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Determination of Physical-Mechanical Properties of Leek Plant (*Allium porrum* L.)

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HIGHLIGHTS

- In this study, physical and mechanical properties were determined using different cutting angles (30°, 45°, 60°) with flat (non-serrated) and serrated knives.
- In the leek plant, the highest cutting force was observed in the different regions (top, middle, bottom) of the plant, showing regional variations.
- The study showed that knife type (flat vs. serrated) significantly affects the cutting force and mechanical properties of leek.
- Cutting angles (30°, 45°, 60°) were found to play a crucial role in the physical and mechanical properties of leek.

Abstract

Leek is a vegetable grown towards the end of summer and harvested during fall. It is commonly found in the Asian diet and is grown worldwide. Consumed both fresh and dry, the mechanical properties of a leek plant need to be well-known with regard to the studies related to its production, processing, packaging, transport, and agricultural mechanization applications. This study aims to define the physical and mechanical properties of the leek plant (*Allium porrum L.*) used for agricultural purposes in Turkey. Conducted with different types of knives (flat, serrated) and different shearing angles (30, 45, 60°), shearing force, bio-yield force, rupture force, energy in rupture force, deformation, shearing stress, stress in rupture force, stiffness values have been determined for three different sections of leek plant. Furthermore, colour measurements have been performed for each section of the leek plant at three different heights. The highest shearing, bioyield force, and rupture force values have been defined respectively as 66.27±3.52, 53.02±2.82 and 48.15±33.71 N during the shearing made with a flat knife. The highest consumed energy value has been defined as 1.10±0.09 J in the studies conducted with the flat knife, while the lowest value has been defined as 0.23±0.12 J in the studies carried out with the serrated knife. The lowest deformation value was 25.37±1.18 mm in the experiments performed at a 45° knife angle with a serrated knife.

Keywords: Leek; Mechanization; Physico-mechanical properties,Turkey

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1. Introduction

In the lands of our country, suitable for ecologic structure and the agricultural production potential, where 81.5% of the 23.2 million hectare total cultivated area consists of field crop cultivation, greenhouse growing and fruit growing, while vegetables are grown in 3,4% (784 thousand hectares) of the cultivated area. In terms of most consistent vegetables over the years in terms of production and price, leek plant is one of the leading ones. Due to the inhibitory properties of Allium vegetables, it is thought to reduce the risk of prostate cancer, colorectal cancer, stomach cancer and breast cancer (Hsing et al. 2002). Leek (*Allium ampeloprasum L.*) is a rich source of secondary metabolites, including phenolic acids, flavonoids, and flavonoid polymers, which have significant health benefits. Leek exhibits various health benefits such as anti-asthma, antiseptic, diuretic, antibacterial, antioxidant, and antifungal properties. It is also beneficial in protecting the skin against damage and reducing the risk of gastrointestinal diseases diseases (Bernaert et al. 2014; Shahrajabian et al. 2021).

Leek is a commonly grown vegetable with significant benefits to human health. In previous times leek was being consumed during the winter only and it was produced accordingly, however, the possibility of growing it in each season has nowadays made it almost a year-long vegetable.

Leek (*Allium porrum L.*), similar to onion and garlic, is a member of Allium variety and Alliceae family, produced in wide areas and in great quantities in Turkey and from time to time it is also exported in fresh form, too (Figure 1). Leek is a vegetable that can be grown in every season and mostly grown for its leaves and stalk. In Turkey it is mostly consumed as a winter vegetable but it can be cultivated in almost all regions as it is not a picky vegetable in terms of climate. In Mediterranean and Aegean Regions it can be left on field surface in winter season and harvested at any time (Altunkanat 2019).

Leek is making up a significant part of winter vegetable consumption in Turkey. Leek production in Turkey takes place in an approximate area of 8.000 ha annually and production figure in 2018 was 252.958 ton (TÜİK 2020).

Along with an increased demand to vegetables in food sector, vegetable prices have a continuous tendency of increasing in the whole world and in recent years total yield in vegetable production has increased by 30-35%. Further to these, leek can be exported by being dried or frozen, all of which makes it possible that leek production will keep growing (Abak et al. 2010).

