Optimization of the Canola Harvester Blade Based on Energy Reduction Approach and Life Cycle Assessment

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Abstract

Grain harvesting operations account for approximately 25-30% of total direct energy consumption in crop production systems. Developing appropriate blades for harvesting canola (*Brassica napus* L.) is crucial due to its distinct characteristics compared to other cereal grains. This study investigated the effects of blade angles (placement angles: 30°, 45°, and 60°; sharpness angles: 30°, 45°, and 60°), reciprocating movement speed (800, 1100, and 1400 courses per minute), and moisture levels (19%, 22%, and 24%) on reducing force, shear stress, and energy consumption during canola harvesting. Results showed that a blade sharpness angle of 30° yielded the lowest shear stress (0.175 N mm^{-2}) compared to 60° (0.303 N mm^{-2}). The 45° blade placement angle demonstrated minimum shear stress (0.177 N mm^{-2}) versus 60° (0.320 N mm^{-2}). Increasing moisture content from 19% to 24% reduced shear stress from 0.256 N mm^{-2} to 0.200 N mm^{-2}. The highest reciprocating speed (1400 courses per minute) resulted in the lowest shear stress (0.167 N mm^{-2}) compared to 800 courses per minute (0.286 N mm^{-2}). Life cycle assessment revealed that varying blade placement angles (30° to 60°) could increase marine aquatic ecotoxicity by up to 55,762.55 kg dichlorobenzene equivalent, while changes in blade sharpness angles and reciprocating speed could lead to increases of 377,429.87 kg and 143,185.69 kg dichlorobenzene equivalent, respectively. The optimal configuration—comprising a sharpness angle of 30°, a placement angle of 45°, a moisture content of 24%, and a reciprocating speed of 1400 courses per minute—significantly reduced both shear energy and environmental impact.

Keywords: Blade placement angle, Blade sharpness angle, Life cycle impact assessment, Shear energy, Shear stress

Introduction

In recent years, reducing energy consumption in agricultural machinery has become increasingly important, particularly in EU open-field agriculture where total energy usage reaches 1431 PJ annually, equivalent to 3.7% of total EU energy consumption. Within this sector, on-farm diesel use, which includes harvesting operations, accounts for 31% of total energy inputs. This significant proportion highlights the importance of optimizing agricultural machinery operations, especially in grain harvesting machines, to reduce overall energy consumption and support the transition towards more sustainable farming practices (Paris *et al.*, 2022). The energy required for cutting canola stems varies from 0.76 kJ to 1.1 kJ, depending on moisture content and cutting height, representing a measurable component of harvesting energy consumption. Understanding these energy requirements is important for optimizing harvester blade design and operational parameters to improve overall harvesting efficiency (Azadbakht, Esmaeilzadeh, & Esmaeili-Shayan, 2015). Numerous studies have already been undertaken to optimize energy consumption related to the cutting process of reciprocating lathes (Kushwaha, Vashnav, & Zoerb, 1983;

Mohammadi Baneh, Navid, Alizadeh, & Ghasem Zadeh, 2012; Yin *et al.*, 2021; Yuan *et al.*, 2023).

Canola cultivation is expanding, particularly in tropical regions, as a crucial source of edible oils. Canola harvesting employs two primary methods: (1) using grain combines with specific adjustments, and (2) utilizing a reciprocating cutter bar followed by product collection using a combine with a pick-up nose. While wheat combines are commonly adapted for canola harvesting, the distinct physical and mechanical properties of canola stems necessitate specialized blade design. A study by Azadbakht *et al.* (2015) demonstrated that cutting energy requirements vary significantly ($P < 0.01$) with cutting height and moisture content, ranging from 0.76 kJ at 11.6% moisture content and 30 cm cutting height to 1.1 kJ at 25.5% moisture content and 10 cm cutting height, with an optimal blade velocity of 2.64 m s^{-1}. Baruah & Panesar (2005) reported that crop throughput for canola ranges from 3.87 to 17.85 Mg h^{-1}, compared to 4.61 to 11.49 Mg h^{-1} for wheat, highlighting the need for crop-specific optimization. Several parameters, including blade edge angle, blade angle, blade cutting speed, and product moisture, significantly influence the power and energy requirements in cutter bar harvesters. Therefore, determining optimal values for these parameters is crucial for designing efficient canola harvesting tools. Therefore, by determining the appropriate value for these parameters, they can be used as criteria in the design of canola harvesting tools.

Several studies have been conducted in relation to the energy consumption of cutter bar mowers. According to many studies, the energy required by the stem cutting unit in the cutter bar includes overcoming air friction, cutting products, overcoming the friction of crushed products, and especially the friction in the mechanism of the machine and the cutting stem (Chattopadhyay & Pandey, 2001; Kronbergs, 2000). Studies have shown that several key factors influence the energy required to cut wheat stems. The moisture content, which refers to the water present in the wheat stem, affects its physical properties and cutting resistance. The cultivar type, meaning the specific variety of wheat with its unique stem characteristics such as thickness and fiber density, also impacts cutting energy requirements. The blade angle, defined as the angle at which the cutting blade meets the wheat stem, and cutting speed, which is the rate at which the blade moves through the stem, are crucial mechanical parameters. When moisture content and blade angle were reduced while increasing cutting speed, the energy required for cutting decreased. The diversity factor, which encompasses the variability in physical properties among different wheat varieties and environmental growing conditions, was also found to significantly affect cutting energy requirements (Persson, 1987).

A study was conducted to examine the impact of various factors on the shear strength and energy consumption of wheat stems during the design and construction of a cutting mechanism for clustered wheat. The research focused on three levels of blade sharpness (17, 20, and 24 degrees), four levels of inclination angle (20, 35, 50, and 65 degrees), and three levels of cutting speed (25, 35, and 45 mm min^{-1}). The results indicated that both the inclination angle and blade sharpness had a significant influence on the shear strength and energy consumption of wheat stems, with significance at the 1% level. However, there was no significant interaction effect observed between the angle of sharpness, inclination angle, and cutting speed. Among the two factors, the inclination angle of the blade had a greater impact on the shear strength and energy consumption of the stems. The average cutting energy consumption per unit area was estimated to be 6.23 mJ mm^{-2}.

A study explored the impact of various cutting unit parameters on energy consumption during the harvesting of Miscanthus plant. The researchers specifically focused on analyzing the effects of cutting speed, diagonal blade angle, and stem diameter on energy consumption. Within their investigation, three different blade cutting angles were taken into consideration. The findings of the study revealed that a diagonal blade angle of 60 degrees and a cutting speed of 12.9 m s^{-1} were identified as the optimal conditions for efficient cutting of the product. Under these conditions, the specific cutting energy was measured to be 741.9 J m^{-1}. However, it was observed that when the cutting speed was increased to 18.7 m s^{-1}, the specific cutting energy experienced a significant rise of 42.6% (Johnson, Clementson, Mathanker, Grift, & Hansen, 2012).

The impact of cutting parameters on the ultimate shear stress and specific cutting energy of Sisal leaves was investigated to design efficient and energy-saving harvesting machinery. In their study, they experimentally examined hybrid (H.) 11648 sisal leaves (at 83% moisture content) using both the single-factor method and response surface methodology under quasi-static cutting conditions. The findings indicated that factors such as cutting speed, blade oblique angle, blade entry angle, and leaf elevation angle significantly affect the ultimate shear stress and specific cutting energy of the leaves. Additionally, the interaction between the blade oblique angle and leaf elevation angle had a notable effect on ultimate shear stress, while the combination of cutting speed and blade oblique angle significantly influenced specific cutting energy. The optimal cutting parameters identified through the multi-objective response equation were a cutting speed of 500 mm min^{-1}, a blade oblique angle of 24.23°, a blade entry angle of -28.8°, and a leaf elevation angle of 20°. With these settings, the ultimate shear stress and specific cutting energy for sisal leaves could be reduced by 43.48% and 10.71%, respectively, compared to conditions typical of practical harvesting. Furthermore, within acceptable limits for ultimate shear stress and specific cutting energy, increasing cutting speed and employing parameter values close to the optimized settings can positively impact peak cutting force reduction, energy efficiency, and the compactness of harvesting machinery (Song *et al.*, 2022).

In a significant study focusing on blade design optimization and energy reduction, Maughan, Mathanker, Grift, Hansen, and Ting (2013) investigated the impact of blade oblique angles on harvesting energy requirements. Their research directly addressed machinery inefficiencies by modifying the disk head of a mower-conditioner and testing different blade angles. Through implementation of blades with 20° and 30° oblique angles, they achieved substantial energy savings. Most notably, the 30° oblique angle blades demonstrated a 27% reduction in energy consumption, requiring only 13.5 MJ Mg^{-1} compared to 18.5 MJ Mg^{-1} for conventional straight (0°) blades. Their study incorporated real-time yield sensing systems to provide point-specific energy consumption data, offering precise measurements of blade performance optimization.

In terms of optimizing harvester blade parameters, Rezahosseini, Jafari Naeimi, and Mortezapour (2019) investigated the effects of forward velocity and blade attack angle on harvesting efficiency. Their findings revealed that both parameters significantly affected harvesting performance at a 5% probability level. The optimal configuration was achieved with a 25-degree attack angle and 2 km h^{-1} forward velocity, resulting in 80% harvesting efficiency. Notably, the highest machine capacity of over 5300 plants per hour was achieved at 3.5 km h^{-1} forward velocity while maintaining the optimal 25-degree attack angle. Their research demonstrates the critical relationship between blade angle optimization and operational parameters.

