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Development and Experimental Validation of a 3D-Printed Force-Sensing Grabber for Automated Pineapple Harvesting

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Abstract— *This study presents a novel 3D-printed grabber designed to assess the mechanical properties of pineapples, crucial for optimizing harvesting and handling processes. This research represents a key component of a larger project aimed at developing a semi-automatic pineapple harvester tailored for the challenging terrain of hilly regions, such as those found in Manipur, India, where the pineapple data for this study was collected. Key physical parameters like including transverse diameter, weight, longitudinal diameter, and compression force were evaluated. The grabber was designed using 3D modelling software and fabricated via 3D printing, enabling rapid prototyping and customization. A compression force sensor unit integrated into the grabber allowed for real-time force measurement during testing. Experimental validation involved applying controlled compression forces to pineapples of varying sizes and maturities. The results demonstrated that the grabber could effectively measure compression force while ensuring minimal fruit damage, even when exceeding the required gripping force. The study successfully determined a safe grabbing force range for pineapples, informing the development of robotic or semi-automatic harvesting systems. Furthermore, the adaptable design of the force-sensing grabber presents a promising approach for assessing the mechanical properties of other fruits and vegetables, potentially reducing damage and improving handling practices across the agricultural sector.*

Keywords— ***Pineapple, Mechanical Properties, 3D Printing, Grabber, Compression Force Sensor.***

I. INTRODUCTION

Pineapple is an important tropical fruit valued for its abundant vitamins A, B, and C, as well as essential minerals like calcium, phosphorus, and iron (Farid Hossain 2015). Consuming pineapple offers numerous health benefits, including improved digestion, immune system support, and anti-inflammatory properties (Mohd Ali et al. 2020). In pineapple-producing regions worldwide, including countries like India, farmers face significant challenges during harvest. This is especially relevant in areas like Manipur, India, where pineapple cultivation thrives in hilly terrains (Rabina, Bose, and Mazhar 2021). However, the pineapple harvesting process remains labour-intensive and inefficient, often relying on manual methods that pose ergonomic risks and are not scalable for large-scale commercial operations (Anjali et al. 2019; Singh and Karmakar 2022).

Manual pineapple harvesting is physically demanding, requiring workers to repeatedly bend, twist, and lift the fruit (Du et al. 2019; Guo et al. 2021). This can lead to various ergonomic problems, such as back pain, shoulder strain, and muscle fatigue. The repetitive motions and awkward body postures associated with manual harvesting can also increase the risk of musculoskeletal disorders among farmers, potentially reducing their productivity and overall well-being (Benos, Tsaopoulos, and Bochtis 2020; Fathallah 2010; Salleh et al. 2019; Singh and Karmakar 2022). Furthermore, the strenuous nature of manual pineapple harvesting can limit the availability of labour, as young agricultural workers may be deterred from pursuing these physically demanding tasks.

To address these challenges and improve the efficiency and sustainability of pineapple harvesting, particularly in hilly regions like Manipur, this research focuses on developing a grabber, a key component of a larger project aimed at developing a semi-automatic pineapple harvester. Recent advancements in agricultural harvesting technologies have demonstrated the promising potential of 3D printed materials and soft robotic systems for fruit harvesting applications. For instance, researchers have designed 3D printed robotic arms for apple harvesting that exhibit enhanced flexibility and precision (Pi et al. 2021; Wang et al. 2023), allowing for more controlled and delicate handling of the fruit. Similarly, prior studies have utilized 3D printing to develop soft robotic grippers capable of gently manipulating fragile produce like berries (Gunderman et al. 2022) without causing damage. These soft-robotic approaches are inspired by the gentle, human-like touch of the human hand, which is well-suited for fruit-picking tasks (Navas et al. 2021; Venter and Dirven 2017). The ability of these grippers to morph and conform around the grasped object increases the contact area, resulting in a more equal distribution of force and a lower effective contact pressure, allowing for a more secure grip to be achieved without damaging the fruit (Kultongkham et al. 2021; Navas et al. 2021, 2023; Venter and Dirven 2017).

This study specifically focuses on developing a sensor-based, microcontroller-enabled compression force testing machine for evaluating the bursting limit of pineapple fruits. This testing machine, incorporating 3D printed PLA grabbers and a force sensing unit, will provide a comprehensive assessment of the optimal gripping force required for harvesting pineapples without causing damage. The insights gained from this research will directly inform the design and development of the semi-automatic harvester, ultimately contributing to a safer, more efficient, and sustainable pineapple harvesting process, especially in challenging terrains like those found in Manipur.