Figure 1. Summer and winter leek plants

Mechanization applications are being employed within agricultural production activities such as harvesting, threshing, transporting, cleaning, industrial processing and packaging. However, these applications are not fulfilled properly and this leads to loss and damaging of products. Such drawbacks need to be decreased and mechanization applications need to be increased and developed to achieve high yield and quality production. Furthermore, characteristics of an agricultural product need to be well-understood to ensure that agricultural products lose their properties at a minimal level during the post-harvest processes (Babayiğit 2010). For many years, studies have been concentrating on the field of harvest mechanisation of cereals and legumes. However, the number of studies on mechanization practises used in harvest and post-harvest processes in vegetable cultivation is not sufficient. The development and increase of such practises require a good knowledge on the mechanical properties of vegetables that are consumed both fresh and dry. The purpose of this study is to determine the mechanization related physical and mechanical properties of leek plant (*Allium porrum L.*) used for agricultural purposes in Turkey. Conducted by using different knife types (flat, serrated) and different knife cutting angles (30, 45, 60°), This study revealed key mechanical properties of the leek plant, including shearing force, bioyield force, and rupture force. Additionally, energy in rupture point, shearing stress, deformation, and stiffness values were determined across three different sections of the plant. Studies took place with 3 repetitions at 700 mm/min knife speed. Furthermore, colour measurements have been taken for each section at 3 different heights of the leek plant.

2. Materials and Methods

As an experimental material, 'İnegöl 92' variety, a summer leek plant (*Allium Porrum L.*) has been used in this study. Summer varieties are in light-green colour, they have soft textures, shorter lifespans and are more vulnerable against cold. Their stem lengths are 2-3 times longer than the winter varieties can extend up to and 80 cm (Anonym 2013). Materials acquired from the market have been brought to Isparta University of Applied Sciences, Faculty of Agriculture and analysed in Harvest Technologies Laboratory.

In the study, the weight, stalk diameter, and stalk length values of the leek, which may be important in mechanization applications, were determined. The leek plant is divided into 3 sections, which are upper, middle, and lower sections, starting from the root and extending to the point where the leaves start bending (Figure 2). Diameter values of Sections A, B, C have been defined, and cutting took place with three repetitions for each section. Stalk diameter is an important and practical parameter to characterise the leek plant. Stem diameter must be known to define the stress occurring on the plant. The impact on stress values by diameter values at different heights needs to be known (Khan et al. 2010).

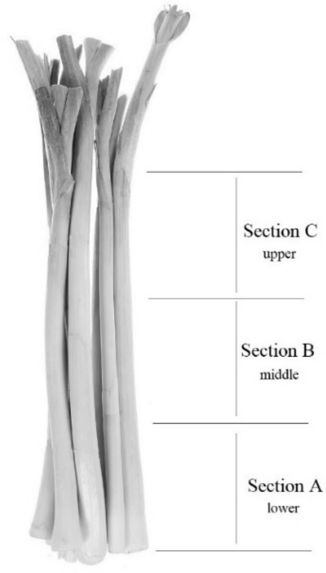

Figure 2. Definition of leak stem.

The physico-mechanical properties of a biologic material are being use for harvest and post-harvest processing to design harvest, transport, storage and grinding machines (Yılmaz et al 2015). Measurements to determine the physical and mechanical properties have been conducted by using a LLoyd (Lloyd Instrument LRX Plus, Lloyd Instruments Ltd, An AMATEK Company) biologic material test device (Figure 3). This device consists of a platform it has been placed in and a moving part, a unit making the movement possible and a data processing unit. The data processing unit consists of a load cell with 500 N capacity, a computer with a

NEXYGEN Plus software where data is transmitted. The technical specifications of the device are provided in Table 1.

