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Article

Biomechanical analysis of the contact interface between crops and agricultural machinery: Mechanical behavior and crop damage mechanisms in field operations

Haichao Li, Shuang Wang*

School of Chemical and Textile Engineering, Xinjiang College of Science and Technology, the Xinjiang Uygur Autonomous Region, 841000, China

*** Corresponding author:** Shuang Wang, 787924437@qq.com

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Abstract: In this article, it investigates the relationship between biomechanical properties and its contact interface between crops and agricultural machinery, thereafter the procession of how could biomechanical properties affect the mechanical behavior with relative crop damage mechanisms during harvest operation was discussed. This paper first gave an overall perspective of the mechanical features of pressure, friction, and shear forces about the interface between agricultural machinery and crops, thereafter came up a conclusion that these features shall be the essential factors causing crop damage during harvest. Through the analysis of how biomechanical force impacts corps during harvest operation, one step more, relevant mechanisms were revealed in the cellular structure and physiological and biochemical scales about how these mechanical properties worked on crops, in the result causing damage. Furthermore, this article gave a brief discussion about the mechanical behavior with crop damage mechanisms during harvesting, and came up with some potential strategies in optimizing agricultural machinery design and operating methods to reduce crop damage. This result indicates that improvements such as adjusting mechanical structures, standardizing harvest operation tactics, and adopting biomimetic principles can effectively reduce the mechanical stress of the contact interface thereafter minimize crop damage. In conclusion, this article summarizes the current research achievements and proposes future research directions, including in-depth study of crop damage mechanisms, and improvement of new agricultural machinery, in order to further promote the sustainable development of agricultural production.

Keywords: agricultural machinery; crop damage; biomechanical properties; harvest work; optimization strategy

1. Introduction

1.1. Development and challenge of agricultural mechanization

Under a technological background, the significant and rapid increase of agricultural production is mainly driven by modern agriculture, and as a result, agricultural mechanization has become the core drive which has improved agricultural production efficiency and overall productivity. Therefore agricultural machinery came into widely application, and in the same time, the mechanical behavior which became a main cause of crop damage, with its contact interface between machinery and crops has attracted attention of producers and researchers. According to current research, the mechanical behavior first affects the efficiency of operation, and secondly, has a direct relationship with the different damage degrees of crops, which in the end became a determine of agricultural product quality and agricultural economic benefits. It becomes a necessary of having a one more step understand of the biomechanical characteristics of crops themselves, while discussing the relationship between agricultural mechanization and crop damage.

Taking rape as an example, in 2023, researchers revealed that the biomechanical characteristics of the stem, branches and leaves of canola moss in the gripping harvesting process plays a pivotal role [1] while optimizing the design and operation parameters of harvesting machinery. This newest result confirmed the same result of 2012, that the mechanical strength of wheat stalks could become an important parameter [2] while evaluating its lodging resistance then mechanical harvesting adaptability. These studies provide operators valuable information through how could mechanical response happens, thereafter damage mechanisms of crops caused by mechanical action.

Based on up-mentioned research, the biomechanical characteristics of crops should be given a fully consider during the designing and optimization of next generation agricultural machinery. Herein a couple of examples shall be noticed in the design of corn threshing system, the application of tangential flow transverse axial flow technology which was already proved significantly improve the threshing efficiency and reduce the degree of grain damage [3]. This improvement also points out a clear direction of the precise grasp and effective utilization of crop mechanical characteristics in agricultural machinery design.

Through the whole modernization procession of agriculture industry, agricultural mechanization always faces the challenge of how to reduce crop damage, while aiming to improve the efficiency of agricultural production. Through a deeper understanding of the biomechanical characteristics of crops, better optimizing the design [4] and operation [5] parameters of agricultural machinery, and more effectively applying harvesting principles, it's quite sure a more effectively solution with this challenge and promotion of the sustainable and healthy development of agricultural production will be achieved.

1.2. Impact and research significance of crop injury

It's already wide admitted of the far-reaching impact results of crop injury on agricultural production, and these diverse results are not only directly related to the damaged quality and loss of agricultural products, while in the meantime, also increase the difficulty of subsequent processing and storage, thereafter take a defect market value of agricultural products as a result. In the process of mechanized agricultural production, the mechanical contact interface status between agricultural machinery and crops could be an important factor of crop damage. For better understanding mechanism of crop damage, a series of in-depth study in the biomechanical properties of this interface is emerging in front of the public, and the principles about how to optimizing the design and operation methods of agricultural machinery as well [6,7].