Recent studies have demonstrated the significant impact of blade design parameters on harvesting efficiency. Okyere *et al.* (2022) conducted a comprehensive analysis of blade angles and operational parameters, finding that a 45° blade angle produced optimal cutting performance compared to 30° and 60° angles. Their study revealed that machine speed significantly affects cutting efficiency, with 2230 rpm yielding the best results when combined with the optimal 45° blade angle.

While their research focused on corn stalks, their findings about blade angle optimization provide valuable insights for harvester blade design across different crops. Their results suggest that blade angle optimization can significantly impact both cutting efficiency and machine performance.

Agricultural harvesting efficiency is highly dependent on crop-specific cutting equipment. Each crop has unique physical properties that demand specialized cutting blades- for instance, wheat stems have different structural characteristics compared to canola stems, making wheat harvester blades unsuitable for canola harvesting. Using inappropriate blades can lead to increased energy consumption, reduced harvesting efficiency, and potential crop damage.

Previous studies on harvester blade optimization have primarily focused on mechanical performance and energy consumption for individual crops. However, these studies lack a comprehensive life cycle assessment approach, which is crucial for understanding the broader environmental implications of harvesting equipment choices. By integrating LCA with energy optimization, this study introduces a novel framework that considers both operational efficiency and environmental impact.

Additionally, this research develops an innovative methodology that combines mechanical testing, energy analysis, and environmental assessment - creating a more holistic approach to agricultural equipment design. This integrated approach not only optimizes harvester blade performance for canola but also establishes a transferable methodology for other crop-specific applications.

Previous studies have indicated that the blade sharpness, blade placement angle, moisture content, and cutting speed play crucial roles in reducing shear energy and energy consumption in cutter bar harvesters. Given that most harvesting combines in Iran are equipped with heads designed for wheat harvesting, it is imperative to explore the impact of these factors on canola harvesting due to the distinct characteristics of wheat and canola. Utilizing optimized reciprocating cutter bars for canola harvesting could be beneficial in this regard. By identifying the optimal values for these parameters, it is possible to minimize energy usage and environmental pollution. Thus, the objective is to assess the potential impact of adjusting the specified parameters on the reduction of energy consumption and the release of pollutants into the environment. This involves determining the extent to which these changes can contribute to minimizing environmental impacts. Therefore, the primary objective of this study was to analyze the influence of blade sharpness, blade positioning angle, moisture, and cutting speed on canola harvesters to ensure sustainable and efficient production. To achieve this aim, the following specific objectives were pursued:

1. To develop an innovative energy-optimization model for canola harvester blades by analyzing the relationship between energy consumption and cutting parameters (moisture content, loading rate, and blade characteristics) using a specially designed laboratory setup.
2. To quantify energy reduction potential through comparative analysis of different blade designs and operational parameters, establishing energy-efficient cutting conditions.
3. To evaluate the environmental impacts through Life Cycle Assessment, creating an integrated framework that optimizes both energy efficiency and environmental performance.

Materials and Methods

Design and development of a cutting mechanism are influenced by many parameters, such as the type of cutting blade, blade angle, cutting speed, and physical and mechanical properties of the stalks. The latter can be identified by measuring the shear force required for stalk cutting. The canola stalk samples were collected from mature plants at physiological maturity. The stalks had an average height of 120 ± 5 cm and stem diameter of 1.5 ± 0.2 cm at the base. For the cutting tests, the load was applied at 15 cm above ground level, which represents the typical harvesting height in commercial canola production. This location was chosen because it provides optimal stubble height for subsequent field operations. Also, it ensures consistent mechanical properties as the lower portion of the stalk typically has higher structural rigidity. Likewise, it matches common harvester header settings.

A test rig (Figure 1) was developed to determine the shear force of the canola stalk, while adjusting the aforementioned parameters. It consisted of a chassis, a stationary blade holder, a cutter bar, a crank drive and crank drive linkage, a 380 V AC motor (Y-802-4, 0.75 kW), and an inverter. In addition, the system included a measuring unit, an electronic board (Uno R3, Arduino Co., Italy), a 24-bit analog-to-digital converter (HX71, China), and a computer for data collection and monitoring. The aim was to identify the most optimal mode in terms of energy consumption during stalk cutting. This was carried out by a measurement system assembled on the crank drive linkage using a 40 kg ± 0.01 g load cell (Top Sensor, China). The load cell was placed between the crank drive linkage and the beginning of the cutter bar to accurately capture the force exerted during cutting operations.

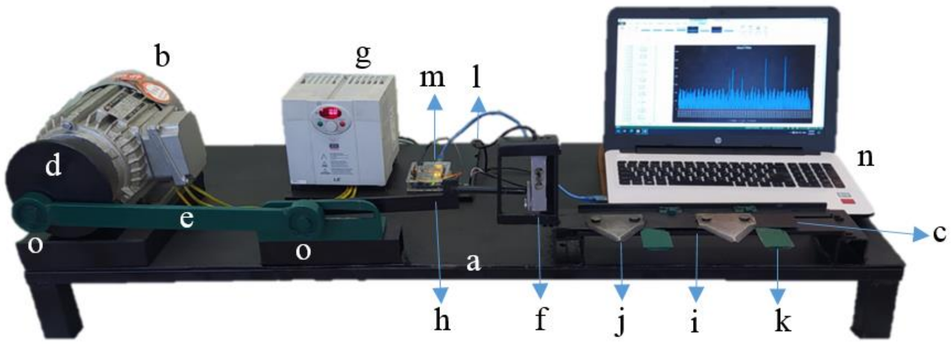

Fig. 1. The fabricated laboratory cutter bar: (a) Chassis, (b) Electric motor, (c) Upper bar, (d) Reluctance center crank drive, (e) Crank drive shaft, (f) Load cell, (g) Inverter, (h) Connecting rod, (i) Lower bar, (j) Cutting blade, (k) Designed blade, (l) HX711 amplifier module, (m) Arduino board, (n) Computer, and (o) Bearing

The experiments were carried out to determine the shearing force of the canola stalks and to analyze the impact of various parameters such as blade edge sharpness angle (30, 45, and 60 degrees), blade angle (30, 45, and 60 degrees), and cutter bar speed at 800, 1100, and 1400 courses per minute. The length of the course was set at 7.6 cm, and the experiments were conducted at three different moisture levels ranging from 18-21%, 21-23%, and 23-25%. The measurements were based on shear force, shear strength, and shear energy, and each condition was tested in triplicate. A sample of the manufactured device is shown in Figure 1. To further investigate the influence of these parameters on the cutting force and shear resistance of canola stalks, a factorial experiment was conducted using a completely random design in SPSS software, with three replications.

Blade angles of 30°, 45°, and 60° were selected based on empirical observations and prior studies (Johnson *et al.*, 2012; Heidari, Chegini, & Kianmehr, 2012). Angles below 30° are avoided in coarse-stemmed crops due to accelerated blade wear (Persson, 1987), while angles exceeding 60° significantly increase shear resistance, as observed in preliminary trials for this study. Reciprocating speeds (800-1400 cpm) were chosen to align with typical combine harvester operations in Iran, where adjustments are often made to balance cutting efficiency and fuel consumption (Yuan *et al.*, 2023). Moisture levels (18-25%) reflect the range observed during canola harvesting in Kurdistan province, as verified by field measurements.

To develop the energy-optimization model, various blade designs were analyzed for their potential energy efficiency. The blade characteristics were first modeled using SolidWorks (2018) to establish baseline designs. These designs were then evaluated using Ansys 2015 software to understand their mechanical behavior under different loading conditions, which directly influences energy consumption during cutting. The key blade characteristics that influence energy consumption are presented in Table 1. The blades were fabricated using CK75 steel (properties shown in Table 2), selected based on its mechanical properties that affect energy transfer during the cutting process (Roudbari, Refahati, & Mehdipour, 2021).

Table 1- Mechanical and physical properties of the designed blades (Roudbari *et al.*, 2021)

Density (kg m^{-3})	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)	Ultimate tensile stress (MPa)	Yield stress (MPa)
7850	200	0.3	76.92	460	250

Table 2-Specifications of the material of the blades (Roudbari *et al.*, 2021)

Mechanical properties		
Quantity	**Value**	**Unit**
Young,s modulus	200000	MPa
Tensile strength	650-880	MPa
Elongation	8-25	%
Fatigue	275	MPa
Yield strength	350-550	MPa
Physical properties		
Quantity	Value	Unit
Thermal expansion	10	e-6 K^{-1}
Thermal conductivity	25	W (m K)$^{-1}$
Specific heat	460	J (kg K)$^{-1}$
Melting temperature	1450-1510	°C
Density	7700	kg m^{-3}
Resistivity	0.55	Ohm mm^2 m^{-1}

The blades were designed and underwent meshing in the Ansys environment, as shown in Figure 2. The design of the blades in this study was guided by rigorous adherence to engineering standards and methodologies to ensure mechanical reliability, environmental sustainability, and alignment with industry practices. Material selection prioritized CK75 steel, a high-performance alloy conforming to ASTM A20/A20M-19 and ISO 6935-1:2018 standards, ensuring optimal tensile strength, fatigue resistance, and thermal stability for agricultural applications. The material's mechanical properties, such as Young's modulus and yield strength, were sourced from standardized databases (e.g., Ansys material libraries) to maintain accuracy in computational simulations.

Finite element analysis (FEA) was conducted using ANSYS 2015, an industry-standard software compliant with ISO 10303 (STEP) for geometric modeling. An automatic meshing strategy was employed to optimize computational efficiency, avoiding the labor-intensive process of manual meshing.