II. LITERATURE REVIEW

2.1. Challenges and Advancements in Pineapple Harvesting

Pineapple Harvesting Challenges: Pineapple harvesting remains a labour-intensive and inefficient process, often relying on manual methods that pose ergonomic risks and are not scalable for large-scale commercial operations (Singh and Karmakar 2022). The manual harvesting of pineapples is physically demanding, requiring workers to repeatedly bend, twist, and lift the heavy fruit (Hasan Samad et al. 2016; He et al. 2024; Bin Salleh et al. 2018). This manual approach not only is strenuous but also limits the overall productivity and scalability of pineapple harvesting. Furthermore, the reliance on manual techniques increases the risk of fruit damage and inconsistent quality, which can negatively impact the overall yield and profitability of pineapple production (Reinhardt et al. 2017; Wahab and Khairuddin 2020)

Recent Advancements: Advancements in agricultural harvesting mechanisms have demonstrated the promising potential of 3D printed materials and soft robotic technologies for fruit harvesting applications (Wang et al. 2023). Researchers have designed 3D printed robotic arms for apple harvesting (Wang et al. 2023) that exhibit enhanced flexibility and precision, allowing for more controlled and delicate handling of the fruit. Similarly, previous studies have leveraged 3D printing to develop soft robotic grippers capable of gently manipulating fragile produce like berries (Gunderman et al. 2022) without causing damage. These soft-robotic approaches are inspired by the gentle, human-like touch of the human hand, which is well-suited for fruit-picking tasks.

Need for Automation: To address the challenges of manual pineapple harvesting, there is a growing need for automated solutions that can enhance efficiency, reduce labour intensity, and improve the overall quality and consistency of the harvested pineapples (Anh et al. 2020; Gunderman et al. 2022; He et al. 2024; Mohd Ali et al. 2023). Existing research has explored the potential of robotic systems (Anh et al. 2020; Bhat and Chayalakshmi 2021; Liu et al. 2022; Mohd Ali et al. 2023) and advanced harvesting mechanisms to automate the pineapple harvesting process, but more specialized solutions are needed to handle the unique characteristics of pineapples.

2.2 Technological Solutions for Automated Pineapple Harvesting

The physical characteristics of pineapples, including their variable size, irregular shape, and tough, spiny exterior, pose significant challenges for automated harvesting mechanisms (Du et al. 2019; Guo et al. 2021; Wang et al. 2012; Zhang et al. 2018). The size variation requires a flexible and adaptable end-effector design that can accommodate the diverse dimensions of the fruit. Additionally, conventional end-effectors developed for other produce, such as smooth-skinned apples or citrus fruits, may not be suitable for the specialized requirements of pineapple harvesting (Zhang et al. 2018). A customized solution is needed to reliably and gently handle pineapples, addressing the limitations of existing robotic harvesting systems.

The use of 3D printing technology has emerged as a versatile solution for developing customized end-effectors and harvesting mechanisms for various agricultural applications (Anh et al. 2020; Bhat and Chayalakshmi 2021; Feng 2021; Liu et al. 2022; Mohd Ali et al. 2023). Prior research has utilized 3D printing technology to develop robotic systems for apple harvesting (Hohimer et al. 2019; Wang et al. 2023; Zhang et al. 2018), demonstrating enhanced flexibility and precision that enables more controlled and gentle manipulation of the fruit. Similarly, researchers have utilized 3D printing to develop soft robotic grippers capable of gently manipulating fragile produce like berries (Elfferich et al. 2024; Gunderman et al. 2022), without causing damage. The advantages of 3D printing (Crisostomo and Dizon 2021; Thakar et al. 2022), such as rapid prototyping, cost-effectiveness, and the ability to create complex geometries, make it a promising approach for designing specialized tools and mechanisms tailored to the unique requirements of different agricultural crops, including pineapples.

2.3. Towards a Novel Pineapple Harvesting Solution

Automated harvesting technologies have gained significant traction in recent years, offering promising solutions for addressing labour shortages and improving efficiency in various agricultural sectors (Zhou et al. 2022). Robotic systems have been successfully implemented for harvesting crops such as strawberries (Parsa et al. 2023), apples (Pi et al. 2021; Wang et al. 2023), and grapes (Vrochidou et al. 2021), demonstrating the potential for automation in delicate fruit handling. However, the unique physical characteristics of pineapples, including their irregular shapes, tough exteriors, and variable sizes, pose significant challenges for existing robotic harvesting technologies. Conventional grippers often struggle to achieve a secure and damage-free grasp on pineapples, leading to fruit bruising, dropping, and subsequent post-harvest losses (Gunderman et al. 2022; Navas et al. 2021). This highlights a critical research gap in the development of specialized harvesting solutions tailored to the specific requirements of pineapple production.