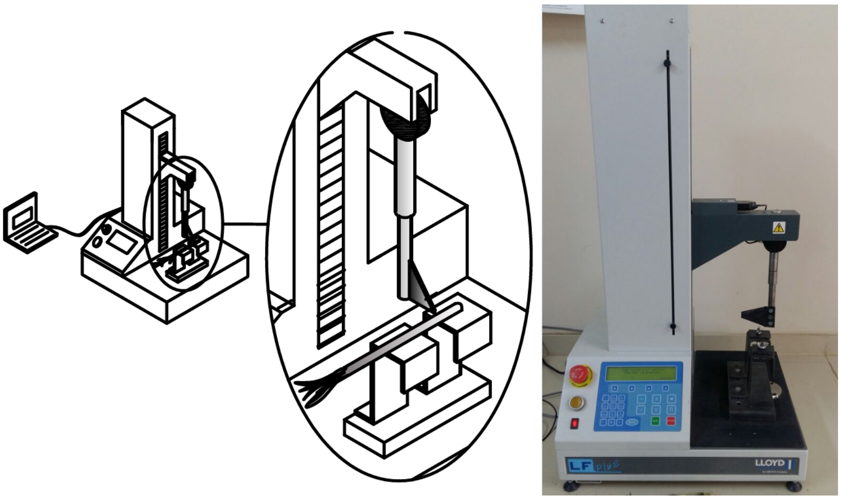

Figure 3. Biologic material test device

Table 1. Technical specifications of the biological material testing device

MODEL	LFPlus
Maximum Load Capacity	1 kN
Movement Speed	0.05-1270 mm/min
Speed Accuracy	<0.2%
Measurement Distance	500 mm
Application Accuracy	Less than 0.005% of the used load cell
Extension Measurement Accuracy	<1.3 microns
Data Storage Rate	8 kHz
Extensometer Input	Digital and Analog
Data Output	Digital RS232, Analog 10V DC max. (Optional)
Measurement System	Complies with BS EN ISO 7500:1999, ASTM E4, DIN 51221 standards
Analysis Software	NEXYGEN FM, NEXYGEN MT Data Analysis Software, and Ondio Software for Advanced Applications
Power Supply	115/230V AC ±10% 50-60 Hz
Weight	46 kg

Experiments in the study have been conducted with 3 repetitions on 3 different heights of plant stalk by using 2 types of knives and 3 different knife angles (Figure 3). Shearing force, rupture force, and deformation were measured using a high-precision testing machine (e.g., Lloyd Instrument LRX Plus) equipped with a calibrated load cell. Leek samples were secured in the apparatus, and the shearing process was conducted at 30°, 45°, and 60° angles. Force-displacement data was recorded in real-time to identify peak and rupture forces, which occurred when the leek structure failed. Deformation was measured by tracking the displacement of the blade through the leek, calculated as the difference between the initial and final positions of the blade, ensuring accurate capture of minimal deformations.

Figure 3. Colorimeter used in experiments

By shearing the leek plant at horizontal plane, its mechanical properties such as stalk shearing force, bioyield force, rupture force, shearing stress, deformation, stress in rupture point, deformation in rupture point, energy in rupture point and stiffness have been defined. Furthermore, L, a* and b* values of Sections A, B and C have been defined by using PCE-CSM colorimeter (Figure 4). The technical specifications of the device are provided in Table 2. CIE Lab is being widely used for the colour measurement of colour space products. CIE Lab colour space has three coordinates. L* value represents black for 0.0, white for 100.0, a* value represents green if negative and red if positive, and b* value represents blue if negative and yellow if positive (Kuş et al. 2017; Çetin 2019).

Figure 4. Colorimeter used in experiments

Table 2. The technical specifications of PCE-CSM colorimeter

Geometry	8°/d
Aperture	Ø 6 mm
Sensor	Silicon photoelectric diode
Color spaces	CIE L*a*b*C*h, CIE L*a*b, CIE XYZ
Color difference formula	ΔE*ab, ΔL*ab, ΔE*C*H
Observation Angle	CIE 10°
Light source / device	D65/ LED blue light
Errors between each equipment	≤0.80 ΔE*ab
Repeatability	Standard deviation within ΔE*ab 0.08; Average of 30 measurements of standard white plate
Power supply	Rechargeable lithium-ion battery; 3.7 V @ 3200-mAh
Lamp life	5 years, more than 1.6 million measurements
Storage conditions	Air temperature: 0 ... 40°C / 32 ... 104°F; Air humidity: 0 ... 85% RH, non-condensing

3. Results and Discussion

In this study, the mechanical properties of leek (*Allium porrum* L.) were investigated using different knife types (flat and serrated) and cutting angles (30°, 45°, 60°). The results indicate that the cutting force, bio-yield force, rupture force, rupture energy and deformation of the leek plant vary significantly depending on the knife type and cutting angle.