Blade geometry was informed by prior research (Nazari Galedar *et al.*, 2008; Song *et al.*, 2022) and designed to balance cutting efficiency, energy consumption, and stress distribution. Angles of 30°, 45°, and 60° were validated via FEA to ensure compliance with von Mises stress criteria, confirming safe operation within CK75 steel's yield strength limits.

Automatic meshing procedure was employed since a tedious trial and error were required to accomplish appropriate mesh size. Automatic meshing with tetrahedral elements was selected to balance computational efficiency and accuracy, given the geometric complexity of the blade edges and mounting slots. A mesh sensitivity analysis was conducted by iteratively refining element sizes until stress convergence (variation <5%) was achieved at critical regions (blade edge and support interface). For 30°, 45°, and 60° blade angles, a total of 10,361 nodes and 5,380 elements, 11,741 nodes and 5,510 elements, and 11,903 nodes and 6,181 elements were employed, respectively.

The boundary conditions applied in Ansys aimed to replicate real-world operational constraints. The base of each blade (mounting region interfacing with the cutter bar) was assigned a fixed support to simulate rigid attachment to the harvesting mechanism. A tension force of 350 N was applied perpendicular to the blade's sharp edge, distributed uniformly across the blade edge, to reflect the maximum shear stress derived from experimental shear force measurements. The safety factor of 5 was incorporated to account for dynamic loading fluctuations during field operations, such as irregular stem density or foreign object impacts.

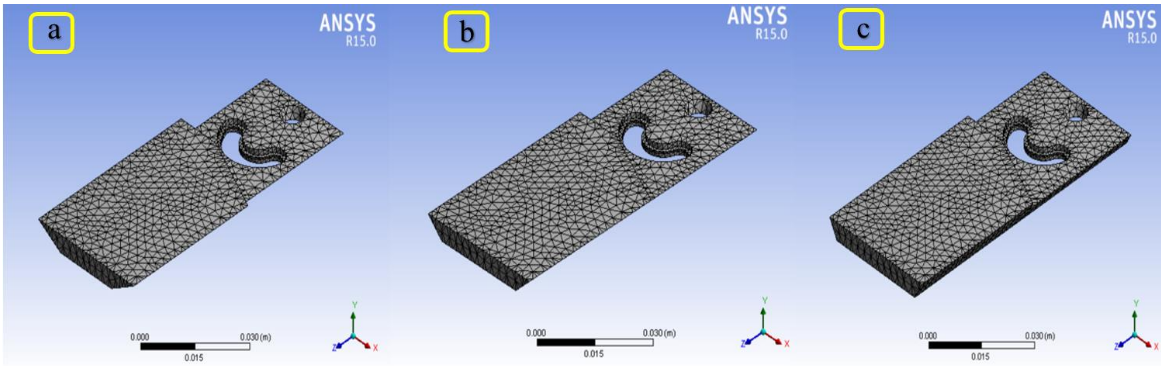

Fig. 2. Meshed models of three different designed blades: (a) the 30-degree blade, (b) the 45-degree blade, and (c) the 60-degree blade

The diagram illustrating the designed blades can be observed in Figure 3. The measurements are expressed in millimeters. The blades were subjected to the maximum force and tension required for cutting canola. To simulate the behavior of the blades during the cutting process, the maximum shear stress needed to cut the stalk was determined. The shear stress was applied to the blades based on the findings of Nazari Galedar *et al.* (2008), with the stress being directed towards the sharp edge of the blades perpendicular to their surface. A tension force of 350 N, with a safety factor of 5, was applied to the edge of the blades and results were expressed as Von Mises stress. Two blades were made for each specification of blade angle degree of 30, 45, and 60 degrees for further reservation.

The FEA simulations were conducted using ANSYS 2015, adhering to ISO 10303 standards for geometric modeling. The analysis incorporated the von Mises criterion to assess yielding, ensuring stresses remained below CK75 steel's yield strength (250 MPa). Elastic deformation was modeled using Hooke's Law, while plastic deformation was accounted for beyond the yield point. A safety factor of 5 was applied to the 350 N tension force, reducing the effective load to 70 N for simulations, aligning with engineering safety protocols.

The theoretical framework for stress analysis included elastic-plastic material behavior, where stresses below the yield point (250 MPa) ensured reversible deformation. Beyond this threshold, plastic deformation was modeled to identify failure risks. The 30° blade angle demonstrated the lowest shear stress (0.737 N mm^{-2}) but required FEA validation to confirm compliance with safety margins. Stress maps revealed potential plastic deformation at blade edges and supports, prompting design adjustments to redistribute loads and enhance durability.

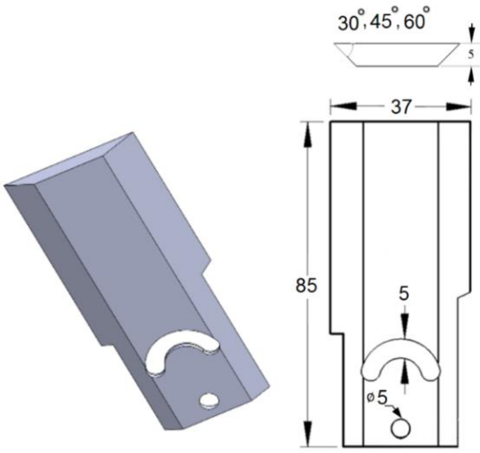

Fig. 3. Schematic of the designed blades (dimensions are in mm)

The Hyola 401 canola cultivar was cultivated in Kurdistan province of Iran during the summer of 2020. This area is situated within the latitudes of 34° to 38°N, and longitudes of 41° to 47°E. Simple random sampling served as the sampling technique for this research.

Once the samples were gathered, they were transported to the laboratory of the Department of Biosystems Engineering, Faculty of Agriculture, University of Kurdistan, Iran to assess the moisture content of canola stalks. The collected stem samples were carefully positioned inside an oven, where they were subjected to a controlled temperature of 103°C for a duration of 24 hours. Subsequently, the moisture content of the samples was measured using Eq. 1, which adheres to established standards and is based on the wet weight of the specimens (Aghbashlo, Kianmehr, & Hassan-Beygi, 2008; Yeganeh & Trystram, 2013):

$$U_w = \frac{G_w}{(G_w + G_{dm})} \quad (1)$$

where, G_w represents the weight of lost moisture, and G_{dm} represents the weight of the dried sample. To measure the dimensions of the canola stem, including length, width, and thickness, a digital caliper (model DC-515, Taiwan) with an accuracy of 0.01 mm was used.

Mechanical attributes refer to a material's mechanical characteristics in various conditions and under diverse external loads. Mechanical qualities vary depending on the substance. Typically, the "tension-compression" examination and the "force-deformation" relationship (stress-strain) are employed to ascertain and elucidate the mechanical properties of materials (Song & Muliana, 2019). When it comes to harvesting agricultural products, these materials are subjected to different mechanical factors such as compressive force, tensile force, and impact. These factors can lead to deformation in the stem of the products, and if the deformation exceeds a certain limit, it can result in breakage and other forms of mechanical damage. To prevent such damage, it is crucial to understand the resistance characteristics of the product's stem under different conditions. This information can be obtained through standardized tests conducted under controlled conditions. The pressure tensile test is one of the key methods used to determine the product's stem tissue properties. Several factors influence the mechanical properties of agricultural products, including the structure and texture of the product, its moisture content, the speed and type of loading, as well as the duration of loading (Amirian, Shahbazi, & Taheri Garavand, 2018).

The quasi-static tests were performed using a hydraulic Instron stand (STM-1 model, 1000±0.01 N) to determine the shear forces, shear stress, and compressive strength of canola, where the specimen is crushed at a very low speed between two cutting edges. A quasi-static test is described as the energy absorption capability of the composite when they are crushed under axial loads (Figure 4). The tests were conducted by crushing specimens at a controlled speed between two cutting edges. The room temperature was (23±2°C) and the relative humidity was 50±5%. The experiments were performed at three different loading rates of 150, 250, and 350 mm min^{-1}, with 50 mm maximum displacement and 100 Hz data acquisition rate. The specimens were prepared with 11.57 mm length and 10.46 mm stem average diameter. Throughout the experiments, various measurements were recorded, including force-displacement curves, maximum shear force (N), shear stress (MPa), energy absorption (mJ), and compressive strength (MPa). The quasi-static test characterizes the energy absorption capability of the specimens when crushed under axial loads, providing crucial information about their mechanical behavior under controlled loading conditions.