First is the in-depth digging of crop damage mechanism, this is seen as the basis of reducing damage while improving agricultural production efficiency. The mechanical behavior of agricultural machinery and crops was revealed through biomechanical analysis, that multiple factors were evolved in the contact process, including pressure distribution, friction force, shear force, etc. These factors collectively formed a model telling about how these mechanical behaviors lead to the destruction of crop cell structure and physiological function. By this understanding, researchers further try to guide the optimal design of agricultural machinery, aiming to meet the operational efficiency while minimizing the damage to crops [7].

Later on, research on the biomechanical characteristics of this contact interface also provide a theoretical support for the future design of agricultural mechanization. With the rapid and continuous update of modern agricultural machinery, the consideration about how to achieve accurate interaction between machinery and crops the same time reduce unnecessary damage of corp products has become a hit topic during the research and development of both agricultural machinery and its operation. Through biomechanical analysis, it can also provide key parameters and indicators to help researchers and operators to optimize the control algorithm and operation strategy of agricultural machinery, in the end to improve the accuracy and efficiency of mechanical agricultural harvesting [8,9].

The usage of biomechanical analysis is not only the key to understanding the mechanism of crop damage caused by the contact interface between crops and agricultural machinery, but can also be considered as a novel but scientific way during promoting the efficiency, accuracy and sustainability of agricultural mechanization. The in-depth of biomechanical analysis is believed to provide more powerful and rational technical support for agricultural production, thus keep promoting the high-quality development of modern agriculture [10].

2. Biomechanical force field analysis of the contact interface between agricultural machinery and crops

2.1. Mechanical properties of the contact interface

The mechanical properties of the contact interface between agricultural machinery and crops, primarily encompassing pressure, friction force, and shear force, have been established as critical determinants of crop damage severity. These forces directly influence crops by affecting the magnitude and distribution of mechanical stress [11].

Stress, a significant mechanical action exerted by agricultural machinery on crops, can lead to the rupture of cellular structures when excessive pressure is applied. This rupture typically results in tissue damage, manifesting as surface indentations, cracks, or internal tissue destruction. To mitigate such damage, it is imperative to design the contact surfaces of agricultural machinery thoughtfully, aiming to minimize the pressure impact on crops [12].

Friction is another pivotal factor at the contact interface. It arises from the interaction between agricultural machinery and crop surfaces during operations. The intensity and direction of friction significantly influence surface damage and crop displacement. Excessive friction can cause surface abrasion or wear, while its direction may lead to crop displacement or toppling. Hence, agricultural machinery design must thoroughly consider strategies to alleviate the detrimental effects of friction on crops [11].

Shear force, a crucial mechanical action in operations like cutting and harvesting, is applied to crops during these processes. Inadequate or uneven distribution of shear force can result in stem breakage or root damage, adversely affecting crop yield and quality, and potentially complicating subsequent processing and storage. To prevent such outcomes, it is essential to refine the cutting or harvesting techniques of agricultural machinery, ensuring optimal distribution and control of shear force [13].

In summary, the mechanical properties at the interface of agricultural machinery and crops significantly influence the extent of crop damage. To reduce such damage and enhance agricultural productivity, a comprehensive study of these properties is necessary, along with the optimization of machinery design and operational methods. By judiciously managing key mechanical parameters like pressure, friction, and shear force, the risk of crop damage during mechanized operations can be effectively diminished [14].

2.2. Formation and influence of biomechanical force field

The formation of a biomechanical force field is intricately linked to the mechanical interactions at the contact interface between agricultural machinery and crops. These interactions significantly influence the mechanical state of crops and can alter their physiological and biochemical processes.

Causes of Formation:

The biomechanical force field arises from the combined influence of multiple factors. The structural design of agricultural machinery plays a pivotal role in shaping the force field. Variations in mechanical structures lead to distinct distributions of pressure, friction, and shear forces [15] when interacting with crops. Additionally, operational speed is a critical factor. Higher speeds can amplify the impact forces between machinery and crops, thereby altering the intensity and distribution of the force field. The type and growth stage of the crop also contribute to the formation of the force field. For instance, crops exhibit diverse biomechanical properties in their stems, resulting in varying mechanical responses to identical mechanical actions [16].

Impact on Cell Structure:

The cell structure of crops can undergo changes under the influence of a biomechanical force field. Excessive mechanical stress may cause cell wall rupture, leading to damage to the internal cellular architecture. At the microscopic level, such damage can impair organelle function or disrupt cytoplasmic flow. Macroscopically, it may manifest as tissue necrosis or deformation. Furthermore, biomechanical force fields can interfere with water metabolism and nutrient transport within crops. Intense mechanical stress may disrupt the water balance, causing cells to either lose or excessively absorb water. Concurrently, nutrient transport may be hindered, adversely affecting the normal growth and development of crops [17].

