

Article

Study of the Physical and Mechanical Properties of Edible Sunflower at Harvest

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Abstract

The optimized design of key components in harvesting equipment is significantly impeded by the significant grain loss from the header and high energy consumption during stalk cutting that result from the lack of physical and mechanical parameters regarding the plant-flower head system during the mechanized harvesting of edible sunflowers. To furnish the design of mechanized harvesting equipment for palatable sunflowers with theoretical support and foundational data, physical parameters measured included geometrical properties, critical bending angle, coefficient of static friction, moisture content, and head seed collision loss rate. Mechanical parameters—radial elastic modulus, shear modulus, and shear strength—were obtained from stalk compression and shear tests using a universal testing machine. Stem-head detachment force was quantified with a universal testing machine fitted with bespoke fixtures, and orthogonal experiments were conducted with tensile speed, head-picking plate spacing, and tensile angle as factors to establish the significance hierarchy and optimal configuration. Considerable heterogeneity was observed: mean plant height, head diameter, and head thickness were (1733 ± 153) mm, (275 ± 28) mm, and (93 ± 19) mm, respectively. The critical bending angle decreased with height, whereas stalk moisture content increased from base to apex. Mean stalk and head moisture contents were 65% and 61.4%. The coefficient of static friction varied from 0.24 to 0.63 depending on contact material. A critical impact velocity of 2–3 m/s induced mechanical damage and seed cracking. The stalk radial elastic modulus was (1.12 ± 0.27) MPa; shear modulus and shear strength increased with decreasing sampling height, with basal stalks exhibiting a mean shear modulus of 2.47 MPa and shear strength of 1.87 MPa. Sampling position significantly influenced shear modulus ($p < 0.05$). The factor significance for stem-head detachment force was head-picking plate spacing > tensile angle > tensile speed. The optimal combination (tensile speed 500 mm/min, head-picking plate spacing 50 mm, tensile angle 10°) yielded a detachment force of (202.3 ± 9.5) N, with a relative error below 5% compared to prior detachment force measurements, confirming the reliability of the optimised results. These data provide essential foundations for developing stalk cutting, head inserting, and combine harvesting equipment.

Keywords: harvest stage; edible sunflower; physical properties; mechanical properties; stalk

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1. Introduction

Edible sunflowers, known as sunflower seeds, demonstrate resilience to environmental challenges including drought, flooding, and salinity, as well as a broad flexibility [1–3]. These crops are widely grown in several regions of China, including Xinjiang, Inner Mongolia, Gansu, and Qinghai [4,5], with yearly planting areas typically exceeding 533,333 hm² [6]. Besides manual harvesting by small-scale farmers, the primary ways of harvesting edible sunflowers include combination harvesting and manual segmental harvesting. Although combined harvesting offers significant efficiency, time savings, and labour reduction [7,8], the high moisture content of mature sunflowers in Xinjiang—resulting from particular cultivar characteristics, climatic factors, and the timing of subsequent crop planting—renders it impractical [9]. Consequently, hand harvesting continues to be the predominant technique in Xinjiang, where flower heads are first detached and then arranged either flat or at a 45° angle on pruned stems for desiccation [10]. Once an ideal moisture content is attained, the flower heads are harvested either manually or by mechanised pickers [11]. This method is significantly dependent on human labour, resulting in elevated labour intensity and diminished operational efficiency [12–14]. These constraints present considerable challenges to the sustainable advancement of the edible sunflower sector. Thus, the development of harvesting technology that can concurrently sever stems and gather flower heads is essential for the mechanisation and modernisation of edible sunflower harvesting methods [15].

The physical and mechanical qualities constitute the essential foundation for agricultural machinery design, directly affecting equipment performance. Examining the physical attributes of sunflowers at harvest yields critical data and theoretical frameworks for machinery like sunflower stalk cutters and disc harvesters, highlighting its considerable significance. Researchers globally have made significant advancements in examining the physical and mechanical qualities of harvested crops. Christopher T. Wright and colleagues [16] investigated the mechanical characteristics of wheat, barley and maize stems. Utilising various testing methods including as compression, tensile, and bending tests, they examined the mechanical properties of stalk cellulose, providing insights for the advancement of harvesting and processing machinery. Lixian Zhang and colleagues [17] investigated the tensile characteristics of maize stalks. Through uniaxial tensile testing, they determined that tensile strength and elastic modulus progressively diminish from the base to the apex of the stalk, offering essential data for the construction of maize harvesting machinery. Yue Jin et al. [18] investigated the physical and mechanical properties of root stems from foliar plants. By employing testing apparatus alongside high-speed photography, they obtained data such as elastic modulus, static friction coefficients between root stems and various materials, and recovery coefficients. These fundamental material properties enable discrete element simulations and offer critical references for reducing damage rates in harvesting machines. Hu Lianglong et al. [19] investigated the mechanical properties of sweet potato vines and stems at the time of harvest. Their study examined differences in stem moisture content and shear strength, along with their correlation to the quality of mechanical shredding and integration processes. This study offers critical criteria for the design of machines for shredding and incorporating sweet potato vines. Li Yudao et al. [20] performed experimental analysis utilising a universal testing machine to investigate the shear strength and shear work of cotton stalks under different temporal and moisture content conditions. Their findings demonstrated a strong correlation between shear strength, shear work, and moisture content, offering significant insights for cotton stalk harvesting. Ma Qiucheng et al. [21] conducted compression tests to ascertain mechanical parameters, including elastic modulus and compressive strength at varying moisture concentrations, demonstrating that elevated moisture content markedly dimin-

ishes mechanical performance. This research provides a theoretical foundation for the design of lotus seed processing machinery. Ma Shaoteng et al. [22] quantified the physical parameters of sunflower seeds, encompassing three-dimensional dimensions, moisture content, density, friction angle, and suspension velocity, thereby supplying essential data for the design of mechanised sunflower processing apparatus. Yang Zheng et al. [23] examined the mechanical properties of sunflower stems utilising an electronic universal testing machine. Their findings indicated that peak shear force diminished as loading speed increased, however the root section constantly displayed elevated peak values. This research furnishes critical information for the advancement of machinery designed for processing sunflower stems. Nevertheless, it exclusively examined the effects of differing loading velocities and sampling locations on stem mechanical properties, which imposes particular limitations. The study inadequately defined the parameter ranges for the physical and mechanical qualities of sunflower stalks. A significant amount of study, both national and international, has mostly focused on the physical and mechanical characteristics of economic crops including maize, cotton, and lotus seeds. These qualities are generally measured using factors such as geometric features, moisture content, elastic modulus, and shear modulus. Conversely, research on the physical and mechanical properties of edible sunflowers is rather limited. Owing to the absence of essential mechanical performance criteria, critical components like the cutting blade and stalk-pulling roller can solely be developed using empirical approaches, leading to significant harvest losses and diminished operational efficiency. leading to an absence of robust theoretical frameworks essential for the development of harvesting equipment. The physical attributes of edible sunflowers dictate the design and operational requirements of harvesting equipment [24,25]. Elements like planting configurations, plant morphology, and static friction coefficients influence the dimensional design of essential components of sunflower harvesters, such as cutterbar height, conveyor chain spacing, and hopper dimensions. Furthermore, the plant's critical bending angle affects the degree of displacement when the divider leads plants, hence minimizing stem fracture during the guidance process [26,27]. The moisture content in the stem significantly influences cutter efficiency [28], while the moisture level of the sunflower head is essential for optimizing harvest timing. The mechanical properties of sunflower stems and heads directly influence the stability and effectiveness of cutting, head removal, and head insertion operations in harvesting gear. The elastic modulus indicates the stem's resistance to elastic deformation, whereas the shear modulus represents its resistance to shear deformation [29]. Both attributes are vital for cutter efficacy and function as fundamental inputs for simulation modeling [30–34]. Additionally, the fracture resistance at the stem-disk junction has been evaluated by stem-disk tensile strength testing, yielding data that underpins the design of roller-type harvesting heads for sunflowers [35]. With an emphasis on sunflower plants at harvest maturity, this study synthesizes both domestic and international literature to conduct a thorough investigation of the mechanical and physical characteristics of edible sunflowers. Geometric features, static friction coefficient, critical bending angle, seed loss rate following head impact, elastic modulus, shear modulus, and stem-head tensile strength are only a few of the parameters that are investigated. The project attempts to produce foundational data to guide the design and optimization of sunflower harvesting technology through thorough experimental examination of these parameters. The results aim to facilitate the sustainable growth of Xinjiang's sunflower industry, bolster rural regeneration efforts, and enhance farmers' earnings.