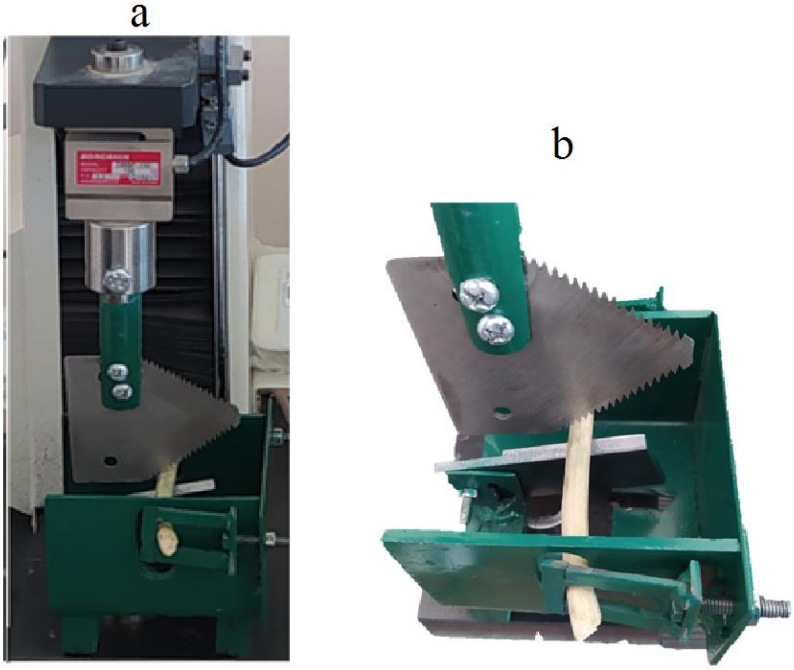

Fig. 4. A mechanism designed for conducting quasi-static tests: (a) an Instron equipped with a blade and counter blade mechanism, and (b) the blade and counter blade mechanism

The Shear Energy Index was determined to evaluate the energy efficiency of the cutting process. This index was calculated as the ratio of the energy absorbed during shearing to the cross-sectional area of the specimen, expressed in mJ mm^{-2}. The energy absorption was obtained by integrating the area under the force-displacement curve up to the maximum shear force using the trapezoidal method. The force-displacement data were recorded through the Instron testing machine’s data acquisition system at a sampling rate of 100 Hz.

In order to assess the environmental impact of utilizing different blades and their placement angles in agricultural combines on a national scale, the life cycle assessment approach was employed. The total amount of pollutants released into the environment was calculated under the assumption that all agricultural combines in the country were outfitted with each of the blade treatments. This analysis aimed to determine the extent to which these treatments could potentially influence the overall level of pollutants emitted nationwide.

Life cycle assessment represents a cutting-edge approach extensively employed for evaluating the energy requirements and possible ecological consequences of a product or manufacturing process from inception to end. The comprehensive "cradle to grave" technique encompasses a thorough examination of all phases, including resource extraction, material production, component manufacturing, and product consumption management in the form of waste, recycling, or final disposal (Mirzaee, Salami, Akhijahani, & Zareei, 2023).

In this research, the SIMAPRO software version 9 utilized the CML 2 baseline 2000 V2.05 life cycle impact assessment method. This particular method, developed by the Swiss Federal Institute of Technology, adopts a comprehensive approach that encompasses various impact groups and injury groups. It incorporates ten midpoint impact groups, providing a holistic perspective on the assessment of life cycle impacts. The midpoint impact categories were: abiotic depletion (elements and fossil fuels), global warming, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication.

Results and Discussion

Finite element analysis of blades

The stress analysis and deformation results of the blades were examined when subjected to a constant force of 350 N, with consideration given to various types of blades that were manufactured.

The stress analysis and blade displacement results obtained through Ansys software for the blades with a sharpness of 30, 45, and 60 degrees are illustrated in Figure 5. Upon closer examination of the stress distribution for the first blade type (I), it was evident that the highest stress concentration occurred at the edge of the blade and in close proximity to the support, reaching a value of 30.618 MPa. This stress concentration is primarily attributed to the blade being constrained within the slot and coming into contact with a steel object (pin) at the support location under actual operating conditions. Analysis of the blade deformation revealed that the maximum displacement of 1.0703×10^{-5} m was observed at the blade tip. Given that the blade can be likened to a beam subjected to a significant lateral load, it is reasonable to expect that the most significant deformation would manifest at the tip of the blade, akin to the tip of a beam. Figure 5 shows the profiles of deformation and maximum stress for the application of a 350 N load.

The stress and deformation analysis outcomes for the second blade type (II) are also illustrated in Figure 5. The findings for the second blade type mirrored those of the first blade type concerning the position of the highest deformation and the peak Von Mises stress. Specifically, the highest deformation was detected at the blade's tip, measuring 7.854×10^{-6} m, while the maximum Von Mises stress was identified at the support's edge, measuring 19.712 MPa.

Figure 5 also presents the stress and deformation analysis results for the third type of blade (III). Similar to the first and second type blades, the third type blade exhibited comparable patterns in terms of the location of the largest deformation and the maximum Von Mises stress. Upon examining the deformation results, it was observed that the tip of the blade experienced a maximum displacement of 6.7606×10^{-6} m, additionally, the highest stress was observed at the edge of the blade and in close proximity to the support, measuring 16.692 MPa.

The maximum Von Mises stress was found to decrease as the blade angle increased, with values of 30.618 MPa, 19.712 MPa, and 16.692 MPa recorded for 30°, 45°, and 60° angles, respectively. Similarly, the maximum displacement at the blade tip demonstrated a decreasing trend with increasing angle, measuring values of 1.0703×10^{-5} m, 7.854×10^{-6} m, and 6.7606×10^{-6} m for the respective angles. For all three configurations, the highest stress concentration was consistently observed at the blade edge near the support region, where the blade was constrained within the slot and contacted the steel pin under operating conditions. The maximum displacement invariably occurred at the blade tip, behaving similarly to a beam under lateral loading. These results indicate that increasing the blade angle from 30° to 60° led to a 45.5% reduction in maximum stress and a 36.8% decrease in maximum displacement, suggesting enhanced structural stability at higher angles.

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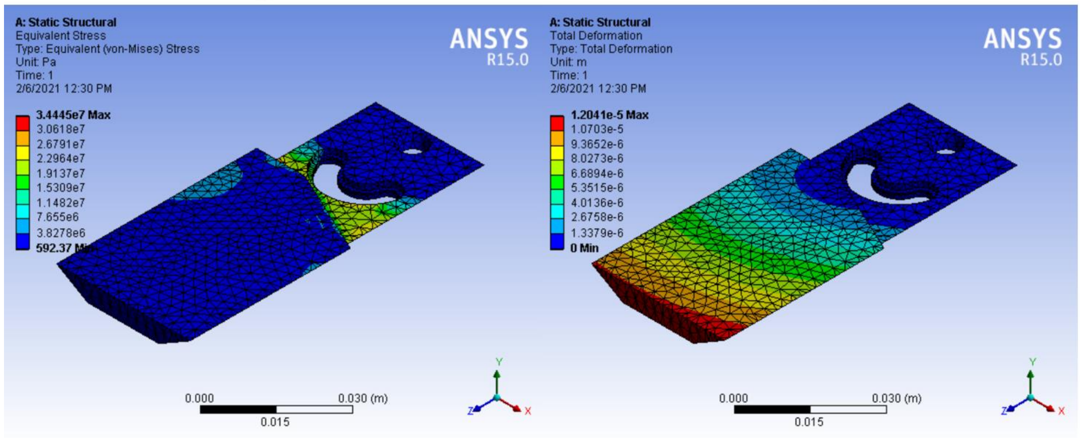

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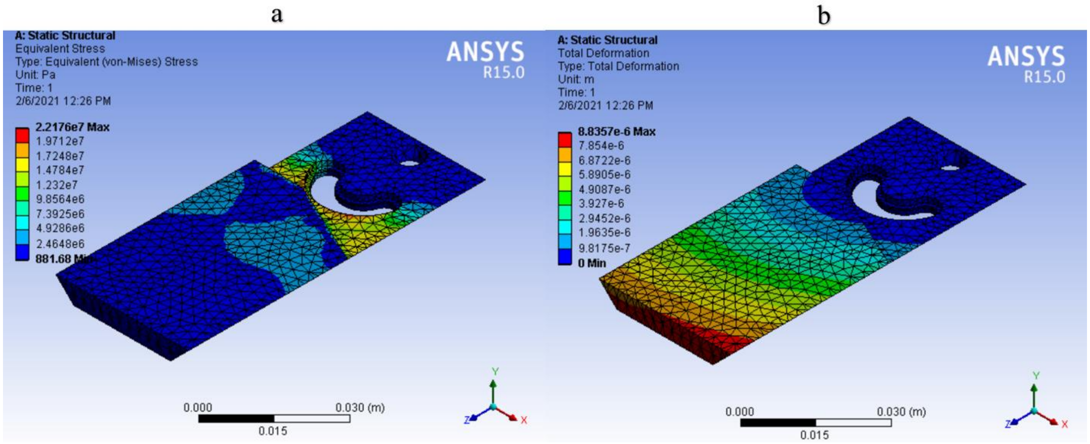

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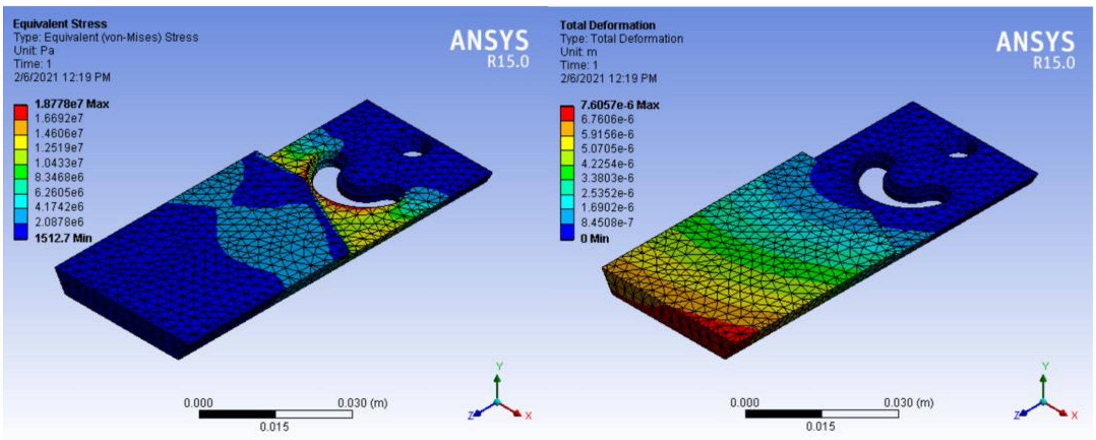

III

Fig. 5. Finite element analysis of the blades with sharpness angles of 30, 45, and 60 degrees (labeled I to III, respectively) under a 350 N force includes: (a) stress analysis, and (b) deformation analysis

Measuring the mechanical properties of canola stalks

Determination of shear energy

The results of the analysis of variance concerning the primary effect treatments involving blade sharpness angle, blade placement angle, canola moisture, blade movement speed, and their interaction effects on the canola stalk shear energy amount, as measured by the Instron device, have been detailed in Table 3. The statistical analysis revealed that the impact of blade sharpness angle, blade placement angle, blade movement speed, as well as the interactive effects of sharpness angle and blade placement angle, blade sharpness angle and moisture, blade placement angle and moisture, and blade sharpness angle, blade placement angle, and moisture were all statistically significant at a 1% significance level.