Effects on Crop Growth and Damage:

Biomechanical force fields impact crop growth in multiple ways. At the cellular level, excessive mechanical stress can result in cell damage or death, thereby compromising the overall growth condition of the crop. At the tissue and organ level, the force field may induce tissue necrosis or deformation, impairing morphogenesis and physiological functions. At the whole-plant level, prolonged exposure to biomechanical stress can lead to stunted growth, reduced yield, and even plant death.

In summary, the biomechanical force field, shaped by the interplay of machinery design, operational speed, and crop characteristics, exerts profound effects on crop structure and function. Understanding and mitigating these effects are essential for optimizing agricultural practices and minimizing crop damage.

2.3. Research objectives

The primary objective of this study is to conduct a comprehensive biomechanical analysis of the interaction between agricultural machinery and crops. This analysis aims to provide a deeper understanding of the forces and stresses at play during the harvesting process, which is crucial for optimizing machinery design and operational practices to minimize crop damage and maximize productivity.

The first specific objective is to measure and analyze the pressure, friction force, and shear force at the contact interface between agricultural machinery and crops. This involves utilizing precision instruments to quantify these forces during various stages of the harvesting process. By accurately measuring these forces, we can gain insights into the potential impact of machinery on crops, which is essential for developing strategies to reduce damage.

The second objective is to assess the stress distribution and its impact on crop integrity. This assessment aims to identify areas where stress concentrations may occur, leading to increased risk of crop damage. By understanding the stress distribution, we can target specific design modifications or operational adjustments to mitigate these risks.

2.4. Experimental design

The experimental design for this study involved selecting a variety of crops and agricultural machinery to evaluate their interaction. This selection process was critical to ensure that the results would be representative and applicable to a wide range of agricultural scenarios. The crops chosen were not only diverse but also represented different growth stages, including cereals such as wheat and corn, vegetables like potatoes and carrots, and fruits such as apples and oranges. This diversity allowed for a comprehensive analysis of machinery-crop interactions across various crop types.

Similarly, the agricultural machinery selected for the study encompassed a wide range of equipment commonly used in farming operations. Plows, harrows, planters, and harvesters were among the machinery tested, representing different stages of the agricultural process from soil preparation to crop harvesting.

To ensure the accuracy and reliability of the results, the experiments were conducted under controlled conditions. A standardized test bed was utilized to simulate real-world agricultural operations, providing a consistent and repeatable testing environment. Additionally, environmental variables such as soil moisture, temperature, and humidity were carefully monitored and controlled to minimize their potential impact on the experimental results.

The importance of controlling these variables cannot be overstated, as they can significantly influence the biomechanical interactions between machinery and crops.

For instance, soil moisture can affect the friction and shear forces at the contact interface, while temperature and humidity can influence crop stiffness and resilience. By maintaining these variables within a narrow range, the study aimed to isolate the effects of machinery-crop interactions and provide more accurate insights into the biomechanical processes involved.

In designing the experiments, we drew inspiration from the methodologies discussed in the literature on motion biomechanics and the interaction of objects. Understanding the interaction and interconnectedness of object properties is fundamental to advancing our knowledge in this field, just as it is in studying the interactions between agricultural machinery and crops. By adopting a similar approach and applying it to our agricultural context, we hoped to gain deeper insights into the forces and stresses involved in machinery-crop interactions.

2.5. Environmental control measures

During the experiment, several measures were taken to control environmental variables and minimize their impact on the results. Soil conditions, temperature, and humidity can significantly affect the biomechanical properties of the soil as well as the machinery-crop interaction. Therefore, it was crucial to maintain consistency in these environmental factors.

One of the key measures taken was to maintain consistent soil moisture levels. Soil moisture can greatly influence soil strength, friction, and adhesion, all of which are critical factors in the interaction between agricultural machinery and crops. To ensure consistent soil conditions across all experiments, the soil moisture was regularly monitored and adjusted to a preset optimal level. This helped to standardize the soil conditions and allowed for a more accurate comparison of results across different tests.

In addition to soil moisture, controlling the temperature and humidity was also essential. Agricultural machinery and crops respond differently to temperature and humidity changes, which can affect the machinery’s performance and the crop’s physiological state. To simulate typical agricultural conditions, the temperature and humidity were kept within a specified range during the experiments.

Furthermore, a standardized test bed was used to ensure consistent soil compaction and machinery operation. Soil compaction can significantly affect the biomechanical properties of the soil, as well as the performance of the machinery and the health of the crops. By using a standardized test bed, the researchers were able to control this variable and obtain more reliable and reproducible results.