2. Test Materials and Methods

2.1. Experimental Materials

The experimental field at the Ershili Dian Community, Shayibake District, Urumqi City, Xinjiang Uygur Autonomous Region, provided the experimental materials. Xin Yin SH363 was the cultivar used; it was seeded on 25 April 2025, and harvested on 13 August 2025. According to the Altay Region Market Supervision Administration of Xinjiang's technical standard DB 6543/T 012—2024 [36], “Operational Technical Procedures for Self-Propelled Sunflower Harvesters,” the harvesting criteria were established based on certain physiological indicators: yellowish-white sunflower stems and undersides of flower heads, pale yellow middle to upper leaves, and the abscission and wilting of ligulate petals. These indicators show that the body has reached physiological maturity and is prepared for tray drying. The wide-narrow row spacing pattern of 90 cm and 40 cm, respectively, was used in the local agronomic planting arrangement along with the application of plastic mulch. As seen in Figure 1, this configuration included two rows per mulch strip and a plant spacing of 60 cm. The wide row spacing varied between 864 and 931 mm, the narrow row spacing between 347 and 424 mm, and the plant spacing between 553 and 609 mm, according to field observations. The design of the harvester header depends on this dimensional data.

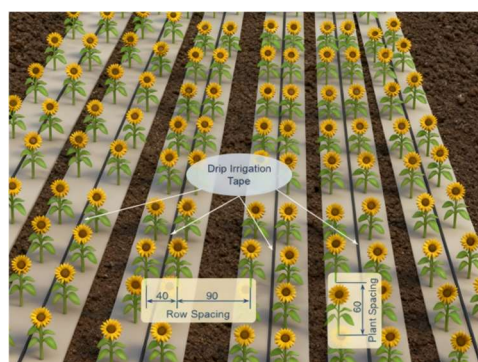


Figure 1. Schematic diagram of the agronomic planting pattern of edible sunflower.

Following the guidelines in GB/T 5262-2008 [37], “General Specifications for Determining Test Conditions of Agricultural Machinery,” a five-point sample approach was used. The square test plot’s four corners were connected by diagonals, and the junction of these diagonals was chosen as the central sample point. At the midpoints of the diagonals connecting this center point to each of the four vertices, four more sample points were set up. The dimensions of each assigned sampling area were four meters by four meters. Ten edible sunflower plants were chosen at random from each sampling area, harvested at the base, and then their branches and leaves were removed. Following collection, the samples were placed in sealed bags, kept in a refrigerator, and sent for analysis within a day.

2.2. Instruments for Experiments

A computer-controlled electronic universal testing machine (Model WDW-2M, Class 1 precision, with a load adjustment range of 0.001 to 500 mm/min) manufactured by Jinan Yongduo Testing Machine Co., Ltd., Jinan, China; A high-temperature OB-type electric heating oven (power rating of 1.3 kW, operating temperature range: RT +10 to 400 °C) produced by Changge Mingtu Machinery Equipment Co., Ltd, Xuchang, China. Supplementary equipment comprised a tension meter (range 0–500 N, accuracy $\pm 0.5\%$), an electronic balance (range 0–3100 g, precision 0.01 g), a tape measure (range 0–5 m, accuracy 1 mm), and a vernier caliper (accuracy ± 0.02 mm).

2.3. Test Method

2.3.1. Determining the Geometric Features of Edible Sunflowers

The geometric properties of edible sunflowers include plant height, head diameter, head thickness, and stem diameter, evaluated at various sites. The head diameter is the distance between two points on the perimeter that intersect the center of the approximately circular head surface. The vertical distance from the upper surface containing the seeds to the stem base at the point of head attachment is referred to as head thickness. A tape measure is utilized to ascertain the plant's height, head diameter, and head thickness. The stem diameter is measured at intervals of 100 mm, 200 mm, and 300 mm from the back of the head using a vernier caliper. When assessing the distance between the head-picking plates on a roller-type header, these measures provide essential information.

2.3.2. Assessment of the Critical Bending Angle for Edible Sunflower

Choose a square tube to serve as a supplementary measurement device. Set a zero calibration line 10 cm above the base of the tube. Subsequently, designate supplementary reference points at vertical intervals of 700 mm, 800 mm, and 900 mm above the zero line to indicate the contact positions between the header's cropp divider and the stem. Align the tube vertically alongside the test plant. At each specified height, utilize a horizontal ruler to ascertain the horizontal displacement (T) at the point of stem fracture. During the measurement process, ensure that the zero calibration line is consistently aligned with the ground level. A tension gauge is employed to exert a steady horizontal stress on the sunflower stem at each designated location, as depicted in Figure 2. Observe the tension gauge reading until stem failure transpires, then discontinue the application of force and record the associated horizontal displacement. Each sunflower specimen undergoes only one test. The essential bending angle of the sunflower is then computed using Equation (1).

$$\alpha = \arctan \frac{T}{H} \quad (1)$$

In the formula provided, α ($^{\circ}$) denotes the critical bending angle of edible sunflower seeds; H (mm) indicates the vertical distance from the specified point to the ground, and T (mm) represents the horizontal displacement of the specified point.



Figure 2. Schematic diagram of the critical bending angle measurement for edible sunflower. (a) Diagram of measurement. (b) Site survey blueprint.

2.3.3. Assessment of the Static Friction Coefficient for Edible Sunflower Seeds

The coefficient of static friction for edible sunflower seeds was assessed using the inclined plane method. Ten-centimeter segments of stems and removed sunflower heads were placed on the apparatus intended for friction coefficient evaluation. Static friction coefficient measurements were performed at the interfaces between the stems and steel, the anterior and posterior surfaces of sunflower heads and steel, and between the anterior

surfaces of two sunflower heads. The angle of inclination of the plane was progressively augmented by revolving a handwheel, while the movement of the test specimens was meticulously observed. Rotation halted when the specimens began to slide. At this point, the vertical height (h) of the slope was measured, together with the horizontal length (l) of the plane. Each experimental condition was duplicated ten times, and the average value was calculated. Thereafter, the coefficient of static friction was determined using the subsequent equation:

$$\mu = \tan \theta = \frac{h}{l} \quad (2)$$

In this context, μ represents the static friction coefficient of the material, θ (degrees) indicates the angle between the inclined plane and the horizontal plane, h (meters) denotes the vertical height of the inclined plane, and l (meters) signifies the length of the inclined plane measured along the horizontal axis.