The lengths of the leek plants which have been subjected to cutting experiments at different harvest heights range between 31-65 cm. Average weight value of leek plant has been defined as 89.56 g. Plant stalk average diameter values calculated as per shearing heights (Sections A, B and C) are given in Table 3. The average brightness value of leek (*Allium porrum L.*) samples used in the study has been defined as (L*) 60.96±13.27, a* value has been defined as 3.49±0.60 and b* value has been defined as 28.44±10.91.

Table 3. Diameter values of leek stem based on cutting heights

Average plant size (cm)	Shearing Heights	Diameter (mm)		
		Average (mm)	Standard Deviation	Variation Coefficient (%)
48.6	Section A	15.84	4.41	27.86
	Section B	14.68	4.21	28.66
	Section C	13.83	4.16	30.04

The diameter values of leek stalk which has been cut at different cutting heights have ranged between 8.07-25.50 mm. Average diameter values in Sections A, B and C have been respectively defined as 15.84±4.41, 14.68±4.21 and 13.83±4.16 mm. A decrease has been observed in the diameter values, depending on plant structure, starting from root and extending to the point where the leaves start making an angle with the stalk.

The results show that flat knives require more cutting force during the shearing process compared to serrated knives. This finding is consistent with the study by Khan et al. (2010), which reported that flat knives encounter greater resistance than serrated knives, primarily due to the latter's ability to better engage the fibrous structure of the plant. The lower cutting force of the serrated knife is attributed to its efficiency in cutting through the fibers with less resistance, thus reducing the overall mechanical load during cutting (Yilmaz et al., 2015). These findings are consistent with the recent work of Petitkan et al. (2019), who also observed that the type of cutting tool significantly affects the mechanical properties of the plants. Mechanical properties of the plant stalk observed through experiments conducted with a flat knife with 3 different cutting angles (30, 45, 60°) and different harvest heights are given in Table 4.

Table 4. Average cutting parameters of plant stalk in different cutting heights and knife angles (flat knife)

Shearing Height	Shearing Angle	Shearing Force	Bio-Yield Force	Rupture Force	Energy in Rupture Point	Deformation	Shearing Stress	Stress in Rupture Force	Stiffness
		(N)	(N)	(N)	(J)	(mm)	(MPa)	(MPa)	(N/mm)
Section A	30°	66.27 ±3.52	53.02 ±2.82	47.19 ±7.63	1.10 ±0.09	38.41 ± 3.78	0.26 ±0.06	0.18 ±0.02	7.13 ±1.56
	45°	61.97 ±34.71	49.58 ±27.77	48.15 ±33.71	0.70 ±0.58	27.25 ±4.48	0.22 ±0.03	0.16 ±0.04	8.02 ±1.36
	90°	60.91 ±18.09	48.72 ±14.47	47.21 ±13.19	1.09 ±0.84	41.30 ±3.82	0.23 ±0.13	0.17 ±0.10	7.58 ±3.52
Section B	30°	59.50 ±14.69	47.60 ±11.75	37.52 ±26.70	0.72 ±0.29	41.18 ± 1.97	0.22 ±0.04	0.13 ±0.09	5.58 ±1.40
	45°	52.70 ±21.88	42.16 ±17.51	36.03 ±26.74	0.50 ±0.28	30.55 ± 2.62	0.23 ±0.09	0.11 ±0.04	5.23 ±1.80
	90°	48.93 ±27.25	39.14 ±21.80	36.98 ±19.14	0.51 ±0.43	36.89 ±7.83	0.19 ±0.13	0.14 ±0.10	5.69 ±1.31
Section C	30°	40.34 ±9.87	32.27 ±7.90	25.62 ±8.83	0.43 ±0.16	43.06 ±1.45	0.15 ±0.04	0.10 ±0.03	4.61 ±0.82
	45°	36.92 ±19.78	29.54 ±15.83	21.01 ±19.53	0.26 ±0.23	29.53 ±4.87	0.16 ±0.08	0.06 ±0.05	4.41 ±1.49
	90°	46.16	36.92	31.76	0.39	42.41	0.17	0.11	5.45