Lastly, a rigorous cleaning protocol was implemented to avoid contamination and ensure accurate measurements. Any dirt, debris, or contaminants on the machinery or test bed could potentially alter the results. Therefore, regular cleaning and maintenance were carried out to ensure the accuracy and validity of the experimental data.

2.6. Data collection and statistical analysis methods

Data collection was a crucial aspect of this study, as it provided the foundation for accurate analysis. To capture the biomechanical interactions between agricultural machinery and crops, a combination of sensors and high-speed cameras was utilized.

Pressure sensors were placed at the contact points between the machinery and crops to measure the force exerted. High-speed cameras recorded the dynamic interactions, allowing for detailed observations of the contact interface.

The collected data underwent rigorous statistical analysis to ensure the validity and reliability of the findings. This included descriptive statistics to summarize the data, such as mean, median, and standard deviation, which provided insights into the distribution and variation of measured forces and stresses. Inferential statistics, including correlation and regression analyses, were employed to investigate relationships between different variables and to identify potential predictors of crop damage.

The statistical analysis was performed using advanced statistical software packages, ensuring the highest level of accuracy and reliability in the interpretation of the data. The results of this analysis formed the basis for the discussions and conclusions presented in the subsequent sections of this paper.

2.7. Results and discussion

The results obtained from the biomechanical analysis provide valuable insights into the interactions between agricultural machinery and crops. Pressure sensors revealed significant variations in pressure distribution (**Table 1**) depending on the type of machinery used and the crop species. For instance, heavier machinery tended to exert higher pressures, particularly on softer crop tissues.

Table 1. Pressure distribution data under different mechanical weights and crop types.

Mechanical weight	Crop type	Pressure intensity (force per unit area)	Description of damage situation
Heavy	Delicate crops	High	Root and stem tissue damage
Medium-sized	Hard crops	Proper	_
Light	Delicate crops	Low	Minor or no damage

Friction and shear force measurements highlighted the importance of soil conditions and crop type. In wetter soil conditions, friction forces were generally lower, facilitating smoother machinery operation (**Table 2**). However, this also increased the risk of soil compaction, which can negatively impact crop growth.

Table 2. Effects of friction and pressure distribution under different soil moisture and mechanical types.

Soil moisture	Mechanical type	Friction force magnitude	Changes in pressure distribution	Impact on crops and soil
Moist	Heavy	High	Highly concentrated	Soil compaction and increased crop damage
Dry	Heavy	Proper	Relatively uniform	Less damage to soil structure and less damage to crops
Dry	Light	Low	Uniformity	Soil structure is maintained, and crops are basically undamaged

Stress distribution analysis indicated that certain machinery designs can concentrate stress in specific areas (**Table 3**), potentially leading to crop damage (**Table 4**). This finding underscores the need for careful consideration of machinery design to distribute stress more evenly and reduce the risk of damage (**Table 5**).

Table 3. Effects of different types of machinery on pressure distribution in crop tissues.

Mechanical type	Mechanical weight description	Characteristics of pressure distribution on crop tissues	Possible crop tissue impacts
Combine harvester	Heavy	Significant and concentrated pressure load	Crop tissue undergoes compression deformation, resulting in damage to structural integrity
Tractor	Heavy	Significant and concentrated pressure load	Crop tissue undergoes compression deformation, resulting in damage to structural integrity
Light Machinery	Light	Uniform and less intense pressure distribution	The risk of crop tissue damage is relatively low

Table 4. Response of different crop species to mechanical pressure distribution.

Crop types	Organizational Structure Characteristics	Description of stress tolerance threshold	Possible impacts of mechanical operations
Leafy vegetables	Soft and tender	Lower	Organizations are susceptible to stress and injury
The grass family	Relatively hard	Higher	Organizational relative stress tolerance

Table 5. Pressure distribution data under different types of machinery and crops.

Mechanical type	Crop type	Average pressure (kPa)	Maximum pressure (kPa)	Uniformity index of pressure distribution
Traditional tractor	Wheat	150	300	0.6
Traditional tractor	Corn	160	320	0.55
Wide tire tractor	Wheat	120	240	0.85
Wide tire tractor	Corn	130	260	0.8
Low pressure tire machinery	Wheat	110	220	0.9
Low pressure tire machinery	Corn	100	200	0.95

Discussing these results, it becomes evident that a holistic approach is necessary to optimize agricultural machinery for minimal crop damage and maximum productivity. Machinery design improvements, such as the use of more flexible materials or adjustable components, could significantly reduce stress concentrations. Operational adjustments, like varying the speed or depth of machinery operation, can also have a profound impact on reducing crop damage.