2.3.4. Moisture Content Determination of Edible Sunflower Seeds

Eight plants were randomly picked from the sample population. Stem segments were removed at three designated intervals from the root base: 450–550 mm, 750–850 mm, and 1050–1150 mm. Furthermore, sunflower head segments with a width of 3 cm, aligned along the diameter, were procured to function as test specimens. The moisture content of these sunflower head segments was deemed indicative of the overall moisture content of the sunflower heads. In accordance with the standards set forth in GB/T 36055-2018, entitled “Determination of Moisture Content in Forestry Biomass Raw Materials” [38], the starting mass of each sample was quantified using an electronic balance and documented as W_1 . Thereafter, samples were positioned in a forced-air drying oven set at a stable temperature of $105\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. Samples were extracted and weighed at 20 min intervals until the variance between consecutive readings was within an established acceptable error limit. The mass measured at this equilibrium point was designated as W_0 . The moisture content was subsequently determined with the following formula:

$$\omega = \frac{W_1 - W_0}{W_1} \times 100\% \quad (3)$$

In this context, ω (%) signifies the moisture content of the palm frond or stalk; W_1 (g) indicates the mass of the palm frond or stalk before the drying process; and W_0 (g) refers to the mass of the palm frond or stalk after drying.

2.3.5. Assessment of Seed Loss Rate Attributable to Effect

Twenty sunflower heads were randomly selected from the test sample for analysis. To minimize experimental error, each test was performed five times, with each sunflower head exposed to a singular impact event. Each sunflower head was firmly affixed to the pendulum equipment bracket with a V-block attachment. The pendulum apparatus was calibrated to a specified angle to guarantee a direct, frontal impact with the sunflower head, as depicted in Figure 3. Collision velocity gradients of 1 m/s, 2 m/s, 3 m/s, and relative velocities of 4 m/s were established to approximate the interactions between sunflower heads and mechanical components during operation. In accordance with the concept of conservation of energy, the pendulum rod was situated at vertical displacements of 0.05 m, 0.20 m, 0.46 m, and 0.82 m above the point of impact. The rod was subsequently let to descend freely and impact the sunflower head. Subsequent to the incident, the sunflower head remained undisturbed for 10 s before being inverted to evaluate seed loss. All seeds displaced during this procedure were gathered and measured. Subsequently, the residual seeds within the sunflower head after the collision were also weighed. The seed loss rate resulting from the impact was determined using the subsequent formula:

$$\eta = \frac{m_1}{m_1 + m_2} \quad (4)$$

In this context, η (%) represents the collision-induced loss rate of grains from the seed head. The variable m_1 (g) denotes the mass of grains detached from the seed head as a result of the collision, while m_2 (g) corresponds to the mass of grains that remain attached to the seed head following the collision.

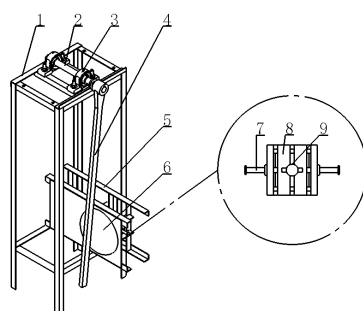


Figure 3. Impact test on sunflower seeds (1. Main frame, 2. Pendulum shaft, 3. Bearing housing, 4. Pendulum arm, 5. Sunflower disc clamp, 6. Sunflower head, 7. Clamping screw, 8. V-Block, 9. Stalk).

2.3.6. Determination of Elastic Modulus of Edible Sunflower Stems

The elastic modulus of edible sunflower stems was evaluated through radial compression testing. A total of twenty-seven stem samples were randomly selected for analysis. Sample preparation followed the procedure outlined in Section 2.3.4. The diameter at the midpoint of each stem segment was measured using a vernier caliper and designated as D . Each specimen was positioned within a universal testing machine, with cylindrical steel indenters—100 mm in diameter and 10 mm in thickness—placed on both the upper and lower surfaces. Radial compression tests were performed at loading rates of 10 mm/min, 20 mm/min, and 30 mm/min, as depicted in Figure 4. To reduce experimental variability, each test was conducted in triplicate, and the mean value was recorded. Load–displacement data were continuously recorded by the computer from the initiation of each test. Testing concluded upon a sudden drop in load concurrent with increasing displacement, and the full load–displacement curves were saved for analysis. The elastic modulus of the sunflower stems was subsequently calculated according to Equation (5).

$$E = \frac{F / A_1}{\delta / D} = \frac{FD}{2\delta L \sqrt{D\delta - \delta^2}} \quad (5)$$

In the given formula, E (MPa) denotes the elastic modulus; F (N) corresponds to the applied load; A_1 (mm²) refers to the contact area; L (mm) represents the test length of the stalk; δ (mm) represents the deformation distance under the applied pressure; and D (mm) indicates the diameter of the stalk.

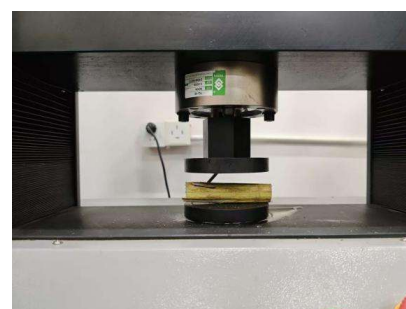
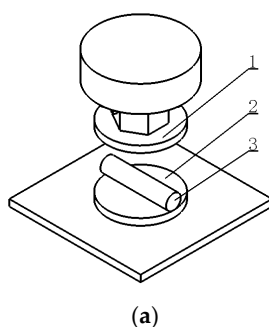


Figure 4. Compression test of edible sunflower stalk: (a) Diagram of measurement: (1) Adaxial surface. (2) Abaxial surface. (3) Culm test specimen). (b) Site survey blueprint.

2.3.7. Shear Strength Measurement of Edible Sunflower Stalks

The shear strength of edible sunflower stalks was evaluated through a stalk shear test. A total of nine edible sunflower stalk specimens were selected and prepared in accordance with the procedures outlined in Section 2.3.6. Testing was performed using a universal testing machine fitted with shear fixtures, as illustrated in Figure 5. A two-factor, three-level experimental design was implemented, incorporating loading speeds of 100 mm/min, 300 mm/min, and 500 mm/min, alongside varying sampling positions as the factors. The specific factor levels are presented in Table 1. Each experimental condition was replicated three times, and the mean values were computed to enhance data reliability. Comprehensive displacement-stress curve data were collected throughout the tests. Subsequently, the shear modulus and shear strength of the sunflower stalks were determined using Equations (6) and (7).

$$G = \frac{\tau}{\gamma} \quad (6)$$

$$\tau_{\max} = \frac{F_{\max}}{A_2} \quad (7)$$

In this context, G (MPa) denotes the shear modulus, τ (expressed in Newtons) represents the shear stress, γ corresponds to the shear strain, $\tau_{\max}$ (MPa) indicates the shear strength, and A_2 (mm²) signifies the shear area.