In this research project, we aim to design and develop a novel pineapple harvesting grabber with integrated force sensing capabilities. By leveraging 3D printing technology and a microcontroller-based system, we will create a customized grabber capable of effectively grasping and handling pineapples. The design process will rely heavily on simulations, utilizing Creo Parametric to model and analyses various grabbing mechanisms. These simulations will allow us to optimize the 3D-printed grabber's geometry, material properties, and gripping strategy to accommodate the irregular shapes, tough exteriors, and variable sizes of pineapples. For instance, finite element analysis within Creo can be employed to simulate the stress distribution on the 3D grabber during gripping, ensuring the applied force remains within safe limits to prevent bruising. The simulations will also guide the integration of a force sensing unit, controlled by a microcontroller, within the grabber design. This sensor will provide real-time feedback on the gripping force, allowing for dynamic adjustments and precise control during the harvesting process. By combining the advantages of 3D printing and microcontroller-based force sensing in the grabber design, this research project seeks to develop a specialized pineapple harvesting tool that can reliably and gently handle the fruit, minimizing the risk of damage and improving the overall efficiency of the harvesting process.

III. MATERIAL AND METHODS

This section outlines the materials and methodologies utilized in this research to design, develop, and assess a novel pineapple harvesting mechanism with integrated force sensing capabilities.

3.1. Pineapple Sample Collection and Parameter Measurement

3.1.1 Pineapple Sample Collection

This study focused on two prominent pineapple cultivars, 'Kew' and 'Queen,' grown in Manipur, India, and known for their distinct flavour profiles, as these are the primary pineapple varieties cultivated in the region. To ensure the 3D-printed grabber could accommodate the natural size variations found in pineapples, a stratified sample of 100 pineapples, comprising 50 each from the 'Kew' and 'Queen' cultivars, was carefully hand-harvested at optimal ripeness from a local farm in Manipur. This sampling approach ensured a representative sample of the two primary pineapple varieties cultivated in the region.

3.1.2 Physical Parameter Measurement

Before outlining the measurement procedure, it is essential to define the key physical parameters of the pineapple that are relevant to the grabber design:

Weight (kg): The overall weight of the pineapple fruit.

Vertical Diameter (mm): The diameter of the pineapple measured along its vertical axis, from the base to the neck of the pineapple.

Transverse Diameter (mm): The diameter of the pineapple measured perpendicular to the vertical axis, representing the widest point of the fruit.

Table 1: Material Selection for 3D Printed Grabber Material Rationale for Selection

Material	Strength	Flexibility	Food-Grade Suitability	Environmental Impact
Polylactic Acid (PLA)	Moderate	Moderate	High	Low
PETG	High	Moderate	High	Moderate
Thermoplastic Polyurethane (TPU)	Low	High	Moderate	Moderate
Nylon	High	Moderate	Moderate	Moderate

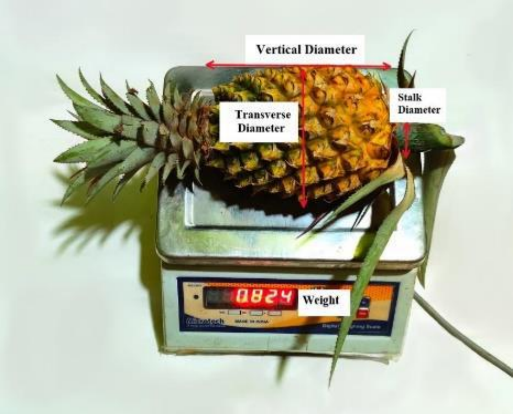

Fig.1: Physical Parameters of Pineapple

Stalk Diameter (mm): The diameter of the pineapple stalk, which is the point of attachment to the plant.

Key physical parameters, including weight (kg), vertical diameter (mm), transverse diameter (mm), and stalk diameter (mm), were measured for each pineapple using a calibrated digital weighing scale and a digital calliper, respectively. Descriptive statistics, such as mean and standard deviation, were calculated for each parameter and cultivar using SPSS software.