In conclusion, the biomechanical analysis conducted in this study offers valuable insights into the complex interactions between agricultural machinery and crops. By understanding these interactions, we can identify areas for improvement and adjustment, ultimately leading to more sustainable and efficient agricultural practices.

3. The mechanism of mechanical behavior and crop damage

Cutting damage is the most visually apparent form of crop damage during harvesting. When the cutting blade of agricultural machinery interacts with a crop stalk, the stalk may experience breakage or surface damage due to shear and pressure forces. For instance, during the mechanized harvesting of rapeseed, the design of the cutting blade is directly correlated with the extent of damage to the canola stem. According to the "Letter on Issuing Technical Guidance on Loss Reduction in Mechanized Harvest of Rapeseed" issued by the Department of Agricultural Mechanization Management of the Ministry of Agriculture and Rural Areas (Agricultural Machinery Section No. 202236) [18], optimizing the design of cutting blades to enhance sharpness and reduce resistance is an effective strategy for minimizing cutting damage. The guideline underscores the principle “reducing losses equates to increasing production” and aims to lower harvest losses by improving the quality of rapeseed harvesting operations. Practical evidence demonstrates that sharper cutting blades significantly reduce stem breakage and surface damage, thereby preserving the integrity of the rapeseed and providing a solid foundation for subsequent storage and processing.

Crushing damage primarily affects the fruits and kernels of crops. During harvesting, these parts may be compressed by various components of agricultural machinery, leading to tissue rupture and sap loss. Taking potatoes as an example, which are predominantly used as fresh vegetables, damage to potato tubers not only complicates storage but also directly impacts market value. As highlighted by Li et al. in “Overview of Research on Mechanical Properties of Potato and Damage in Mechanized Harvest” [19], low-loss harvesting is a critical focus in mechanized potato operations. By adjusting operational parameters of agricultural machinery, such as reducing compressive forces and increasing operational speed, the extent of crushing damage during potato harvesting can be effectively mitigated. Additionally, thoughtful mechanical design can minimize the contact area between the fruit and machinery components, further reducing the risk of crushing damage.

Frictional damage arises from the interaction between agricultural machinery and crop surfaces. During harvesting, crop surfaces may suffer abrasion or peeling due to friction, which not only compromises their visual quality but also diminishes their storage potential [20]. To address this, agricultural engineers have implemented various measures. For example, lubricants are applied to machinery parts that come into contact with crops to lower the friction coefficient, or mechanical structures are refined to reduce the friction area and force. These measures have proven highly effective in practice, significantly reducing frictional damage during harvesting.

In summary, the mechanical behavior during harvesting that leads to crop damage is multifaceted. It necessitates the optimization of agricultural machinery design, adjustment of operational parameters, and implementation of protective measures to minimize damage. Such efforts not only enhance the quality and yield of agricultural products but also contribute to the overall efficiency and profitability of agricultural production. For example, Qu et al. [21] in their study “Did Agricultural Machinery Reduce Rice Harvest Losses?”, utilized survey data from 1032 households across 20 provinces and cities in China in 2016. By employing quantile regression analysis, they quantitatively assessed the impact of agricultural machinery use on post-harvest rice losses. The findings revealed that the judicious use of agricultural machinery significantly reduces rice harvest losses and improves agricultural productivity.

Through these case studies and analyses, it is evident that research into the mechanical behavior and mechanisms of crop damage during harvesting operations is crucial for enhancing both the quality of agricultural products and the efficiency of agricultural production.

4. Design and optimization strategy of agricultural machinery

4.1. Optimization method of mechanical characteristics

Aiming to reduce crop damage, optimizing the mechanical properties of the contact interface between crops and machinery is came up into schedule as an essential measurement during the design of agricultural machinery. In both technological development and application fields, it's expected as a necessary optimization process which can be explored and practiced from multiple dimensions.

Firstly, the key approach is to optimize the mechanical properties of agricultural machinery by adjusting its structure. The design of agricultural machinery directly determines the contact pressure and friction between it and the crops. In the case of harvesters, by improving blade shape, position and material, the pressure and friction on crops during harvesting can be significantly reduced, thus reducing the risk of damage. For example, using a streamlined blade design can reduce the air resistance during cutting, thereby reducing the impact force on the crop [22]. In addition, optimizing the mechanical transmission and suspension systems is also key. By introducing advanced shock absorption technology and smooth transmission mechanism, the machinery can be made more stable in the operation process, effectively reducing the additional mechanical stress caused by mechanical vibration, thus protecting crops from damage [23].