The analysis of variance results (Table 3) revealed several significant relationships between cutting parameters and shear energy requirements. The blade sharpness angle demonstrated a significant effect ($P < 0.01$) on shear energy, where increasing the angle from 30° to 60° resulted in a 27.3% increase in energy consumption. This behavior can be attributed to the increased contact area between the blade and stalk material at higher angles, leading to greater resistance during the cutting process. These findings align with Gan *et al.* (2018), who reported a 25.1% reduction in energy consumption when implementing optimized blade angles in Miscanthus harvesting.

The blade placement angle also had a significant influence ($P < 0.01$), indicating that the 45° configuration required 18.9% less energy compared to the 60° placement angle. This optimal angle can be explained by the balance achieved between the normal and tangential forces during cutting, minimizing the total energy requirement. The significant interaction between sharpness and placement angles ($P < 0.01$) indicates that their effects are interdependent, suggesting that optimal blade design requires simultaneous consideration of both parameters.

Moisture content emerged as a critical factor, showing significant interactions with both blade angles ($P < 0.01$). Higher moisture levels (23-25%) resulted in 13.2% lower shear energy compared to drier stalks (18-21%), likely due to reduced material brittleness. This moisture-dependent behavior is almost similar to the findings by Wang *et al.* (2020), who reported a 25% reduction in cutting force for citrus stems, highlighting the unique mechanical properties of canola stalks.

The three-way interaction between sharpness angle, placement angle, and moisture content ($P < 0.01$) suggests that optimal blade configuration should be adjustable based on crop conditions, particularly moisture levels, to maintain energy efficiency throughout the harvesting process.

Table 3- Analysis of variance of the impact of various factors including blade sharpness, blade angle, moisture level, and loading speed on shear energy index measured with the Instron device

Source	df	Sum of Squares	Mean Square	F	p-value
Treatment	81	9516.01	117.48	47.79**	<0.001
Sharpness	2	2212.64	1106.32	449.99**	<0.001
Blade angle	2	50.14	25.07	10.20**	<0.001
Moisture	2	9.89	4.95	2.01ns	0.137
Speed	2	130.70	65.35	26.58**	<0.001
Sharpness × Blade angle	4	130.27	32.57	13.25**	<0.001
Sharpness × Moisture	4	33.62	8.41	3.42**	0.010
Sharpness × Speed	4	25.39	6.35	2.58*	0.039
Blade angle × Moisture	4	54.89	13.72	5.58**	<0.001
Blade angle × Speed	4	0.81	0.20	0.08ns	0.988
Moisture × Speed	4	4.81	1.20	0.49ns	0.743
Sharpness × Blade angle × Moisture	8	93.42	11.68	4.75**	<0.001

Sharpness × Blade angle × Speed	8	12.08	1.51	0.61ns	0.766
Sharpness × Moisture × Speed	8	18.98	2.37	0.97ns	0.464
Blade angle × Moisture × Speed	8	2.30	0.29	0.12ns	0.998
Sharpness × Blade angle × Moisture × Speed	16	16.46	1.03	0.42ns	0.976
Error	162	398.29	2.46		
Total	243	9914.30			

** p-value < 0.01, * p-value < 0.05, ns Not significant (p-value > 0.05)

Determination of shear stress

Table 4 presents the outcomes of the analysis of variance conducted to evaluate the main effects of blade sharpness angle, blade placement angle, canola moisture, blade movement speed, and their interaction effects on canola shear stress, as measured by the Instron device. The data analysis revealed that the influence of blade sharpness angle, blade placement angle, stem moisture, blade movement speed, as well as the interaction effects of sharpness angle and blade placement angle, blade sharpness angle and moisture, blade placement angle and moisture, placement angle and blade movement speed, blade sharpness angle, blade placement angle and moisture, and blade sharpness angle, and blade placement angle and blade movement speed were all statistically significant at a significance level of 1%.

Table 4- Analysis of variance of the impact of various factors including blade sharpness, blade angle, moisture level, and loading speed on shear stress index measured with the Instron device

Source	df	Sum of Squares	Mean Square	F	p-value
Treatment	81	214.90	2.65	97.80**	<0.001
Sharpness	2	9.53	4.76	175.63**	<0.001
Blade angle	2	1.57	0.79	28.94**	<0.001
Moisture	2	0.26	0.13	4.80**	0.009
Speed	2	3.17	1.58	58.37**	<0.001
Sharpness × Blade angle	4	0.91	0.23	8.35**	<0.001
Sharpness × Moisture	4	1.28	0.32	11.78**	<0.001
Sharpness × Speed	4	0.14	0.03	1.26^ns	0.288
Blade angle × Moisture	4	0.42	0.11	3.89**	0.005
Blade angle × Speed	4	0.77	0.19	7.09**	<0.001
Moisture × Speed	4	0.09	0.02	0.79^ns	0.532
Sharpness × Blade angle × Moisture	8	1.40	0.18	6.45**	<0.001
Sharpness × Blade angle × Speed	8	0.29	0.04	1.31^ns	0.242
Sharpness × Moisture × Speed	8	0.28	0.04	1.29^ns	0.250
Blade angle × Moisture × Speed	8	1.36	0.17	6.26**	<0.001
Sharpness × Blade angle × Moisture × Speed	16	0.32	0.02	0.74^ns	0.753
Error	162	4.40	0.03		
Total	243	219.29			

** p-value < 0.01, * p-value < 0.05, ns Not significant (p-value > 0.05)

The impact of the main factors on stem shear stress was significant. To assess the variations among these factors, Duncan's test comparison method was employed. By comparing the average blade sharpness factor at a 1% probability level, a notable difference in shear stress was observed between sharpness angles of 30 and 45 degrees, when compared to 60 degrees. However, no significant difference was found between the 30 and 45-degree angles. The acute angle of 30 degrees exhibited the lowest shear stress value at 0.737 N mm^{-2}, whereas the acute angle of 60 degrees showed the highest shear energy at 1.171 N mm^{-2}.

Altering the orientation of the blade can be done in order to diminish the shear stress of the stem. Within the three different blade angles tested, namely 30, 45, and 60 degrees, it was observed that the 45-degree angle resulted in the lowest shear stress value of 0.779 N mm^{-2}, while the 60-degree angle exhibited the highest shear stress value of 0.961 N mm^{-2}. Furthermore, the comparison between the average shear stress values of the 30 and 60-degree angles did not yield statistically significant results at the 1% probability level.

Moisture played a significant role in influencing the shear stress of canola stems. The results indicated that the canola stems with 19% moisture exhibited the highest shear stress, while those with 24% moisture had the lowest shear stress. The difference in shear stress between the 19% and 24% moisture levels was statistically significant at the 1% level. However, no significant difference was observed between the 22% moisture level and the other two moisture levels. Specifically, the canola stems with 24% moisture had the lowest shear stress value of 0.885 N mm^{-2}, whereas those with 19% moisture had the highest shear stress value of 0.934 N mm^{-2}. In a study conducted by Wang *et al.* (2020), it was concluded that an increase in stem moisture content leads to a decrease in shear strength. This finding aligns with the results obtained in the present research.

The statistical analysis revealed an interesting phenomenon regarding the influence of moisture content on cutting parameters. While moisture content significantly affected shear stress ($F = 4.802$, $P < 0.01$), it showed no significant effect on shear energy ($F = 2.012$, $P > 0.05$). This apparent discrepancy can be explained by understanding the fundamental differences between these two parameters. Shear stress represents the instantaneous resistance force per unit area that must be overcome to initiate and maintain the cutting process. In contrast, shear energy encompasses the total work done throughout the entire cutting operation, including both the initial penetration and the complete separation of the stem.

The significant effect of moisture on shear stress suggests that water content directly influences the stem's immediate resistance to cutting. This could be attributed to moisture's role in cellular turgidity and tissue elasticity, which affect the stem's instantaneous mechanical response to the blade. Higher moisture levels (24%) resulted in lower shear stress values (0.885 N mm^{-2}) compared to lower moisture levels (19%, 0.934 N mm^{-2}), indicating that increased water content may facilitate easier initial penetration of the blade.

However, the non-significant effect on shear energy implies that the total work required to complete the cutting process remains relatively consistent across different moisture levels. This suggests that while moisture content may alter the instantaneous resistance to cutting, it does not substantially affect the overall energy requirements of the complete cutting operation. This finding has practical implications for harvester design and operation, indicating that while moisture content should be considered for optimizing cutting force requirements, it may be less critical for overall energy consumption calculations.