		±8.44	±6.76	±4.56	±0.05	±1.49	±0.08	±0.05	±1.92

As the plant shearing height increased (Sections A, B and C) in experiments conducted with a flat knife in different cutting angles, a decrease in shearing force, bioyield force, rupture force, consumed energy and stress values has been observed, depending on diameter values. Highest shearing and bioyield force values have been observed as 66.27±3.52 and 53.02±2.82 N respectively in Section A at 30° cutting angle. The highest rupture force has been observed as 48.15±33.71 N in Section A in experiments conducted at 45° cutting angle. Energy values consumed for cutting have been observed to be higher in experiments conducted at 30° and 90° cutting angles in Section A. The highest energy value in rupture point has been observed as 1.10±0.09 J while the lowest value has been observed as 0.26±0.23 J in Section C with a 45° cutting angle. Studies have shown that the peak force and specific energy required to cut vegetables are heavily influenced by the knife edge angle and the texture of the vegetable. Our findings indicate that a lower cutting angle, such as 30°, requires higher shearing force due to increased fiber engagement in the leek stalk. This observation is supported by Singh et al. (2016), who demonstrated that lower knife edge angles, particularly at low cutting speeds, result in higher resistance and specific energy requirements when cutting vegetables with diverse textures.

Deformation during the shearing process was measured using a test device that recorded the movement of the blade as it cut through the leek. Deformation was calculated as the difference between the initial and final positions of the blade, ensuring that even small changes in the structure of the leek were accurately captured. An increased amount of deformation has been observed in plant stalk in cutting experiments conducted with 30° and 90° cutting angles. An increase in leek stalk stiffness value is leading to decreased deformation. The lowest deformation amount has been observed as 27.25±4.48 mm in Section A with a 45° cutting angle. The surface graphic which shows the interactions between cutting parameters of flat knife experiment and cutting height and cutting angle is given in Figure 5.

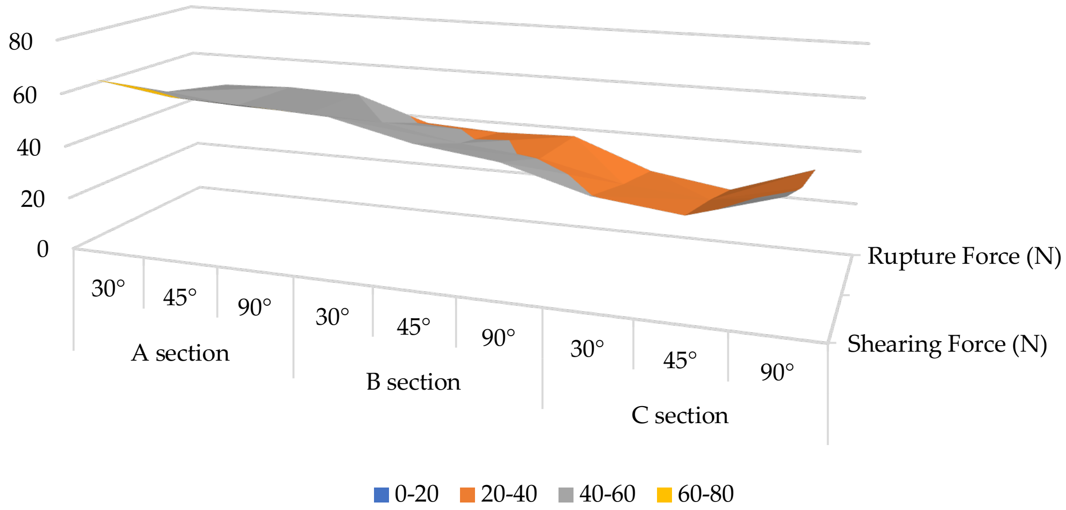

Figure 5. The interaction between cutting parameters of flat knife experiment and cutting height and cutting angle

The figure effectively illustrates the significant effect of both cutting angle and section height on the mechanical properties of the leek. The results suggest that a 45° cutting angle provides a balanced approach that minimizes both shear and fracture forces at different section heights, while a 30° angle requires the highest forces due to increased fiber engagement. These findings are critical for optimizing cutting techniques in agricultural practices to achieve efficiency while maintaining product integrity.