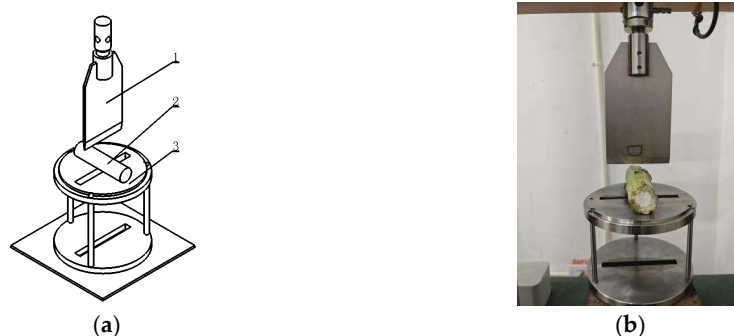


Figure 5. Shear test of edible sunflower stalk: (a) Diagram of Measurement: (1) Cutting blade. (2) Culm test specimen. (3) Shearing fixture. (b) Site survey blueprint.

Table 1. Factors and levels in shear test.

Experimental Factors	Factor Symbols	Treatment 1	Treatment 2	Treatment 3
Sharing location	a	1050–1150 mm section	750–850 mm section	450–550 mm section
Loading rate/(mm·min ^{−1})	b	100	300	500

3. Physical Properties Results and Analysis

3.1. Geometric Characteristics of Edible Sunflower Plants

Figure 6 depicts the statistical study of the geometric parameters of sunflower stalks. The statistics indicate that the heights of edible sunflower plants range from 1562 mm to 1985 mm. Figure 6a illustrates that plant heights predominantly fall within the intervals of 1550–1650 mm and 1750–1850 mm, accounting for 40% and 30% of the total sample population, respectively. Figure 6b displays stem diameter measurements recorded at distances of 100 mm, 200 mm, and 300 mm from the sunflower head, with ranges of 19.3–

31.7 mm, 19.1–32.9 mm, and 18.8–36.8 mm, respectively. Figure 6c indicates that the diameter of edible sunflower heads ranges from 207 mm to 324 mm, with the predominant samples (40%) situated between 260 mm and 280 mm. Figure 6d demonstrates that flower head thickness varies from 52 mm to 116 mm, with the majority of values (35%) clustered between 100 mm and 110 mm. The data reveal significant heterogeneity in the geometric traits of edible sunflower plants, primarily due to cultivar variances, planting density, and field management approaches. Therefore, it is essential that the primary components of harvesting apparatus for edible sunflowers demonstrate significant plasticity to handle variations in plant size, thereby enabling efficient harvesting with minimal waste.

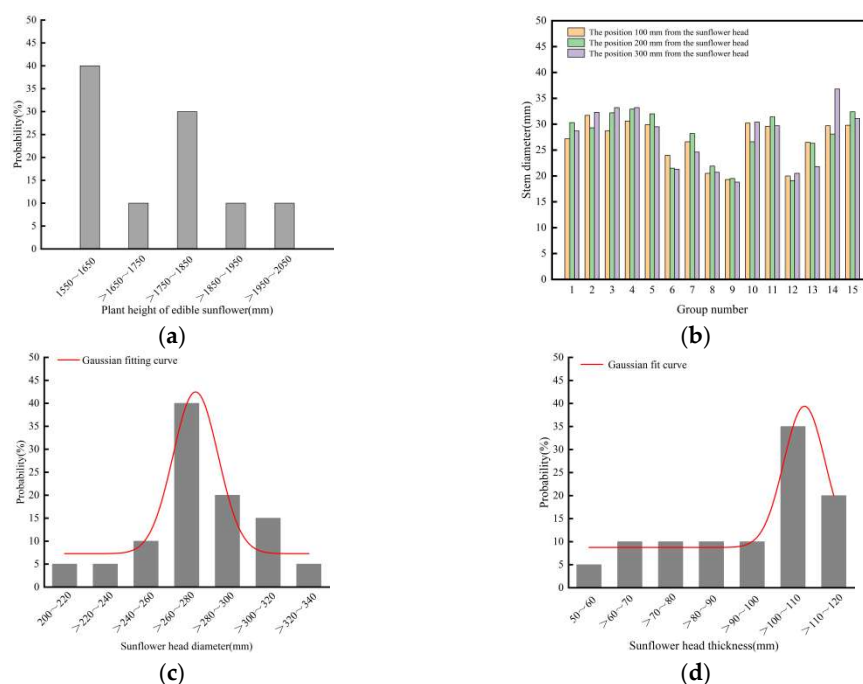


Figure 6. Preferential distribution of major physical parameters of edible sunflower. (a) Plant height distribution of edible sunflower, (b) Diameter distribution at different positions of edible sunflower stalk, (c) Head diameter distribution of edible sunflower, (d) Head thickness distribution in edible sunflower.

3.2. Critical Bending Angle of Edible Sunflower

The critical bending angles of sunflower plants were found to be $36.1 \pm 7.7^\circ$, $32.0 \pm 3.9^\circ$, and $26.9 \pm 6.3^\circ$ at heights of 700 mm, 800 mm, and 900 mm, respectively, as shown in Figure 7. With the increase in stem height, these findings suggest that the crucial bending angle is increasingly reduced. Stem diameter, wall thickness, and the degree of lignification all decrease as height increases, which is the primary cause of this pattern [39]. When stems were bent at 700 mm, fracturing was most prevalent in the root region. The stem segment between the marked point and the root exhibited increased thickness, lignification, and mechanical strength. As a consequence, the critical bending angle was elevated due to the necessity of a greater bending angle to induce fracture. In contrast, fracturing typically occurred near the mid-stem region at 900 mm, where the segment from the marked point to the root contained lower cellulose content and reduced lignification relative to the 700 mm segment. This structural composition increased the section's flexibility and susceptibility to fracture, resulting in a decrease in the critical bending angle to $26.9 \pm 6.3^\circ$. The essential bending angles at various marked positions along the edible sunflower stems exhibited statistically significant differences. As a result, the minimum critical bending angle should serve as the reference parameter for the design of crop dividers for edible sunflower headers in order to ensure structural integrity.

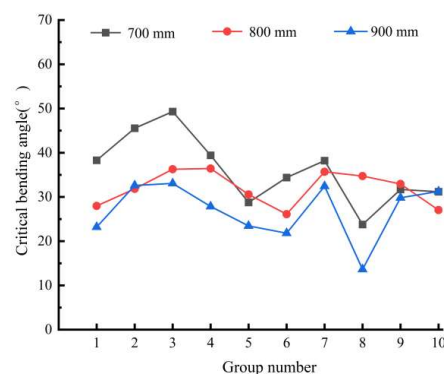


Figure 7. Critical bending angle at different marked positions of edible sunflower.