The statistical analysis revealed a significant difference in the average comparison among three loading speeds of 150, 250, and 350 mm min^{-1} at a 1% probability level. Notably, the speed of 350 mm min^{-1} exhibited the lowest stem shear stress at 0.764 N mm^{-2}, while the speed of 150 mm min^{-1} demonstrated the highest at 1.041 N mm^{-2}. Wang *et al.* (2020) conducted a study where they reported that the blade movement speed had a substantial impact on the shear stress of citrus fruit stems. Their findings indicated that an increase in blade movement speed led to a decrease in stem shear stress. Similarly, Heidari *et al.* (2012) conducted a study focusing on the shear stress and shear energy of Lilium stem. They observed a significant effect of blade movement speed on these parameters at a 1% level, using speeds of 30, 40, and 50 mm min^{-1}. Their results showed that an increase in blade movement speed resulted in a decrease in shear stress and shear energy of the stem, aligning with the outcomes of the current research.

Measuring the canola stem's shear stress using the designed cutter bar device

The evaluation tests of the cutter bar system involved measuring the mechanical properties of the canola stem, specifically the shear stress, using both the Instron device and a custom-designed device. The effects of various treatments, such as blade sharpness angle, blade placement angle, canola moisture, blade reciprocating movement speed, and their interactions, on the canola shear stress were analyzed using the designed cutter bar device. The results of the analysis of variance, presented in Table 5, indicated that the blade sharpness angle, blade placement angle, blade movement speed, stem moisture, and their interactions had a significant impact on the canola shear stress at a 1% level of significance. These findings suggested that there was a substantial and robust effect among the different levels of each treatment, highlighting the importance of considering these factors in the cutter bar system.

Table 5- Analysis of variance of the impact of various factors including blade sharpness, blade angle, moisture, and reciprocating movement speed on shear stress index measured with the designed cutter bar device

Source	df	Sum of Squares	Mean Square	F	p-value
Model	81	196368.65	2424.30	104.18**	<0.001
Sharpness	2	7764.41	3882.21	166.84**	<0.001
Blade angle	2	11250.51	5625.25	241.75**	<0.001
Moisture	2	1376.71	688.36	29.58**	<0.001
Stroke per minute	2	6061.95	3030.97	130.26**	<0.001
Sharpness × Blade angle	4	23122.02	5780.51	248.42**	<0.001
Sharpness × Moisture	4	3705.82	926.45	39.81**	<0.001
Sharpness × Stroke per minute	4	417.56	104.39	4.49**	0.002
Blade angle × Moisture	4	1391.30	347.83	14.95**	<0.001
Blade angle × Stroke per minute	4	417.46	104.37	4.49**	0.002
Moisture × Stroke per minute	4	478.22	119.56	5.14**	<0.001
Sharpness × Blade angle × Moisture	8	6366.84	795.86	34.20**	<0.001
Sharpness × Blade angle × Stroke per minute	8	671.65	83.96	3.61**	<0.001
Sharpness × Moisture × Stroke per minute	8	892.87	111.61	4.80**	<0.001
Blade angle × Moisture × Stroke per minute	8	972.96	121.62	5.23**	<0.001
Sharpness × Blade angle × Moisture × Stroke per minute	16	2686.51	167.91	7.22**	<0.001
Error	162	3769.64	23.27		
Total	243	200138.28			

** p-value < 0.01, * p-value < 0.05, ns Not significant (p-value > 0.05)

The Duncan's test comparison of blade sharpness factor at the 1% probability level revealed a notable difference among the shear stress values at 30, 45, and 60-degree inclinations. The minimum shear stress value was associated with the acute angle of 30 degrees (0.175 N mm^{-2}), whereas the maximum shear stress value was linked to the acute angle of 60 degrees (0.303 N mm^{-2}).

Within the three blade positioning angles of 30, 45, and 60 degrees, it is observed that the 45-degree angle exhibited the lowest shear stress value of 0.177 N mm^{-2}, while the 60-degree angle demonstrated the highest shear stress value of 0.320 N mm^{-2}. Furthermore, the comparison between the average values of the 30 and 45-degree angles did not yield a significant result at the 1% probability level.

The shear stress of canola stem was also affected by moisture. The difference in shear stress among these moisture levels was found to be statistically significant at a 1% probability level. Among the moisture levels tested, it was observed that 24% stem moisture exhibited the lowest shear stress at 0.200 N mm^{-2}, while 19% stem moisture showed the highest shear stress at 0.256 N mm^{-2}. In a related study by Wang *et al.* (2020), it was concluded that an increase in stem moisture content led to a decrease in shear strength.

This finding aligns with the results obtained in the current research.

The statistical analysis revealed a significant difference in the average comparison among three loading speeds: 800, 1100, and 1400 courses per minute, at a 1% probability level. Notably, the speed of 1400 strokes per minute exhibited the lowest stem shear stress (0.167 N mm^{-2}), while the speed of 800 strokes per minute demonstrated the highest stem shear stress (0.286 N mm^{-2}).

LCA results

The life cycle impact assessment (LCIA) was evaluated using the CML 2 baseline 2000 V2.05 method. Throughout the evaluations, all inputs remained constant except for the specific factor being investigated. This approach allowed for the determination of changes solely related to that factor. The LCIA was analyzed by comparing the blade placement angle, blade sharpness angle, and the reciprocating speed of the cutter bar.

To assess the reliability of the LCA results, an uncertainty analysis was conducted using the Pedigree matrix approach within SimaPro 9 software. This method evaluates the uncertainty of data quality based on five characteristics: reliability, completeness, temporal correlation, geographical correlation, and technological correlation. The analysis focused on the laboratory measurements data used as inputs for the LCA calculations. The uncertainty ranges for key impact categories were calculated using Monte Carlo simulation with 1000 iterations. The results showed coefficient of variation (CV) values of: Marine aquatic ecotoxicity: 15.3%, Global warming potential: 12.7%, and Abiotic depletion: 10.5%.

These CV values indicate moderate uncertainty levels in the results, primarily stemming from variations in laboratory measurements. The relatively controlled laboratory environment helped maintain uncertainty within acceptable ranges. However, it should be noted that these uncertainty estimates are specific to this laboratory setup and may not reflect the full range of variabilities that could be encountered in field conditions.

Figure 6 presents comparative findings regarding the variances in environmental impacts among three different blade placement angles. These findings demonstrated that altering the angle of the blades can significantly affect the influx of pollutants into the environment. The results are particularly noteworthy. For instance, in terms of the global warming index, when the blade placement angle was set at 45 degrees, the quantity of carbon dioxide pollutants amounted to 18,085.78 kg CO_2 eq. Conversely, this index reached 22,295.41 kg CO_2 eq for a blade angle of 60 degrees. This indicated that a mere 15-degree alteration in the blade placement angle of canola combine harvesters in Iran can result in an increase or decrease of approximately 4,209.63 kg CO_2 eq. The marine aquatic ecotoxicity index indicated a substantial difference of 55762.55 kg of dichlorobenzene equivalent between the two mentioned angles. While variations were observed in other indices as well, the most substantial disparity was observed in the marine aquatic ecotoxicity and global warming indices. This can be attributed to the fact that modifying the blade placement angle leads to changes in shear energy, consequently impacting the fuel consumption of combines on a large scale. Considering that the consumption of fossil fuels directly influences the mentioned indices, it becomes evident that this angle adjustment can ultimately generate a significant volume of pollutants. Thus, the significance of the blade placement angle becomes even more pronounced than before.

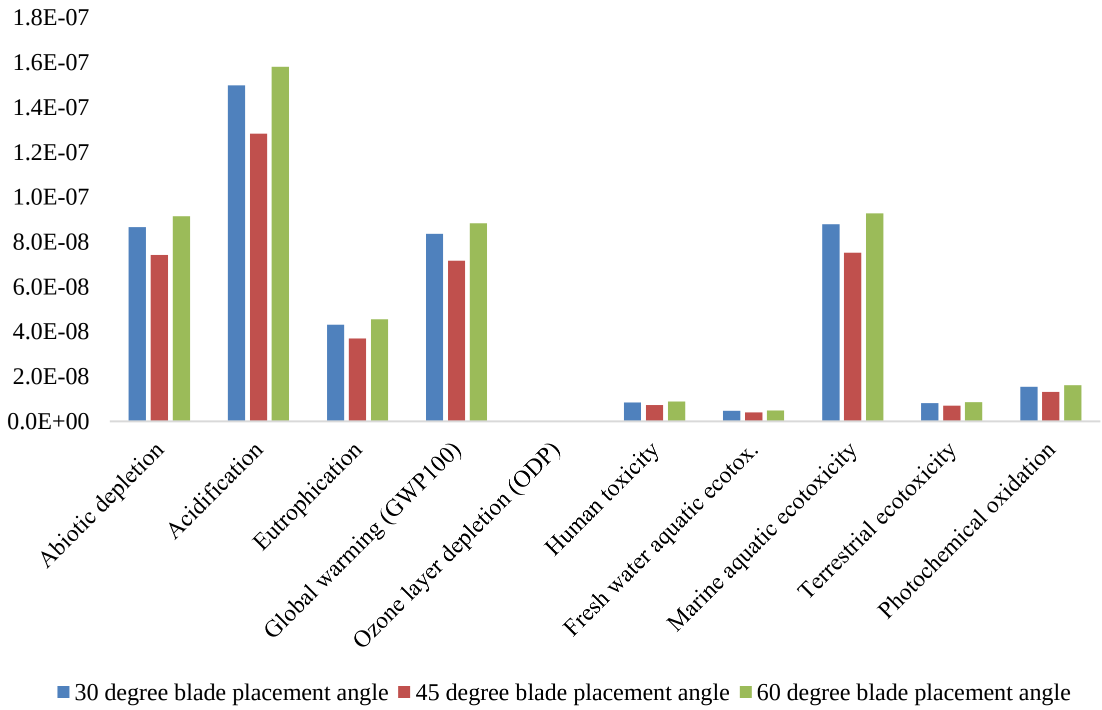

Fig. 6. A diagram of the LCIA normalized dimensionless indices among three distinct blade positioning angles for canola combine harvesters