Mechanical properties of the plant stalk cut by serrated knife in 3 different cutting angles (30, 45, 60°) and in different harvest heights is given in Table 6.

Table 6. Average cutting parameters of plant stalk in different cutting heights and cutting angles (serrated knife)

Shearing Height	Shearing Angle	Shearing Force	Bio-Yield Force	Rupture Force	Energy in Rupture Point	Deformation	Shearing Stress	Stress in Rupture Force	Stiffness

		(N)	(N)	(N)	(J)	(mm)	(MPa)	(MPa)	(N/mm)
Section A	30°	47.70 ±14.01	38.16 ±11.21	23.38 ±12.32	0.54 ±0.20	41.61 ± 1.57	0.28 ±0.08	0.13 ±0.02	4.75 ±0.96
	45°	46.56 ±6.74	37.25 ±5.40	20.70 ±9.86	0.44 ±0.01	25.37 ±1.18	0.39 ±0.08	0.17 ±0.07	4.50 ±0.90
	90°	61.03 ±18.09	48.82 ±14.47	22.75 ±13.19	0.70 ±0.46	49.63 ±1.41	0.51 ±0.12	0.16 ±0.13	5.14 ±0.93
Section B	30°	38.58 ±9.89	30.86 ±7.91	24.24 ±8.05	0.39 ±0.13	44.57 ± 2.35	0.23 ±0.04	0.14 ±0.02	4.12 ±0.89
	45°	43.36 ±15.40	34.69 ±12.32	22.21 ±11.45	0.38 ±0.14	27.21 ± 1.73	0.36 ±0.15	0.25 ±0.14	3.79 ±0.95
	90°	54.33 ±20.23	43.47 ±16.18	20.73 ±24.64	0.57 ±0.33	53.28 ±4.07	0.40 ±0.03	0.14 ±0.14	4.44 ±1.23
Section C	30°	30.55 ±12.78	24.44 ±10.23	21.71 ±3.72	0.23 ±0.12	44.71 ±2.06	0.17 ±0.01	0.13 ±0.04	3.15 ±1.16
	45°	36.64 ±12.99	29.31 ±10.39	16.10 ±12.11	0.32 ±0.12	29.58 ±2.16	0.31 ±0.12	0.13 ±0.09	3.51 ±0.94
	90°	46.74 ±21.24	37.39 ±16.99	21.44 ±25.16	0.44 ±0.27	53.45 ±0.56	0.35 ±0.09	0.16 ±0.15	4.29 ±1.32

In experiments conducted with serrated knife, decrease has been observed in shearing and bioyield force values as the cutting height of leek plant increased. However, the same values have been observed to be high again in experiments conducted with a 90° cutting angle. The highest shearing and bioyield force values have been observed in Section A at 90° cutting angle as 61.03±18.19 and 48.82±14.47 N, respectively. Plant stalk rupture force value has been observed to be higher, 24.24±8.05 N, at the mid-part of the plant stalk (Section B). Energy values in rupture point were lower in Section C, while the highest value has been observed in Section A of the plant stalk as 0.70±0.46 J when cut by a 90° cutting angle. With regards to the experiments conducted by using a serrated knife, the highest shearing stress value has been observed in Section A by 0.51±0.12 MPa at 90° cutting angle, while the highest stress in rupture point has been observed in Section B by 0.25±0.14 MPa at 45° cutting angle. And the amount of deformation that occurred as a result of cutting with a serrated knife has showed a tendency to increase, in parallel to the increase in cutting height and the amount of deformation decreases as plant stiffness decreases. The lowest deformation amount has been observed, again, in Section A as 25.37±1.18 mm in experiments conducted at 45° cutting angle. The surface graphic which shows the interactions between cutting parameters of serrated knife experiment and cutting height and cutting angle is given in Figure 6.