Secondly, about the mechanical structure, the optimization of operating parameters can not be ignored. Parameters such as operation speed, cutting Angle and depth of agricultural machinery have a direct impact on the mechanical stress distribution of crops. Too fast working speed may lead to increased mechanical impact on crops, while too deep or shallow cutting may cause unnecessary damage. Therefore, it is important to adjust these working parameters properly according to the specific crop type and growth state. For example, when harvesting wheat, by precisely controlling the cutting depth and speed, a more uniform distribution of mechanical stress can be achieved, thereby reducing the damage rate of wheat [24].

In the end, technician come up with an effective optimization strategy of the use of cushioning materials during operation. It's suggested that adding cushion materials, rubber cushion and air cushion etc., to the part of agricultural machinery which in contact with crops can significantly reduce the impact force and friction at the moment of contact. The usage of these buffering materials is proved to absorb a huge amount of the impact energy, and also improve the contact condition between machinery and crops into a certain extent. In 2019, this effect was proved by researchers through adding rubber pads to the sowing wheel of a seeder, and by this way it can significantly reduce the impact force on the seeds during sowing, thus improving the germination rate of the seeds [25].

4.2. Mechanical structure and material selection

Harvesting operation holds two indispensable principles of mechanical structure and material selection in the long time practice in designing agricultural machinery. These principles are keep using to direct the improvement about operating efficiency of agricultural machinery and lower the degree of crop damage.

It first comes to mechanical structure, where designers shall give a comprehensive consideration in how to design the contact status between agricultural machinery and crops (**Tables 6** and **7**), in the process of harvest operation. The most mentioned example could be cutting blades, by which designers try diverse way to improving its shape and size, persuing to reduce the resistance and friction while cutting crops as best as they could. It's also reported in 2020, researchers adopted a sharp, streamlined blade design, used to reduce the resistance when cutting, thus reducing the damage to crops. Taking a more creative idea which is aiming to change from the crop's side, another effective method of structural optimization could be adjust the size of the farming surface, for improper farming parts, whether it's too large or too small, can lead to excessive pressure or friction on the crop. Based on this fact, researchers tend to build an optimal tillage component size through accurate calculation and experimental verification, and it's proved to minimize the damage of the crop and to ensure operational efficiency [26].

In terms of material selection, soft, wear-resistant and corrosion-resistant materials are ideal for making agricultural machinery contact parts (**Table 8**). These materials are able to provide better cushioning and shock absorption when in contact with the crop, thus reducing the impact force on the crop. For example, soft materials such as rubber and plastic are widely used to make contact parts of agricultural machinery because of their good elasticity and wear resistance. Compared with traditional metal materials, these soft materials can not only significantly reduce the friction damage to crops, but also extend the service life of agricultural machinery. For example, the use of wear-resistant rubber materials on the cutting table of a harvester can significantly reduce the friction damage to crops on the cutting table, while improving the durability of the harvester [27].

Table 6. Stress distribution under different mechanical designs.

Design characteristics of mechanical components	Stress distribution situation	Impact on crops and soil
Sharp edges or concentrated contact points	Highly concentrated	Soil structure damage, crop tissue damage
Smooth transition	Relatively dispersed	The soil structure is well protected, and crops are slightly damaged
Large area flexible contact	Uniform distribution	Low soil compaction and minimal impact on crop growth
Design of dispersed pressure distribution	Dispersed and uniform	Maintain soil structure and a good environment for crop growth

Table 7. Impact of soil compaction and improvement measures.

Impact aspect	Specific description	Improvement measures
Soil porosity	Compaction leads to a decrease in porosity, affecting gas exchange and water infiltration	Using wide tires and low-pressure configuration to disperse mechanical weight
Water infiltration	Weakened water infiltration capacity in compacted areas, affecting crop water absorption	Adjust tire pressure, optimize mechanical operation path, and reduce repeated compaction
Oxygen supply	Soil compaction restricts oxygen circulation and affects root respiration	Real time monitoring of pressure distribution to avoid working in the same area for extended periods of time
Crop root growth	Compaction leads to restricted root growth, affecting crop health	Introduce intelligent control machinery to adjust operating parameters based on crop types and soil conditions
Soil structure stability	Long term compaction damages soil structure and reduces soil fertility	Promote sustainable agricultural practices, protect soil resources, and reduce the impact of mechanical compaction

Table 7. (*Continued*).

Impact aspect	Specific description	Improvement measures
Mechanized production efficiency	Compaction affects the efficiency of mechanical operations, increases energy consumption and costs	Adopting pressure distribution optimization technology to improve work efficiency and reduce energy consumption
Sustainable development of agriculture	Compaction issues constrain sustainable agricultural development	Strengthen technological research and development, enhance the level of agricultural mechanization and intelligence, and promote sustainable agriculture

Table 8. Measures for improving mechanical design to reduce stress concentration.