A comparison was conducted to survey the impact of different blade sharpness angles on the results of the life cycle impact assessment. The findings, presented in Figure 7, revealed interesting insights. Specifically, when analyzing the marine aquatic ecotoxicity index, it was evident that the lowest value of 99133.43 kg of dichlorobenzene equivalent was associated with an acute angle of 30 degrees. On the other hand, the highest value of 476563.30 kg of dichlorobenzene equivalent was observed at an acute angle of 60 degrees. This indicated that a change of 30 degrees in the blade sharpness of canola harvesters in the country can result in a significant alteration of 377429.87 kg dichlorobenzene equivalent in the marine aquatic ecotoxicity index. Similarly, the global warming index also exhibited a notable difference between the 30 and 60 degree blade sharpness angles, with a variance of 28492.91 kg of carbon dioxide equivalent. This outcome is quite astonishing, as it implies that a mere change in blade sharpness at a macro level can introduce approximately 28.5 tons of additional carbon dioxide equivalent and 377.4 tonnes of additional dichlorobenzene equivalent pollution into the environment solely from canola harvesters. The underlying reason for this discrepancy, as previously explained, lies in the variation in fuel consumption.

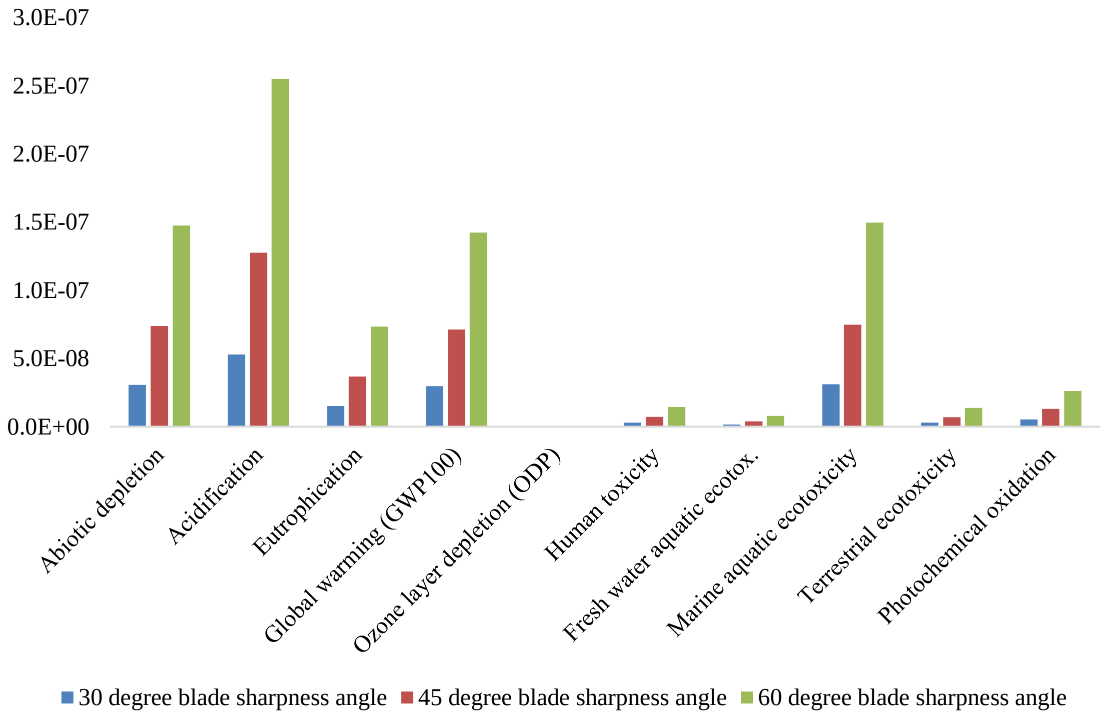

Fig. 7. A diagram of the LCIA normalized dimensionless indices among three distinct blade sharpness angles for canola combine harvesters

Finally, a comparison was carried out to estimate the impact of different blades' reciprocating speed on the outcomes of the LCIA. The results of this comparison can be found in Figure 8. Specifically, when analyzing the marine aquatic ecotoxicity index, it became evident that the lowest value of 200887.39 kg of dichlorobenzene equivalent was associated with 1400 courses per minute. Conversely, the highest value of 344073.07 kg of dichlorobenzene equivalent was observed at 800 courses per minute. This indicated that a change of 600 courses per minute in the blade reciprocating speed of canola harvesters can lead to a significant alteration of 143185.69 kg dichlorobenzene equivalent in the marine aquatic ecotoxicity index in the country. Analogously, the global warming index also showed a noticeable difference between the 800 and 1400 courses per minute in the blade reciprocating speed, with a variance of 25974.74 kg of carbon dioxide equivalent. This finding is quite surprising, as it suggested that a simple adjustment in the blade reciprocating speed at a larger scale can introduce approximately 143 tons of additional dichlorobenzene equivalent and 10.8 tons of additional carbon dioxide equivalent pollution into the environment solely from canola harvesters. The underlying reason for this difference, as explained earlier, lies in the variation in fuel consumption.

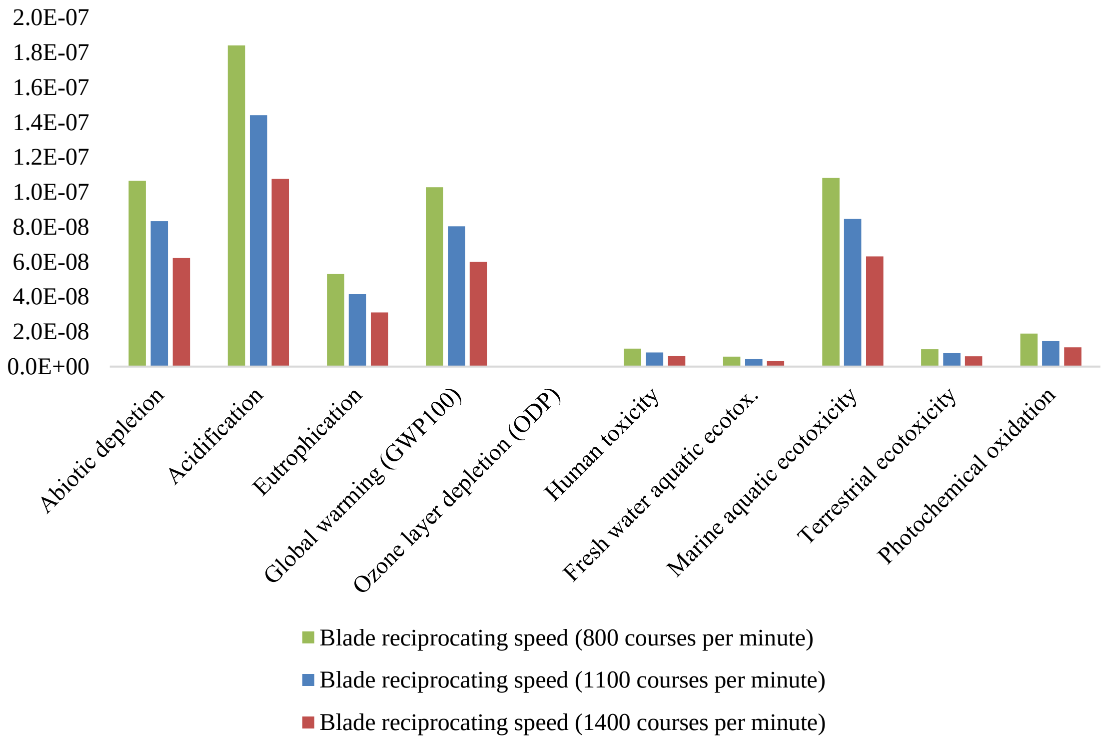

Fig. 8. A diagram of the LCIA normalized dimensionless indices among three distinct blade reciprocating speeds for canola combine harvesters

The main factors' significance is evident in their impact on the stem's shear energy. Duncan's mean comparison method was utilized to analyze the differences among these factors. The comparison of the average blade sharpness factor at the 1% probability level revealed a notable significance in cutting energy at 30, 45, and 60-degree angles. The data indicated that the lowest shear energy value corresponds to the 30-degree angle (1.92 mJ mm^{-2}), while the highest shear energy value corresponds to the 60-degree angle (9.23 mJ mm^{-2}).

Heidari *et al.* (2012) conducted a study that yielded similar findings. Their research focused on the impact of loading rate and blade sharpness angle at 30, 45, and 60 degrees on shear stress and specific shear energy in Lilium stems. The results showed that as the blade sharpness angle increased from 30 to 60 degrees, shear stress rose from 0.76 to 1.31 MPa, and specific shear energy increased from 4.02 to 7.34 mJ mm^{-2}.

The modification of blade type and blade angle can be employed to minimize the energy consumption associated with cutting. Among the three blade positioning angles (30, 45, and 60 degrees), the 45-degree angle exhibited the lowest cutting energy (4.64 mJ mm^{-2}), while the 60-degree angle demonstrated the highest cutting energy (5.72 mJ mm^{-2}). Furthermore, the average comparison between the 30-degree and 60-degree angles did not exhibit statistical significance at the 1% probability level.