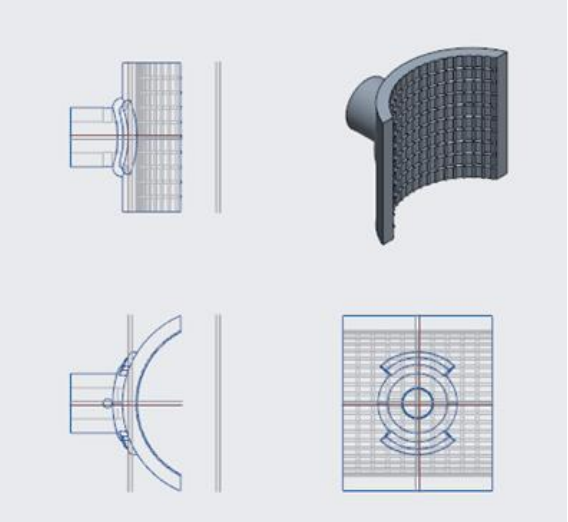

Fig.2: Pineapple grabber design in Creo Parametric Software

3.2. 3D Printed Grabber Design and Material Selection

3.2.1 Grabber Design

A semi-hemispherical grabber design with an inner diameter matching the averaged transverse diameter of the pineapple was chosen to mimic the grasping action of a human hand, providing a secure and stable grip while minimizing bruising. This design, created using the 3D design software Creo Parametric 7.0, allowed for the development of a detailed and customized 3D model of the pine apple grabbing mechanism. The use of parametric 3D modelling software enabled us to iteratively refine the grabber design, ensuring it would effectively accommodate the unique physical characteristics of pineapples. The grabber fingers were designed with a textured surface and soft, flexible tips to enhance traction and conform to the irregular pineapple shape, reducing the risk of slippage.

3.2.2 Material Selection

The selection of material for the 3D printed grabber is crucial to ensure its functionality, durability, and safety for handling food products. Several factors were considered during the material selection process:

Strength: The material should be strong enough to withstand the weight of the pineapple and the forces applied during grabbing.

Flexibility: The grabber requires a certain degree of flexibility to conform to the irregular shape of the pineapple and provide a secure grip without causing damage.

Food-Grade Suitability: As the grabber will be in direct contact with the pineapple fruit, the material must be food-safe and non-toxic.

Environmental Impact: The environmental impact of the material, including its biodegradability and recyclability, was also taken into consideration.

Table 1 presents a comparison of potential materials for the 3D printed grabber, along with a rationale for their selection based on the aforementioned criteria.

To determine the optimal 3D printing material for the grabber fabrication, a range of options, including PLA, PETG, and TPU were evaluated. The selection was based on the materials' mechanical properties, flexibility, and suitability for food-grade applications. The specific selection criteria used for the 3D printing material to be used in the grabber design are outlined in the table below.

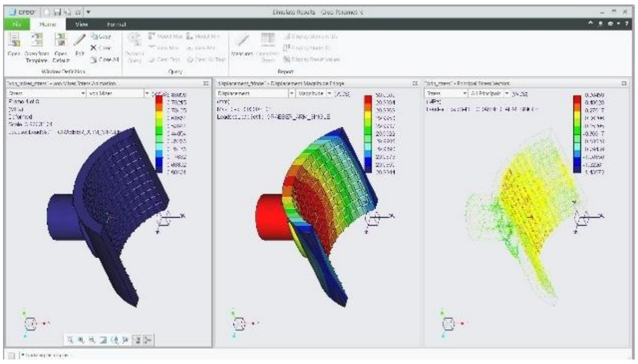

Fig 1: Finite element analysis visualization of the 3D printed grabber under simulated loading conditions.

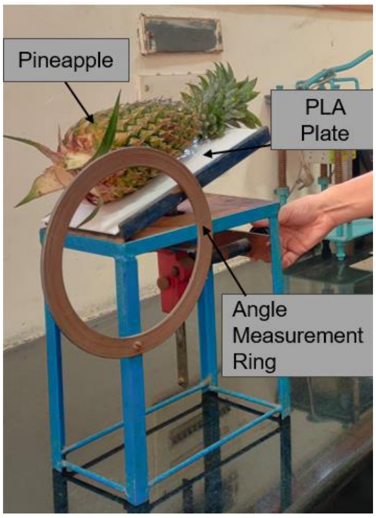

Fig. 2: Coefficient of Static Friction Test

Static and dynamic analyses were conducted using Creo Parametric software to simulate the loading conditions on the grabber during pineapple handling. Finite element analysis assessed the structural integrity of the grabber under various loading conditions, including the gripping force and impact forces encountered during the harvesting process. This analysis provided insights into the stress distribution, deformation, and potential failure modes of the grabber design, enabling further refinement and optimization. The results of the static and dynamic analyses were visualized using detailed FEA plots (figure 3), which were used to validate the grabber's ability to withstand the expected loads and ensure a secure, damage-free pineapple handling. Based on the analysis, the thickness and design of the grabber were iteratively redesigned until the desired performance was achieved.