3.3. Static Friction Coefficient of Edible Sunflower

Friction angle measurements between edible sunflower components and a variety of interfacing materials are illustrated in Table 2. The static friction coefficient between sunflower stems and steel was measured to be between 0.24 and 0.31, while the coefficient between the rear surface (seedless side) of the edible sunflower head and steel was measured to be between 0.55 and 0.63. In the case of the edible sunflower head's front surface (seed-bearing side) in contact with steel, the static friction coefficient ranged from 0.39 to 0.45. Meanwhile, the static friction coefficient between two sunflower heads (front surfaces) ranged from 0.38 to 0.57. The data indicate that the static friction coefficients of the first three material pairings have a relatively low standard deviation and coefficient of variation, which suggests that the measurement is highly reliable and that there is minimal data dispersion. In contrast, the static friction coefficients between sunflower heads exhibit a higher standard deviation and coefficient of variation than the antecedent pairs. The intrinsic heterogeneity and non-uniformity of sunflower head material, along with surface attachments, interfacial processes, and unstable contact geometry conditions, are likely contributors to this increased variability [40–42]. Sunflower seed heads are intrinsically diverse, featuring densely arranged seed chambers that display spatial differences in density, fiber orientation, and rigidity. Friction measurements that indicate localized traits and hence display significant variability arise from the failure to accurately reproduce the microgeometry of the contact surfaces. Furthermore, the surfaces of sunflower seed heads may harbor residual moisture or other exudates, which, upon contact, might provide unpredictable and varied adhesive forces at the interface. Moreover, ensuring constant contact among similar sections of the seed heads throughout numerous tests is challenging, as minimal differences in placement can lead to markedly varied contact geometries.

Table 2. Static friction coefficient of edible sunflower.

Contact Material	Group Number										Average Value	Standard Deviation	Coefficient of Variation/%
	1	2	3	4	5	6	7	8	9	10			
Stem and steel	0.24	0.24	0.27	0.28	0.27	0.29	0.31	0.27	0.28	0.29	0.27	0.02	7.9
Sunflower disk back and steel	0.58	0.61	0.58	0.59	0.58	0.62	0.55	0.56	0.63	0.60	0.59	0.03	4.3
Sunflower head front and steel	0.40	0.39	0.42	0.42	0.45	0.40	0.43	0.41	0.44	0.45	0.42	0.02	5.1
Sunflower head front and front	0.38	0.44	0.45	0.54	0.52	0.45	0.42	0.57	0.49	0.53	0.48	0.06	12.6

3.4. Sunflower Seed Moisture Content

The moisture content of sunflowers encompasses both the stem and the flower head components. The results of the measurements are illustrated in Figure 8. As depicted in Figure 8, moisture content exhibits variation among different stem segments. Specifically, the moisture content within the 450–550 mm stem segment ranges from 55.7% to 72.8%, the 750–850 mm segment ranges from 57.7% to 73.7%, and the 1050–1150 mm segment ranges from 60.5% to 75.0%. Additionally, the moisture content of the flower head varies between 55.2% and 65.5%.

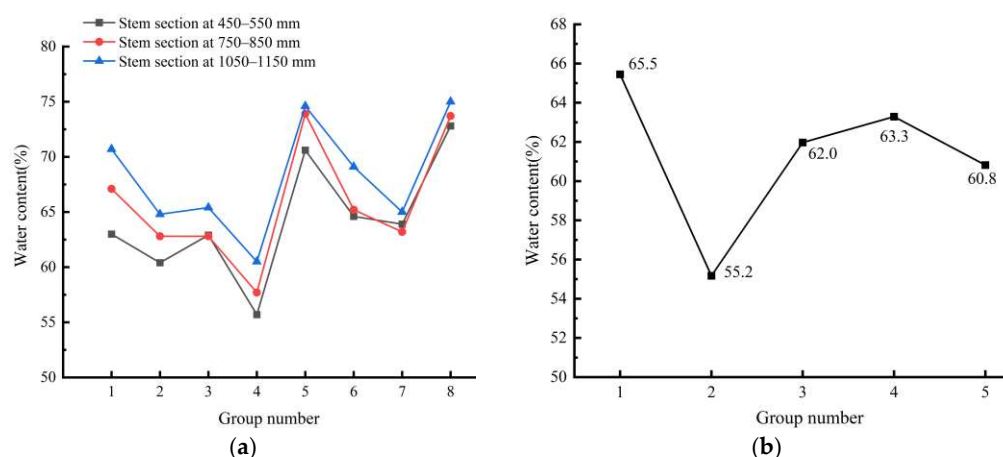


Figure 8. Results of moisture content measurement in edible sunflower. (a) Moisture content distribution in stalks, (b) Moisture content distribution in heads of edible sunflower.

The figure demonstrates that the moisture content of the stem segment between 450 and 550 mm is inferior to that of the segment between 1050 and 1150 mm, indicating a general elevation in stem moisture content with height. This pattern is ascribed to a decrease in lignification with increasing stem height. The basal stem areas include thicker cell walls that are rich in cellulose and lignin, which are characterized by low hydrophilicity. The lower stem's water retention capacity is intrinsically inferior to that of the upper parts [43]. The higher stem serves as the principal growth zone in edible sunflowers, characterized by significant cell division and metabolic activity. Elevated metabolic processes require significant water availability, serving both as a medium and substrate for biochemical reactions, and to sustain cell turgor pressure vital for growth. The moisture content of sunflower heads has a standard deviation of 3.87 and a coefficient of variation of 6.31%. This coefficient falls within the lower-middle range characteristic of physical property measures for agricultural materials, suggesting that the samples were sourced from recently harvested plants of the same cultivar grown under similar conditions. The constant-temperature drying technique utilized to ascertain moisture content is exceptionally precise, exhibiting minimal random error. Thus, the diversity in the observed data predominantly indicates biological variation across the samples rather than experimental errors [44].

3.5. Sunflower Head Seed Collision Loss Rate

The collision-induced loss characteristics of sunflower seeds were quantitatively assessed via impact testing. The correlation between collision velocity and loss rate is depicted in Figure 9. The findings reveal a distinct dependence of seed loss behavior on the velocity of impact. Specifically, when the collision velocity was less than 2 m/s, no seed loss was detected across all samples, indicating that the structural integrity of the sunflower head is maintained at velocities below this threshold.

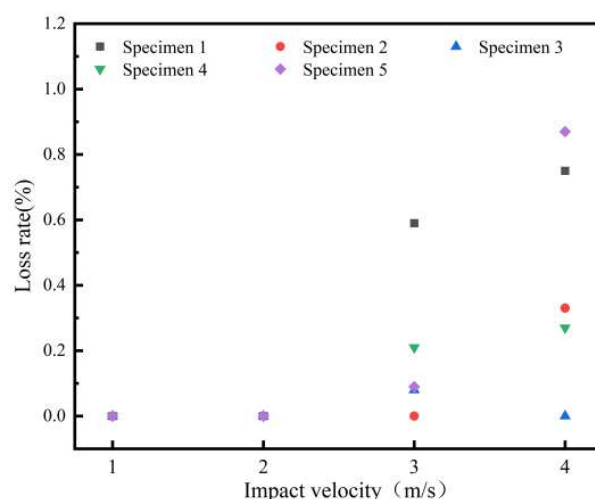


Figure 9. Impact velocity versus shatter loss for sunflower seeds.

