yielded the best performance, with maximum productivity, minimal fruit damage, low energy consumption, and reduced criterion cost. These findings underscore the potential of precision-calibrated harvesting systems to improve efficiency, product quality, and economic viability in large-scale pomegranate cultivation, especially under labor-scarce conditions.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgment:

The authors extend their appreciation to the Ongoing Research Funding Program (ORF-2025-1061), King Saud University, Riyadh, Saudi Arabia. The authors also gratefully acknowledge the support of the Agricultural Engineering Research Institute (AEnRI) and the Faculty of Agriculture, Zagazig University, for providing the facilities, technical assistance, and field access necessary for this study.

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