3.3. Determination of Coefficient of Friction and Grabbing Force

Determining the appropriate clamping force is crucial to ensure the grabber can securely grab the pineapple without causing damage. This force is influenced by factors such as the pineapple's weight, the friction between the grabber and the fruit's surface, and a safety factor to account for variations in these parameters. To calculate the theoretical minimum clamping force (F), the following equation 1, derived from the principle of force balance, was used:

$$F \geq k.\frac{F_J}{2\mu} = k.\frac{mg}{2\mu} \qquad (1)$$

where:

F is the forward pressure from the grabber (N)

k is the grabbing safety factor (set to 3)

F_J is the maximum static friction (N)

μ is the static friction coefficient (determined experimentally)

m is the pineapple mass (kg)

g is gravitational acceleration (m/s²) (9.81 m/s²)

The static friction coefficient (μ) between the grabber material and the pineapple skin is a key parameter in this calculation. To determine experimentally, the coefficient of friction between the 3D-printed grabber material and the pineapple skin, an inclined plane method as shown in figure 4 was used. A 3D-printed PLA sheet served as the adjustable inclined plane. Pineapple samples were carefully placed on the plane, with their skin in contact. The angle of the plane was gradually increased until the pineapple began to slide and the angle was termed as "tilt angle". The tilt angle was recorded for 10 pineapples, with 5 pineapples from each of the two cultivars viz. Kew and queen, and 3 trials per pineapple, and the coefficient of friction was calculated using the formula: $\mu = \tan(\theta)$, where θ represents the tilt angle.

3.4 Development of the Compression Force Analysis Unit

Sensor Selection and Calibration: An FSR sensor was chosen to measure the gripping force due to its thin profile, flexibility, and ability to measure a wide range of forces. To establish a reliable relationship between the sensor's output and the actual force applied, the sensor was calibrated using known weights.

Sensor Attachment: The FSR sensor was attached to the concave, inner surface of the 3D printed grabber, where it would make direct contact with the pineapple skin. Double-sided adhesive tape was chosen for its suitability in bonding the sensor's flexible material to the 3D printed surface.

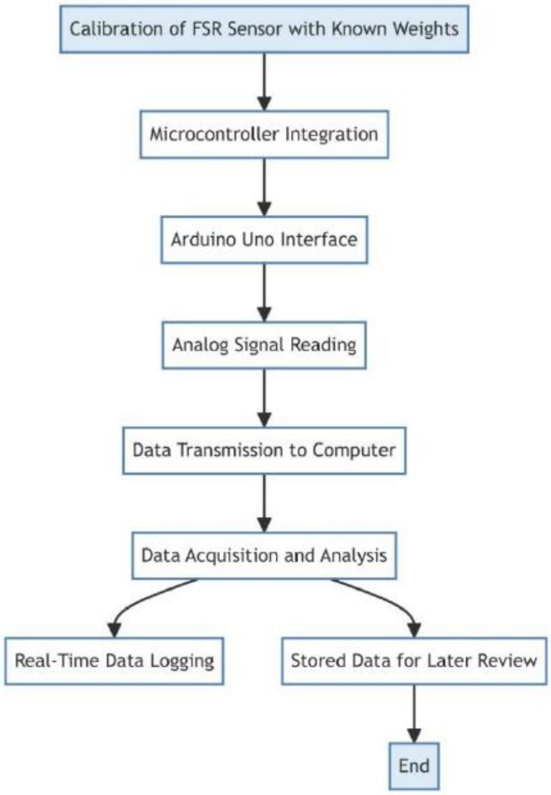

Fig. 3: Flowchart of Compression Unit

Procedure for Sensor Attachment:

Surface Preparation: Both the grabber surface and the back of the FSR sensor were thoroughly cleaned with isopropyl alcohol and a lint-free cloth to remove any dust, grease, or residue, ensuring strong adhesion.

Tape Application: The double-sided adhesive tape was carefully applied to the back of the FSR sensor, ensuring even pressure and avoiding air bubbles. The tape was then trimmed to match the sensor's dimensions.

Sensor Bonding: The adhesive backing of the tape was peeled off, and the FSR sensor was carefully positioned on the concave surface of the grabber. Firm and even pressure was applied to ensure a secure bond between the sensor and the grabber.

Microcontroller Integration: An Arduino Uno board was used to interface with the FSR sensor. This microcontroller reads the analogue signal from the sensor, processes it, and transmits the data to a computer for analysis.

Data Acquisition and Analysis: The Arduino program sends the force data to a laptop or PC, where it is logged and analyzed in real-time or stored for later review.

3.5 Compression Testing of Actual Pineapples in the Laboratory Using the Compression Test Unit

Sample Selection: 5 Pineapples each of the two cultivars i.e. kew and queen, were randomly selected for testing.

Controlled Compression: The pineapple samples were placed on the grabber assembly, and the compression force was gradually increased up to the average gripping force determined in the previous stage of the research (Section 3.3).

Damage Assessment: To evaluate potential damage from the gripping force, pineapple samples were assessed both immediately after compression testing for any visible bruising or damage, and again after one week of storage under controlled conditions to determine if any delayed bruising or spoilage occurred.