Mathanker, Grift, & Hansen (2015) concluded that specific cutting energy increases with cutting speed, with the lowest average specific energy recorded at 0.26 mJ mm^{-2} for a 60° oblique cut at an average speed of 7.9 m s^{-1}, and the highest at 1.24 mJ mm^{-2} for a straight cut at 16.4 m s^{-1}. They found a strong correlation between specific cutting energy and both stem diameter and cross-sectional area. For instance, at a 30° oblique angle and an average speed of 11.3 m s^{-1}, cutting energy ranged from 4.5 to 15 J as the sugarcane stem diameter increased from 11 to 17 mm. Additionally, comparisons with sugarcane studies suggested that optimizing cutting speed and blade oblique angle could lead to significant energy savings while enhancing cut quality.

The findings indicated that there were no notable differences in the shear energy levels at different moisture levels, with a 5% probability level. Notably, the cutting energy was found to be the lowest (5.05 mJ mm^{-2}) for 24% stem moisture, while the highest cutting energy (5.53 mJ mm^{-2}) was observed for 19% stem moisture.

The analysis revealed a significant difference in the average comparison across three loading speeds: 150, 250, and 350 mm min^{-1}, at a 1% probability level. Notably, the speed of 350 mm min^{-1} exhibited the lowest cutting energy (4.31 mJ mm^{-2}), while the speed of 150 mm min^{-1} demonstrated the highest cutting energy (6.10 mJ mm^{-2}).

Soleimani, Kamandar, Khoshnam, and Soleimani (2023) found that the cutting of sesame stalks is a dynamic process primarily characterized by impact cutting. As cutting speed increases, preliminary compaction decreases due to the stalk's inertia and plastic behavior, resulting in lower energy requirements for cutting. They observed that at loading rates of 0.5-2 m s^{-1} and a moisture content of 15%, the cutting force ratios were approximately 58%, 55%, and 40% for the upper, middle, and lower regions of the stalk, respectively. Similarly, the specific shear energy ratios at the same loading rates and moisture content were around 66%, 37%, and 39% for the upper, middle, and lower regions. Given that sesame is typically harvested with low stalk moisture and that cutting occurs in the lower region, a cutting speed of 2 m s^{-1} could lead to reductions in the required cutting force, specific shear energy, and shear strength by about 40%, 39%, and 60%, respectively.

Hence, the appropriate and optimal cutting can be achieved by selecting treatments with the lowest shear stress. The similarity between the treatments can be observed in the analysis of variance and Duncan's test comparison of average shear stress measurements from experimental data obtained from the cutter bar system and the mechanical properties from Instron device data. The comparison of the mechanical properties and evaluation tests of the cutter bar system revealed similar results. While the main treatments had a significant effect in both experiments, the interaction effects were not significant in the mechanical properties test. One possible explanation for this could be the significant difference in blade movement speed between the two experiments. The blade movement speed in the mechanical properties test was 350 mm min^{-1}, whereas in the evaluation tests of the cutter bar system, it was at least 800 strokes per minute, equivalent to 60,800 mm min^{-1}. This speed is approximately 174 times higher than the maximum blade speed in the mechanical properties test. The substantial increase in momentum at high speed, which is obtained by multiplying the object's mass by its speed and represents the force required to stop the object, could account for this difference. Consequently, when the blade speed is 174 times higher, the momentum of the blade will also be proportionally 174 times higher.

In a study conducted by Nazari Galedar *et al.* (2008), an investigation was carried out on the ultimate shear strength of alfalfa stems within the inter-row intervals using a direct cutting method. The findings revealed a range of shear strength values varying from 0.4 to 18 MPa. Additionally, it was noted that an increase in the moisture content percentage along the entire length of the stem led to a decrease in shear resistance. A critical aspect in the development of various grain combines and harvesting machines is the resistance to cutting of agricultural products during the harvesting process.

The findings regarding blade angle effects can be compared with the comprehensive study by Gan *et al.* (2018) on Miscanthus Giganteus harvesting. While a 45-degree blade placement angle resulted in the lowest shear stress (0.779 N mm^{-2}), it was demonstrated that angled blades (30°) consumed less energy (11.31 MJ Mg^{-1}) compared to straight blades (12.31 MJ Mg^{-1}). The consistent enhancement of performance with angled blades across different crops suggests that optimizing blade angles is crucial for energy efficiency in harvesting operations. However, the magnitude of energy reduction differs between studies due to variations in crop properties and testing conditions.

The life cycle impact assessment findings revealed that altering the blade placement angles, blade sharpness angles, and blade reciprocating speed can lead to significant increases in the marine aquatic ecotoxicity index. Specifically, the amount of dichlorobenzene equivalent can rise up to 55762.55 kg, 377429.87 kg, and 143185.69 kg, respectively.

Conclusion

The results from the analysis of variance indicated that various parameters, including blade placement angle, blade sharpness angle, blade reciprocating movement speed, and stem moisture, significantly influenced both shear energy and shear stress at a 1% significance level. The blade sharpness angle of 30 degrees and 60 degrees corresponded to the lowest and highest shear stress values, respectively. Similarly, the blade placement angle at 45 degrees and 60 degrees exhibited the lowest and highest shear stress values, respectively. Furthermore, the moisture content of the canola stalk had a significance impact on shear stress at the 0.01 level, with the lowest and highest values observed at stem moisture levels of 24% and 19%, respectively. Additionally, the blade reciprocating speed of 1400 courses per minute resulted in the lowest stem shear stress, while a speed of 800 courses per minute led to the highest shear stress. Therefore, the combination of a blade sharpness angle of 30 degrees, a blade placement angle of 45 degrees, a stem moisture of 24%, and a blade reciprocating movement speed of 1400 courses per minute was predicted to decrease the shear energy and shear stress of canola stalks. The life cycle assessment results quantified the potential environmental impact of using the designed blades on a national scale. The LCIA findings showed that adjusting the blade placement angles, blade sharpness angles, and blade reciprocating speed can significantly increase the marine aquatic ecotoxicity index. Notably, the amount of dichlorobenzene equivalent can rise up to 55762.55 kg, 377429.87 kg, and 143185.69 kg, respectively.

Authors Contribution

Gh. Ahmadzade: Data acquisition, Data pre and post processing, Software services, Statistical analysis

M. R. Maleki: Supervision, Conceptualization, Methodology, Technical advice, Text mining, Writing the original text

P. Salami: Supervision, Conceptualization, Methodology, Technical advice, Statistical analysis, Software services, Numerical/computer simulation, Writing the original text

K. Mollazade: Conceptualization, Methodology, Validation, Visualization, Review and editing services

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بهینه‌سازی تیغه برش دروگر برداشت کلزا با رویکرد کاهش مصرف انرژی و ارزیابی چرخه زیست

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چکیده

عملیات برداشت غلات حدود ۳۰–۲۵٪ از کل مصرف مستقیم انرژی در سیستم‌های تولید محصولات کشاورزی را شامل می‌شود. با توجه به ویژگی‌های خاص کلزا در مقایسه با سایر غلات، طراحی تیغه‌های مناسب برداشت آن ضروری است. این پژوهش به بررسی تأثیر زوایای تیغه (زوایای قرارگیری و تیزی: ۳۰، ۴۵ و ۶۰ درجه)، سرعت حرکت رفت و برگشتی (۸۰۰، ۱۱۰۰ و ۱۴۰۰ رفت و برگشت در دقیقه) و سطوح رطوبتی (۱۹، ۲۲ و ۲۴ درصد) بر نیروی برش، تنش برشی و مصرف انرژی در برداشت کلزا پرداخت. نتایج نشان داد زاویه تیزی ۳۰ درجه و زاویه قرارگیری ۴۵ درجه به‌ترتیب کمترین تنش برشی (۰/۱۷۵ و ۰/۱۷۷ نیوتن بر میلی‌متر مربع) را نسبت به زاویه ۶۰ درجه (۰/۳۰۳ و ۰/۳۲۰ نیوتن بر میلی‌متر مربع) ایجاد می‌کنند. افزایش رطوبت از ۱۹ به ۲۴ درصد، تنش برشی را از ۰/۲۵۶ به ۰/۲۰۰ نیوتن بر میلی‌متر مربع کاهش داد. سرعت ۱۴۰۰ رفت و برگشت در دقیقه کمترین تنش برشی (۰/۱۶۷ نیوتن بر میلی‌متر مربع) را در مقایسه با ۸۰۰ رفت و برگشت (۰/۲۸۶ نیوتن بر میلی‌متر مربع) نشان داد. ارزیابی چرخه حیات نشان داد تغییر زوایای قرارگیری، تیزی و سرعت رفت و برگشتی به‌ترتیب می‌تواند سمیت اکولوژیکی آبزیان دریایی را تا ۵۵۷۶۲/۵۵، ۳۷۷۴۲۹/۸۷ و ۱۴۳۱۸۵/۶۹ کیلوگرم معادل دی‌کلروبنزن افزایش دهد. ترکیب بهینه (زاویه تیزی ۳۰ درجه، قرارگیری ۴۵ درجه، رطوبت ۲۴ درصد و ۱۴۰۰ رفت و برگشت در دقیقه) انرژی برشی و اثرات زیست‌محیطی را به‌طور قابل‌توجهی کاهش داد.

واژه‌های کلیدی: ارزیابی اثرات چرخه زیست، انرژی برشی، تنش برشی، زاویه تیزی تیغه، زاویه قرارگیری تیغه

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