As shown in Table 3, the data indicate that mechanical damage resulting in considerable grain loss begins at a velocity of 3 m/s, with an average loss rate of $(0.19 \pm 0.23)\%$. As the collision velocity reaches 4 m/s, the average loss rate markedly rises to $(0.44 \pm 0.36)\%$, reflecting a 132% increase. This trend suggests that increased contact energy amplifies the degree of seed loss. The experimental results within the velocity range of 3 to 4 m/s exhibit significant variability, attributable to the inherent variety of biological materials. This diversity presumably arises from individual variances among sunflower head samples, encompassing changes in moisture content, microstructural characteristics, and other aspects [45]. These elements jointly influence the material's response to external mechanical forces. The results indicate that the critical velocity threshold for mechanical damage and seed loss in sunflower heads ranges from 2 to 3 m/s. This insight provides essential guidance for the mechanical design of sunflower stalk cutting and heading equipment, along with the optimization of harvesting technology. It is advisable to keep the relative speed of mechanical contact components during operations below this essential threshold. Moreover, the intrinsic diversity of biological materials must be meticulously acknowledged. By reducing relative operating speeds or refining contact methods, seed loss during planting or harvesting can be minimized, hence improving the quality and efficiency of mechanical sunflower harvesting.

Table 3. Mean detachment rate of samples at different impact velocities.

Impact Velocity/(m·s ⁻¹)	Sample Size	Mean Loss Rate/(%)	Standard Deviation	Standard Error
1	5	0		
2	5	0		
3	5	0.19	0.23	0.10
4	5	0.44	0.36	0.16

4. Mechanical Properties Results and Analysis

4.1. Radial Modulus of Elasticity for Stems

Figure 10 illustrates typical load–displacement and stress–strain curves obtained from radial compression tests conducted on sunflower stems. Initially, the curves demonstrate quasi-linear behavior, indicative of elastic deformation. Upon reaching a peak value, this quasi-linear trend experiences a sudden decline. The maximum point of the quasi-linear region corresponds to the failure of the specimen, signifying the initiation of plastic deformation.

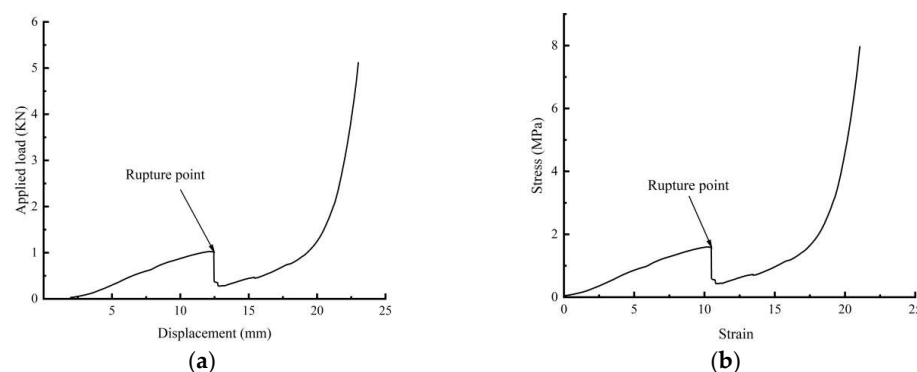


Figure 10. Representative load–displacement and stress–strain curves from radial compression of edible sunflower stalks. (a) Radial compression load–displacement curve, (b) Radial compressive stress–strain curve.

Employing Equation (5), the elastic modulus values were ascertained, and the results of the radial compression tests performed on edible sunflower stems are encapsulated in Table 4. The data reveal that the average radial elastic modulus for the stem segment measuring 450–550 mm is (1.26 ± 0.33) MPa; for the 750–850 mm segment, it is (1.16 ± 0.26) MPa; and for the 1050–1150 mm segment, it is (0.94 ± 0.18) MPa. The findings indicate a clear longitudinal gradient in the elastic modulus along the stem, likely due to a functional gradient in lignification. The basal section of the stem has heightened levels of lignin and cellulose, which visually correlate with enhanced elastic modulus and bending stiffness, therefore improving resistance to lodging [46]. Conversely, the apical part of the stem, serving as the principal growth zone, requires enhanced flexibility to endure environmental challenges and sustain active metabolic functions. The relatively reduced lignification in this area leads to a lower elastic modulus, consistent with the observed differences in the critical bending angle of sunflower stems.

Table 4. Elastic modulus from radial compression of stalks.

Elastic Modulus/MPa	Impact Velocity/(mm·min ^{−1})			Average Value	Standard Deviation	95% Confidence Interval
	10	20	30			
At 450–550 mm	1.58	0.93	1.27	1.26	0.33	[1.01,1.51]
At 750–850 mm	1.46	0.96	1.06	1.16	0.26	[0.96,1.36]
At 1050–1150 mm	1.14	0.81	0.86	0.94	0.18	[0.80,1.08]

4.2. Stem Shear Performance Parameters

Figure 11 illustrates a representative load–displacement curve obtained from the shear testing of sunflower stem specimens. In the initial phase of shear loading (Region I), the applied load exhibits a quasi-linear increase with displacement, reflecting reversible elastic deformation of the stem. Subsequently, in Region II, the rate of load increment diminishes, coinciding with localized plastic deformation and the progressive accumulation of microdamage within the stalk. Finally, in Region III, the applied load sharply declines to zero as displacement further increases, culminating in shear failure of the stalk and total structural collapse.

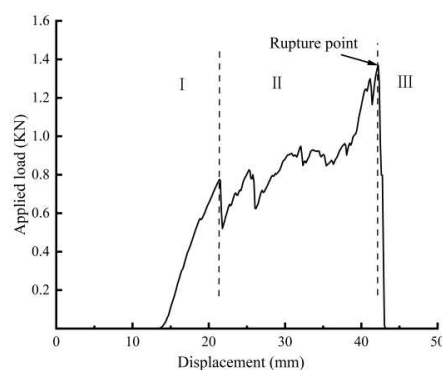


Figure 11. Representative load–displacement curve of edible sunflower stalk specimen during shear testing.

The protocol and outcomes of the stalk shear test are detailed in Table 5 below. As indicated in the table, the mean shear modulus for the stalk segment between 450 and 550 mm is 2.47 MPa, accompanied by an average shear strength of 1.87 MPa. In the 750 to 850 mm segment, the mean shear modulus decreases to 1.77 MPa, with an average shear strength of 1.56 MPa. For the segment spanning 1050 to 1150 mm, the average shear modulus further declines to 1.60 MPa, while the average shear strength is recorded at 1.51 MPa.

Table 5. Shear test experimental design and results.

Strength and Shear Modulus/MPa		Treatment Combination								
		a1b1	a2b1	a3b1	a1b2	a2b2	a3b2	a1b3	a2b3	a3b3
Shear modulus	Average value	1.34	1.78	2.64	1.48	1.71	1.89	1.97	1.83	2.87
	Standard deviation	0.25	0.10	0.88	0.47	0.33	0.26	0.68	0.36	0.20
Shear strength	Average value	1.78	1.57	1.65	1.36	1.39	1.65	1.39	1.72	2.30
	Average value	0.44	0.27	0.27	0.50	0.25	0.32	0.22	0.28	0.50

A range analysis was conducted using SPSS 26.0 software on a two-factor, three-level orthogonal experimental design to examine the stem shear modulus and shear strength. The results of this analysis are encapsulated in Table 6. Examination of the table reveals that the range values associated with factor a (shear location) consistently exceed those corresponding to factor b (loading rate). Thus, shear location becomes the primary determinant influencing both the shear modulus and shear strength.

Table 6. Range analysis table.