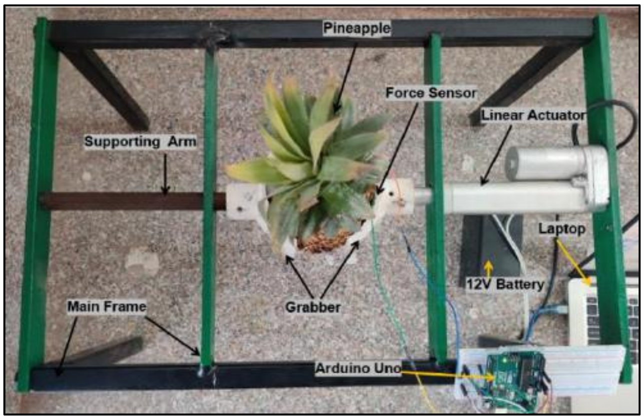

Fig. 4: Compression testing of pineapple samples using the developed compression force analysis unit.

IV. RESULTS AND DISCUSSION

This section outlines the findings from the experimental validation of the 3D-printed grabber designed to evaluate the mechanical properties of pineapples. The results are discussed within the context of the existing knowledge surrounding the challenges associated with automated pineapple harvesting, with a particular emphasis on the need to minimize fruit damage.

4.1 Physical Parameter Measurements

A total of 100 pineapples, encompassing both Queen and Kew cultivars, were sampled to capture a representative range of sizes and maturities for analysis. Table 2 summarizes the measured physical parameters, including transverse diameter, weight, longitudinal (vertical) diameter, and stalk diameter.

As shown in Table 2, significant variations in physical dimensions were observed between the Queen and Kew cultivars. The Kew cultivar exhibited consistently larger dimensions, with a mean vertical diameter of 152.12 mm, which was 20.8% greater than the Queen cultivar's mean vertical diameter of 113.66 mm. Similarly, the Kew cultivar had a larger mean transverse diameter (109.57 mm) and stalk diameter (22.78 mm) compared to the Queen cultivar (94.65 mm and 18.97 mm, respectively). This size disparity was also reflected in the weight measurements, with the Kew cultivar exhibiting a 27.5% greater mean weight (1.403 kg) than the Queen cultivar (0.822 kg). The observed size variations between cultivars, and even within a single cultivar, underscore the importance of a grabber design capable of accommodating a range of fruit dimensions. The observed size variations between cultivars, and even within a single cultivar, underscore the importance of a grabber design capable of accommodating a range of fruit dimensions. This data informed the design of the 3D-printed grabber, ensuring its adjustable mechanism could effectively grasp and handle pineapples across the observed size range of both cultivars.

4.2. 3D-Printed Grabber Design and Material Selection

The success of this research hinged on the development of a 3D-printed grabber capable of securely and safely handling pineapples of varying sizes. A novel approach, distinct from a fixed-size grabber, was implemented. Two identical grabber halves were designed, forming a complete circle when joined. A semi-circular section was then trimmed from each half, creating an opening and resulting in a highly adaptable gripping mechanism. This innovative design serves two crucial purposes

Accommodating Size Variations: The opening created by trimming the semi-circular sections allows the grabber to accommodate a wide range of pineapple sizes. Smaller pineapples can be gripped securely within the inner circumference of the circle, while the grabber can expand outwards to securely grasp even the largest pineapples.

Adjustable Grip: This design eliminates the need for complex mechanisms to adjust the grip size. The flexibility of the material, combined with the circular design, allows the grabber to naturally conform to the shape of the pineapple, ensuring a secure hold regardless of size variations.

Material Selection: Choosing the appropriate 3D printing material was crucial, as it directly influences the grabber's durability, rigidity, and potential impact on the fruit. Several materials were carefully evaluated:

Polylactic Acid (PLA): PLA offers moderate mechanical properties and flexibility, making it suitable for applications requiring a balance of strength and adaptability. Its high food-grade suitability, due to its biocompatibility and biodegradability, makes it an excellent choice for the pineapple grabbing mechanism. Additionally, PLA has a low environmental impact.

Polyethylene Terephthalate Glycol-modified (PETG): PETG is known for its high mechanical properties, providing excellent strength and durability. While it offers moderate flexibility, its high food-grade suitability makes it

Table 2: Variation in physical properties of two cultivars of pineapple

Cultivar	Physical Parameters	Mean	Std. Deviation	Minimum	Maximum
Queen	Vertical Diameter (mm)	113.66	21.29	78.00	156.00
	Transverse Diameter (mm)	94.65	11.03	78.00	123.40
	Stalk Diameter (mm)	18.97	4.09	12.33	24.63
	Weight (kg)	0.822	0.256	0.360	1.355
Kew	Vertical Diameter (mm)	152.12	27.43	105.00	197.00
	Transverse Diameter (mm)	109.57	6.53	94.00	125.00
	Stalk Diameter (mm)	22.78	3.22	15.67	28.47
	Weight (kg)	1.403	0.216	0.930	1.869