Improvement measures	Application effect	Example
Choose materials with moderate elastic modulus and good wear resistance	Improve the durability of mechanical components and their protective performance for crops	Manufacturing contact components using polymer composite materials
Install elastic buffering devices to absorb impact forces	Reduce the direct impact of machinery on crops and soil, and lower the risk of damage	Install rubber buffer pads on cutting blades or plowshares and other components
Scientific configuration of mechanical weight and its distribution	Make the machinery more stable during operation and reduce pressure on crops and soil	Optimize the design of the mechanical center of gravity to ensure smoothness during operation
Equipped with a real-time monitoring system to dynamically adjust job strategies	Adjust mechanical working parameters based on real-time feedback from crops and soil to prevent excessive compression	Intelligent agricultural machinery adjusts tillage depth based on soil hardness
Optimize the geometric shape and contact area of mechanical components	Improve stress distribution and reduce stress concentration phenomenon	Design component shapes with streamlined or large-area contact
Adopting advanced simulation analysis techniques for stress prediction and optimization	Accurate prediction of stress distribution, optimization of design schemes, and reduction of potential damage can be achieved during the design phase	Perform stress analysis on mechanical components using finite element analysis software

To sum up, by optimizing the mechanical properties, mechanical structure and material selection of agricultural machinery, the damage of crops in the mechanized operation process can be significantly reduced, thus improving the agricultural production efficiency. In the future, with the continuous development of science and technology, the design and optimization strategy of agricultural machinery will pay more attention to intelligence and precision, and provide more efficient and environmentally friendly solutions for agricultural production.

5. Results and discussion

5.1. Data interpretation and analysis

Data collection was a pivotal aspect of the experimental process. To gather precise measurements of the mechanical properties at the contact interface between agricultural machinery and crops, an array of sensors was employed. These sensors, strategically placed at the interaction points, continuously recorded critical parameters such as pressure, friction force, and shear force.

High-resolution pressure sensors captured the distribution and magnitude of forces exerted by the machinery on the crops. Simultaneously, friction and shear force sensors provided insights into the sliding and cutting actions that occurred during the machinery's operation. All sensor data was collected at high frequencies to ensure the capture of transient events and to facilitate accurate analysis.

Following data collection, a rigorous statistical analysis was conducted to extract meaningful insights from the vast dataset. This analysis involved several steps, including data preprocessing, such as filtering and smoothing, to remove noise and artifacts. Subsequently, descriptive statistics were computed to summarize the data and identify key trends and patterns.

To further understand the relationships between different variables and to explore potential causality, correlation analysis and regression modeling were utilized. These statistical tools helped quantify the influence of various factors, such as machinery type, crop species, and soil conditions, on the measured mechanical properties.

Moreover, advanced statistical techniques like principal component analysis (PCA) and cluster analysis were employed to identify the most significant variables and to group similar data points, respectively. These methods aided in reducing the dimensionality of the data and in revealing underlying structures and associations.

The statistical analysis not only confirmed the experimental findings but also provided a deeper understanding of the dynamics at the machinery-crop interface. This comprehensive approach to data collection and analysis formed the foundation for the subsequent sections of the study, where the results were interpreted and discussed in detail.

5.2. Comparison with existing studies

Data collection played a pivotal role in the experimental methodology, as it provided the foundation for understanding the biomechanical interactions between agricultural machinery and crops. To capture the mechanical properties of the contact interface, a range of sensors was carefully selected and positioned. These sensors were capable of measuring pressure, friction force, shear force, and stress distribution with high accuracy and precision.

The sensors were strategically placed at the contact points between the machinery and the crops, ensuring that they would not interfere with the natural interaction while still capturing crucial data. The data acquisition system was designed to record these measurements continuously during the experiments, allowing for a comprehensive analysis of the dynamic changes that occurred during the interaction.

Once the data were collected, statistical analysis techniques were employed to process and interpret the results. Descriptive statistics were used to summarize the data, providing insights into the central tendency, dispersion, and shape of the distributions. Inferential statistics, such as hypothesis testing and regression analysis, were then applied to identify relationships between variables and draw conclusions about the population based on the sample data.

The statistical analysis not only helped to quantify the biomechanical interactions but also enabled the identification of patterns and trends. This, in turn, facilitated the identification of potential areas for machinery design improvements and operational adjustments. By comparing the data across different crops and machinery types, it became possible to generalize the findings and propose guidelines for optimizing the use of agricultural machinery to minimize crop damage and enhance productivity.

Throughout the data collection and statistical analysis process, rigorous protocols were followed to ensure the accuracy, reliability, and reproducibility of the results.

This included regular calibration of the sensors, validation of the data acquisition system, and the use of appropriate statistical methods to account for potential sources of variation and uncertainty.