Test Index		a	b	Empty Column	
				1	2
Shear modulus	K1	4.79	5.76	5.06	5.92
	K2	5.32	5.08	6.13	5.95
	K3	7.40	6.67	6.32	5.64
	k1	1.60	1.92	1.69	1.97
	k2	1.77	1.69	2.04	1.98
	k3	2.47	2.22	2.11	1.88
	R	0.87	0.53	0.42	0.10
Shear strength	K1	4.53	5.00	5.15	5.47
	K2	4.68	4.40	5.23	4.73
	K3	5.60	5.41	4.43	4.61

k1	1.51	1.67	1.72	1.82
k2	1.56	1.47	1.74	1.58
k3	1.87	1.80	1.48	1.54
R	0.36	0.34	0.26	0.04

An analysis of variance (ANOVA) was performed to evaluate the significant effects of shear location and loading speed on the test parameters, namely shear modulus and shear strength. The findings of this investigation are encapsulated in Table 7. Table 7 demonstrates that shear position significantly influenced the shear modulus of the stems, but loading speed did not exert a statistically significant effect on this parameter. Moreover, neither shear location nor loading velocity exhibited a substantial impact on shear strength.

Table 7. ANOVA for the stalk shearing test.

Index	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	p	Significance
Shear modulus	a	1.269	2	0.634	7.758	0.042	*
	b	0.424	2	0.212	2.594	0.190	
	c (Total Error)	0.327	4	0.082			
Shear strength	a	0.224	2	0.112	1.633	0.303	
	b	0.172	2	0.086	1.255	0.377	
	c (Total Error)	0.274	4	0.069			

Note: An asterisk (*) indicates that the experimental factor is significant at the 0.05 level.

5. Investigation of Factors Influencing the Tensile Strength of Sunflower Stems and Heads

Conventional oilseed or grain heads are insufficient for the automated harvesting of sunflowers due to the plant's dimensions and distinct harvesting attributes [47]. In contrast, corn-harvesting stem-pull roll headers utilize rollers to apply downward force on the stems, aiding in the separation of stem heads through exerted pulling forces [48]. This method provides consistent and reliable traction, thereby addressing the difficulties posed by tall and robust sunflower plants [35]. Furthermore, it guarantees that the harvested heads have an upward-facing seed orientation, which is essential for subsequent head insertion procedures. The force required for stem-head separation is a critical determinant of the effectiveness of stem-pulling roller headers, impacting structural and operational attributes such as roller velocity, mounting configuration, and the spacing of head-removal plates. Consequently, examining the determinants affecting the breakage force of sunflower stem-head junctions and determining its optimal value is crucial for achieving an ideal amalgamation of operational parameters for effective, low-loss stem cutting and head insertion. This research offers essential data to guide the design and improvement of sunflower harvesting heads.

A sample of 27 sunflower plants was selected to investigate the factors influencing the breakage force of sunflower stem heads. The stems were severed 300 mm below the head and affixed to a self-made mechanical fixture that was intended to replicate the operation of a snapping-roller header. The fixture was composed of a fixed steel frame, a pair of adjustable head-picking plates, and a mounting bracket with a series of pre-drilled bolt holes, as shown in Figure 12. To accommodate varying head diameters, the spacing between the two plates can be adjusted to 50, 70, or 90 mm by repositioning the fasteners. The stalk-pulling roller-type header described in References [49–51] and the inherent limitations of the test equipment. Orthogonal experimental design was utilized, with tensile

speed (factor A), stalk-head separation distance (factor B), and tensile angle (factor C) identified as independent factors, while the stalk-head separation force served as the dependent variable. The elements and their respective levels are outlined in Table 8. To minimize experimental variability, each condition was assessed in triplicate, and the average value was documented.

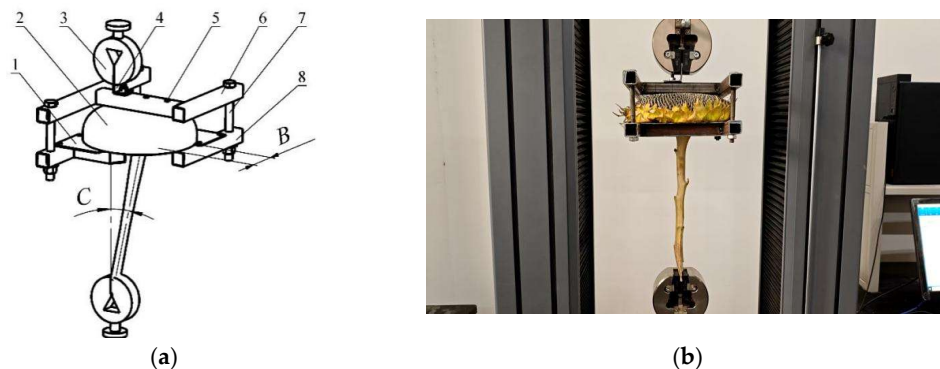


Figure 12. Tensile test for stalk-head separation force of edible sunflower. (a) Diagram of measurement: (1) Snapping plate. (2) Edible sunflower. (3) Fixture. (4) Fixed plate. (5) Angle adjustment hole. (6) Upper fixed frame. (7) Fastening bolt. (8) Lower fixed frame. (b) Site survey blueprint.

Table 8. Factors and levels in stalk-head tensile test.

Treatment	Experimental Factors		
	Tensile Speed A/(mm·min ⁻¹)	Snapping Roll Spacing B/mm	Tensile Angle C/°
1	100	50	0
2	300	70	5
3	500	90	10

Table 9 delineates the experimental design, outcomes, and range analysis. The mean tensile failure force from stem to harvesting plate is (256.1 ± 35.0) N, with the hierarchy $R2 > R3 > R1$. This signifies that the determinants affecting tensile failure force, ordered from most to least significant, are plate spacing, tensile angle, and tensile speed. The best factor combination for this test response, given that lower tensile failure force values are preferable, is A3B1C3. An analysis of variance (ANOVA) was performed to assess the statistical significance of the experimental conditions on tensile failure force, with the results presented in Table 10. The findings indicate that the distance between the harvesting plate and the sunflower head (factor B) significantly influences the tensile failure force ($p < 0.01$), due to fluctuations in the contact pressure at the interface between the sunflower head and the harvesting plate. The tensile angle (factor C) considerably influences the tensile failure force ($p < 0.05$), likely due to alterations in the spatial arrangement of the separation-layer structure under varying tensile directions. The cells in the separation layer exhibit heightened sensitivity to the orientation of the applied external force; stem-head separation transpires with minimal tensile force solely when the tensile direction aligns with or closely approximates the optimal fracture orientation of the separation layer. Tensile speed (factor A) does not significantly influence tensile failure force ($p > 0.05$). The insignificance may be attributed to the biomechanical characteristics of sunflower head separation, which demonstrates minimal sensitivity to changes in tensile speed. Within a specific speed range, the tensile force necessary for stem-head separation is predominantly determined by the mechanical characteristics of the separation layer and the orientation of the applied tensile force, rather than the tensile speed itself.

Table 9. Analysis results table.