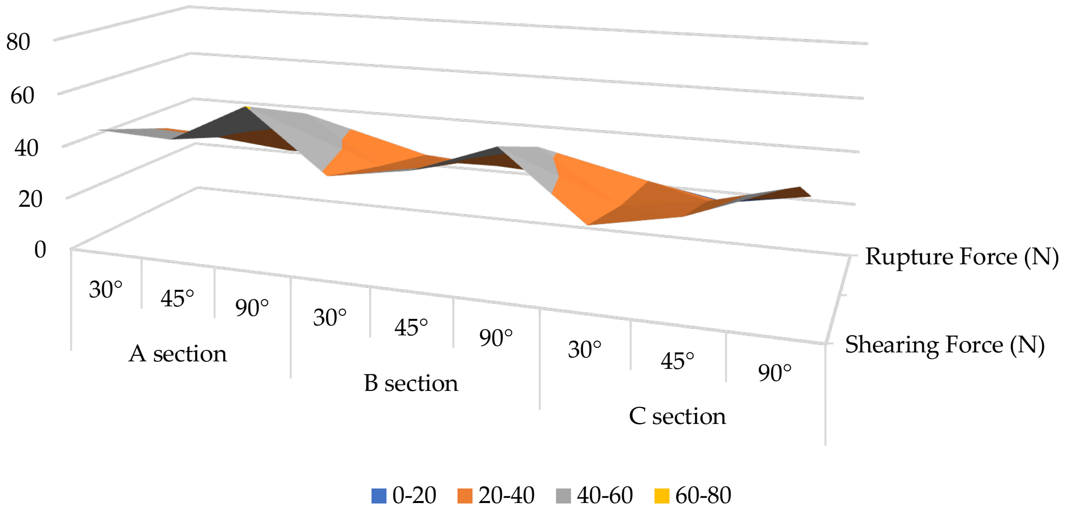

Figure 6. The interaction between cutting parameters of serrated knife experiment and cutting height and cutting angle

The figure clearly demonstrates the benefits of using a serrated knife for cutting leek, particularly in terms of reducing the required shearing and rupture forces. The results indicate that a 45° angle may be the most efficient for cutting across different sections of the leek, balancing force requirements and cutting precision. These findings can inform the selection of cutting tools and angles in both agricultural and industrial applications to optimize efficiency and product quality.

4. Conclusions

In this study, the effects of knife type and cutting angle on the mechanical properties of leeks were investigated in detail. Our results indicate that both factors significantly influence the efficiency and quality of the cutting process. According to study results, cutting parameters of leek plant vary depending on harvest heights and knife type. Shearing force, bio-yield force, rupture force, energy in rupture point and stiffness values of cutting actions at different stalk heights have been observed to be higher in experiments conducted with a flat knife than those conducted with a serrated knife. Deformation and stress values, on the other hand, are observed to be higher in experiments conducted with a serrated knife.

The comparison between flat and serrated knives showed that the serrated knife required less cutting force and improved the precision of the cut, minimizing tissue damage. This is attributed to the serrated knife's ability to better engage the fibers of the leek, thereby reducing the resistance encountered during cutting.

Furthermore, the analysis of the cutting angles showed that the angle at which the knife intersects the leek plays a key role in determining the mechanical response of the vegetable. Among the angles tested, a cutting angle of 45° was found to be optimal, balancing the applied cutting force and minimizing the deformation of the leek tissue. This suggests that knife orientation during cutting can be optimized to improve cutting efficiency and product quality.

In conclusion, this research highlights the importance of selecting appropriate cutting tools and angles to improve the mechanical processing of leeks. These findings can be useful for both agricultural practices and the food processing industry, contributing to improved cutting techniques and quality control. Future studies can explore the application of these findings to other vegetables and cutting scenarios, thereby extending the scope of this research

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