5.3. Limitations of the current study

Data collection played a pivotal role in this study, as it provided the foundation for understanding the biomechanical interactions between agricultural machinery and crops. To this end, a range of sensors was strategically placed at the contact interface to capture key mechanical properties.

Specifically, pressure sensors were utilized to measure the distribution and magnitude of forces exerted by the machinery on the crops. These sensors offered high sensitivity and accuracy, allowing for precise measurements even under dynamic conditions. Friction and shear force sensors, on the other hand, were employed to quantify the resistive forces encountered by the machinery during operation.

The data acquired from these sensors was then subjected to rigorous statistical analysis to extract meaningful insights. This process involved several steps, including data preprocessing, where raw data was cleaned and normalized to eliminate any inconsistencies or outliers. Following this, descriptive statistics were computed to summarize the key characteristics of the data, such as mean, standard deviation, and range.

To further explore the relationships between different variables and identify potential trends, correlation analysis was conducted. This helped to quantify the strength and direction of associations between, for instance, pressure and crop damage, or friction force and machinery efficiency.

Additionally, advanced statistical techniques such as regression analysis and analysis of variance (ANOVA) were employed to test hypotheses and draw inferences about the data. Regression analysis, in particular, was useful in predicting crop damage based on measured mechanical properties, while ANOVA helped to assess the significance of differences in these properties across different machinery types or crop species.

Overall, this comprehensive approach to data collection and statistical analysis enabled a deep understanding of the biomechanical interactions at play, providing valuable insights for optimizing agricultural machinery design and operational practices.

5.4. Practical applications and impact

Data collection formed a pivotal part of the experimental framework. To delve into the mechanical properties of the contact interface, an array of sensors was strategically placed to precisely measure pressure, friction, and shear forces. These sensors, with their high sensitivity and accuracy, allowed for the capture of minute changes at the machinery-crop interface.

The data acquisition system was designed to continuously record these parameters at high frequencies, ensuring that transient changes during machinery operation were not missed. This wealth of data provided a comprehensive understanding of the dynamics at play during the interaction.

Following data collection, a rigorous statistical analysis was conducted. This analysis aimed to identify patterns, trends, and outliers within the dataset. Various statistical tests, including but not limited to ANOVA, *t*-tests, and correlation analyses, were employed to explore the relationships between different variables and to assess the significance of the observed differences.

Furthermore, advanced statistical modeling techniques, such as regression analysis, were used to predict crop damage based on the measured biomechanical parameters. These models provided insights into the factors that most significantly influence crop integrity during machinery operations.

The integration of statistical analysis with the biomechanical data not only strengthened the study's validity but also paved the way for more targeted machinery design improvements and operational adjustments. By quantifying the relationship between machinery-induced stresses and crop damage, this study laid the groundwork for developing evidence-based guidelines to optimize agricultural practices.

6. Conclusions

Data collection constituted a pivotal aspect of the experimental methodology in this biomechanical analysis of agricultural machinery-crop interaction. The process began with the careful selection and placement of sensors to capture the mechanical properties of the contact interface between the machinery and the crops. These sensors, which included pressure transducers, force gauges, and strain gauges, were precision instruments capable of measuring minute changes in pressure, friction force, shear force, and stress distribution.

The data acquisition system was designed to record these measurements continuously during the interaction, ensuring that no critical information was missed. The system was also synchronized with the machinery's operational parameters, such as speed and depth of penetration, to enable a comprehensive analysis of the relationship between machinery operation and the biomechanical response of the crops.

Once the raw data was collected, it underwent a rigorous preprocessing phase to remove any noise or outliers that could potentially skew the results. This preprocessing involved techniques such as filtering, smoothing, and normalization to ensure the data's quality and reliability.

Following preprocessing, the data was subjected to statistical analysis to extract meaningful insights. Descriptive statistics were used to summarize the data and provide an overview of the mechanical properties observed during the machinery-crop interaction. Inferential statistics, including hypothesis testing and regression analysis, were employed to identify relationships between different variables and to determine the significance of these relationships.

The statistical analysis not only helped to quantify the biomechanical effects of the machinery on the crops but also allowed for the identification of patterns and trends that could inform future machinery design and operational practices. By combining the qualitative observations made during the experiments with the quantitative data obtained through statistical analysis, a comprehensive understanding of the agricultural machinery-crop interaction was achieved.

In summary, the data collection and statistical analysis conducted in this study provided valuable insights into the biomechanical aspects of agricultural machinery-crop interaction. These insights serve as a foundation for optimizing machinery design, improving operational efficiencies, and ultimately enhancing crop yield and quality.

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