Number	Tensile Speed A/(mm·min ⁻¹)	Snapping Roll Gap B/mm	Tensile Angle C/°	Error D	Tensile Failure Force F/N
1	1	1	1	1	240.6
2	1	2	2	2	252.8
3	1	3	3	3	273.8
4	2	1	2	3	232.5
5	2	2	3	1	228.8
6	2	3	1	2	316.7
7	3	1	3	2	201.7
8	3	2	1	3	268.2
9	3	3	2	1	290.0
K1	767.2	674.8	825.5	759.4	
K2	778.0	749.8	775.3	771.2	
K3	759.9	880.5	704.3	774.5	
k1	255.7	224.9	275.2	253.1	
k2	259.3	249.9	258.4	257.1	
k3	253.3	293.5	234.8	258.2	
R	6.0	68.6	40.4	5.1	
Order of fac- tor signifi- cance			B > C > A		
Optimal combination			A3B1C3		

Table 10. ANOVA for the stalk-head tensile test.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	η^2	Partial η^2	F	p	Significance
A	55.3	2	27.6	0.006	0.568	1.316	0.432	
B	7224.4	2	3612.2	0.738	0.994	171.947	0.006	**
C	2472.3	2	1236.1	0.252	0.983	58.842	0.017	*
D (error)	42.0	2	21.0	0.004				

Note: An asterisk (*) denotes a statistically significant effect at the 0.05 significance threshold, while a double asterisk (**) indicates a highly statistically significant effect at the 0.01 significance threshold.

To evaluate the reliability of the optimal parameter combination obtained from the orthogonal experiment, three sunflower heads were randomly chosen and subjected to repeated verification tests at a tensile speed of 500 mm/min, a tensile angle of 10° and a head-to-platen distance of 50 mm. The resultant stem-head break forces were 191.5 N, 209 N, and 206.5 N, respectively, with a coefficient of variation under 5%, signifying consistent and stable optimization results under these parameters. Moreover, in comparison to earlier recorded data, the relative error in break force was determined to be under 5%, which is within the permissible limits of engineering tolerance. These findings validate the dependability of the optimization outcomes.

6. Discussion

This work addressed the crucial lack of design specifications for mechanized harvesting equipment by methodically determining the mechanical and physical characteristics of edible sunflower (cv. SH363) at harvest maturity.

6.1. Analysis of Variability and Comparison with Current Data

The general pattern of diminishing lignification up the stem, as observed in maize and cotton stalks [17,20], is consistent with the mean stalk moisture content of 65% and the rising gradient from base to apex. This gradient explains the longitudinal decrease in the critical bending angle and radial elastic modulus: the more metabolically active upper stem shows increased flexibility, a functional characteristic that strikes a balance between lodging resistance and environmental resilience, while the higher lignification and thicker cell walls in the basal internodes confer greater rigidity [46]. Although the measured shear strength (1.65 MPa) and shear modulus (1.95 MPa) are similar to the shear mechanical parameters of sorghum stalks that have been previously reported [52], the wide dispersion suggests that biological heterogeneity has a major impact on the measured responses.

Compared to stem–steel (7.9%) or head–steel (4.3–5.1%) contacts, the static friction coefficient between sunflower capitula showed a coefficient of variation of 12.6%. The complex surface micro-topography of the seed-bearing face, unequal exudate and residual moisture distribution, and irregular contact geometry during inclined plane testing are all responsible for this increased variability [40–42]. The calibration of parameters for the discrete element method (DEM) is complicated by this fluctuation. Consequently, rather than using single deterministic values in simulation models, contact parameters for sunflower heads should be described by statistical distributions.

6.2. Rationale for Sample Size and Biological Diversity Representation

The limitations of testing novel biological materials with time-sensitive features are reflected in the sample sizes used in this investigation. Long testing times introduce systematic bias because sunflower stalk moisture content and mechanical qualities deteriorate quickly after harvest. In order to maintain the material's in situ harvest condition, sample sizes were chosen by striking a balance between statistical needs and the requirement to finish all measurements within 24 h of field collection.

In accordance with accepted procedures in agricultural material testing, a typical full factorial design with two variables and three levels is used for the orthogonal shear test [23,53]. Sampling location was effectively found as a significant factor ($p = 0.042$) by the analysis of variance (Table 7), indicating that the experimental design had sufficient statistical power to identify biologically relevant effects. Even though it is higher at collision velocities of 3–4 m/s, the coefficient of variation for impact loss rates (Table 3) effectively reflects the intrinsic variability of biological systems, which is an important engineering factor in and of itself. We recognize that bigger multi-location, multi-cultivar studies would improve the results' generalizability even more, and this is a top focus for future research.

6.3. Restrictions and Prospects for Further Research

This study has a number of limitations that should be noted. Only one cultivar (SH363), one harvest date, and one site (Urumqi, Xinjiang) were used in the tests. As a result, cultivar type, growth conditions, and harvest moisture content may all affect the reported parameter values. Furthermore, it is still unknown whether the identified parameters can successfully increase harvest performance, lower losses, or improve operational efficiency in actual field settings because the stem–head detachment test results have not been validated under field conditions using an actual harvester or prototype system.

In order to optimize overall harvest performance, future work should go in three main directions: (1) the measured physical and mechanical parameters should be used to calibrate discrete element method (DEM) simulation models of sunflower stalks and heads, enabling virtual prototyping of harvester headers; (2) the optimal snapping roll

spacing and tensile angle identified in this study should be combined with varying forward speeds and cutting heights in multi-factor field experiments; and (3) the dataset should be extended to multiple cultivars and moisture content levels in order to establish generalizable design envelopes for sunflower harvesting equipment that can be used in China's various production regions.

7. Conclusions

This study investigated the physical and mechanical properties of mature edible sunflower (cv. SH363) to support the parametric design of harvesting machinery and clarify biomechanical correlations with header performance. The core findings and engineering implications are summarized below.

1. Significant morphological heterogeneity was found in sunflower plants (1733 ± 153 mm plant height, 275 ± 28 mm head diameter, 93 ± 19 mm head thickness), requiring flexible and adjustable header cutting and snapping structures. Stem critical bending angles were 36.1° at 700 mm height and 26.9° at 900 mm height. Controlling stem deflection within this range avoids breakage and ensures stable crop feeding, providing key parametric constraints for crop divider design.
2. The head-to-head friction coefficient was 0.48, and the static friction between sunflower tissues and steel ranged from 0.24 to 0.63. A 12.6% variation in head contact friction indicates prominent parameter discreteness, demonstrating that probabilistic friction calibration is necessary for accurate discrete element method (DEM) simulation of sunflower material flow.
3. Sunflower stems showed an inverse longitudinal moisture gradient (55.7–72.8% at the base vs. 60.5–75.0% at the apex), corresponding to reduced lignification, elastic modulus and shear strength upwardly. Cutters should be optimized for low-moisture, rigid basal stems to reduce energy consumption and blade wear. Seed shedding occurs at a critical impact velocity of 2–3 m/s; limiting header conveying speed below 2 m/s effectively reduces harvest seed loss.
4. Orthogonal tests verified that snapping roll spacing extremely significantly affected head detachment force ($p < 0.01$), followed by tensile angle ($p < 0.05$), while tensile speed had no obvious effect. The optimal parameters (500 mm/min speed, 50 mm spacing, 10° angle) yielded a detachment force of 202.3 ± 9.5 N. Adjustable-spacing adaptive snapping mechanisms are therefore optimal for high-efficiency, low-loss head stripping.

This study quantifies key harvesting mechanical parameters and clarifies the internal harvesting mechanisms of SH363 sunflower. The obtained data and design criteria lay a foundation for developing regionally adaptive, high-efficiency, low-loss harvesting equipment and support the sustainable development of Xinjiang's edible sunflower industry.

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