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Table 3:Coefficient of Static Friction for two cultivars of Pineapple

Cultivars	Sample	Tilt angle			Average	Coefficient of static friction	Mean Coefficient of Static Friction
Kew	K1	26.5	26.0	26.4	26.30	0.494	0.538±0.043
	K2	26.0	26.5	26.0	26.17	0.491	
	K3	26.0	26.5	26.0	26.17	0.491	
	K4	26.7	26.8	26.9	26.80	0.505	
	K5	27.0	26.7	26.8	26.83	0.506	
		Average			26.45	0.498	
Queen	Q1	30.0	30.5	30.0	30.17	0.581	
	Q2	29.9	30.1	30.3	30.10	0.580	
	Q3	30.0	30.3	30.1	30.13	0.580	
	Q4	30.0	29.5	30.0	29.83	0.573	
	Q5	30.0	30.2	30.3	30.17	0.581	
		Average			30.08	0.579	

ideal for applications where both strength and compliance with food safety standards are critical. PETG has a moderate environmental impact.

Thermoplastic Polyurethane (TPU): TPU is characterized by its high flexibility, which allows for significant deformation without breaking. However, it has lower mechanical properties compared to PLA and PETG. Its moderate food-grade suitability limits its use in certain applications, but it remains a viable option for components requiring high flexibility. TPU also has a moderate environmental impact.

Nylon: Nylon provides high mechanical properties and moderate flexibility. Its moderate food-grade suitability and excellent strength make it a strong candidate for applications where durability and moderate flexibility are required. Nylon has a moderate environmental impact.

Based on this analysis, PLA was selected as the primary material for the 3D-printed grabbing mechanism due to its favourable balance of mechanical properties, flexibility, high suitability for food-grade applications, and low environmental impact and cost-effectiveness.

Through an iterative process of computer-aided design and finite element analysis, the dimensions and geometry of the grabber were carefully refined to ensure optimal performance. The final grabber design was capable of accommodating pineapple samples with transverse diameters ranging from 86.53 mm to 125.00 mm, effectively encompassing the observed size variations within the test sample set.

PLA was selected as the material for the 3D-printed grabber due to its combination of advantageous properties. Its biodegradability, derived from renewable resources, makes it a more environmentally friendly option compared to traditional plastics, aligning with the sustainability goals in agricultural applications. Furthermore, PLA is renowned for its ease of printability, facilitating rapid prototyping and design iterations, which proved particularly beneficial in the research and development phases. Finally, certain formulations of PLA are considered food-safe, rendering it a suitable material for applications involving direct contact with fruits and vegetables, ensuring both produce safety and quality.

4.3 Coefficient of Static Friction Analysis

The inclined plane friction tests revealed a significant difference in the coefficient of static friction between the two pineapple cultivars, directly impacting the required gripping force for secure harvesting. The minimum tilt angle at which the pineapples began to slide down the PLA surface directly corresponds to the coefficient of static friction. The Kew cultivar exhibited a minimum tilt angle of 26.17°, while the Queen cultivar required a steeper angle of 30.17° to initiate movement. This difference in tilt angle directly translates to a difference in the coefficient of static friction. A larger tilt angle indicates a higher coefficient of friction, meaning a greater force is required to overcome the static friction and cause slipping. As shown in Table 3, the calculated mean coefficient of static friction for the Queen cultivar was 0.579 (± 0.043), which was 16.41% greater than that of the Kew cultivar (0.498).

This difference in friction, evident in the tilt angle measurements, translates to a substantial difference in the minimum force required to grip each cultivar without slippage. Using the average coefficient of friction for each cultivar and their respective mean weights (1.403 kg for

Kew and 0.822 kg for Queen), the minimum grabbing force(F) were calculated for Kew and Queen cultivars as shown equation (2) and (3):

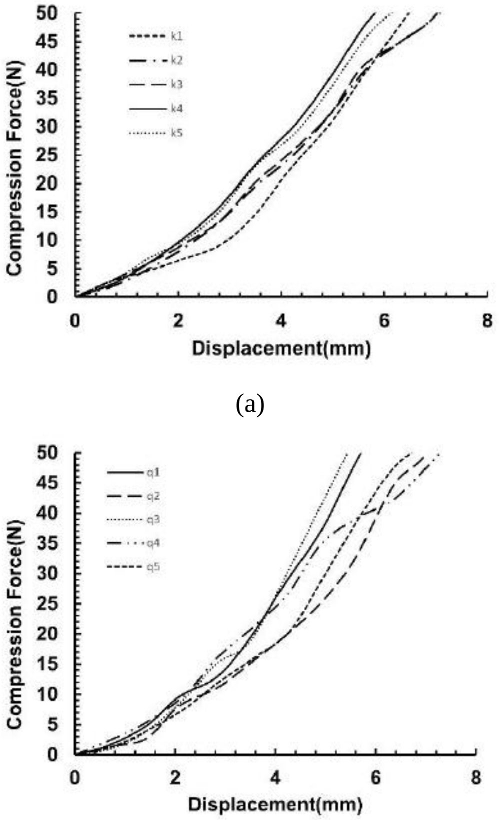
Kew:

$$\boldsymbol{F} = 3 * \frac{1.403*9.81}{2*0.498} = \mathbf{41.46}\ \boldsymbol{N} \qquad (2)$$

Queen:

$$\boldsymbol{F} = 3 * \frac{0.822*9.81}{2*0.579} = \mathbf{20.89}\ \boldsymbol{N} \qquad (3)$$

This significant difference in required gripping force (nearly double for the Kew cultivar) underscores the importance of a cultivar-aware design for robotic pineapple harvesters. A gripping system that can adjust its force based on the specific cultivar being harvested would minimize the risk of fruit damage while ensuring a secure hold, ultimately improving harvesting efficiency and yield.



(a)

(b)

Fig. 5: Graph between Compression Force(N) vs Deformation (mm) graph of (a) Kew Cultivar (b) Queen Cultivar.

The higher coefficient of static friction observed in the Queen cultivar suggests that a lower gripping force would be required to prevent slippage compared to the Kew cultivar. This information is crucial for optimizing the grabber's design and control system. By adjusting the grabbing force based on the cultivar and its corresponding friction coefficient, we can ensure a secure grip while minimizing the risk of fruit damage.

4.4 Compression Force and Displacement Analysis

Having established the minimum gripping force required to prevent slippage, we next investigated the relationship between applied compressive force and potential fruit damage. Using the compression testing unit, controlled compressive forces were applied to pineapple samples, gradually increasing up to 50 N – a value exceeding the minimum force required for both cultivars, ensuring a secure grip even for the higher-friction Queen cultivar.

The compression tests revealed a strong linear correlation (R-squared = 0.955) between the displacement of the pineapple skin and the applied compressive force for both cultivars. This indicates that, within the tested force range, deformation is directly proportional to the applied force. Interestingly, at the maximum tested force of 50 N, the Kew cultivar exhibited a slightly higher displacement (7.08 mm) compared to the Queen cultivar (7.06 mm). However, this difference was not statistically significant ($p > 0.05$), suggesting that both cultivars exhibit similar resistance to compressive forces within the tested range.

Importantly, visual inspection of the pineapple samples after compression testing, both immediately and after one week, revealed no signs of bruising or internal damage to the fruit's flesh. This finding, coupled with the lack of statistically significant differences in displacement, suggests that a maximum grabbing force of 50 N is likely within a safe range for both Queen and Kew cultivars, minimizing the risk of both external and internal damage during the harvesting process.

4.5 Grabber Performance, Implications, and Future Applications

The 3D-printed grabber, designed and evaluated in this study for its gripping capabilities and force application, successfully grasped both the "Kew" and "Queen" pineapple cultivars without causing visible damage to the fruit. The integrated force sensor accurately measured the applied force during grasping, ensuring it remained within the optimal range determined by the compression tests (Section 4.4). This precise force control is crucial for minimizing fruit damage during automated harvesting, as excessive force can lead to bruising and reduced shelf life.

The friction analysis conducted in Section 4.3 provides valuable data for the development of robotic and semi-automatic pineapple harvesting systems. By understanding the frictional properties of different pineapple cultivars, appropriate materials and surface treatments can be selected for robotic grippers to ensure both a secure grip and minimal surface abrasion during the harvesting process. This information, along with the successful force control demonstrated in this study, are essential building blocks for a complete grabbing mechanism.

Future research should investigate the grabber's performance with a wider range of pineapple cultivars and maturities to validate its broader applicability. Additionally, this research should be expanded to incorporate the design and development of a fully functional grabbing mechanism, integrating the 3D-printed grabber and force sensor with other necessary components for field testing. Exploring the integration of machine vision systems with the robotic grabber could enable the identification of ripe fruits based on color and size, allowing for selective harvesting. This advancement would further enhance harvesting efficiency and reduce post-harvest losses by targeting only mature fruits. The insights gained from this study, particularly regarding force control and damage prevention, could also be applied to the development of improved handling equipment for other delicate fruits with similar characteristics to pineapples, contributing to overall advancements in postharvest handling practices.

V. CONCLUSION

This research explored the potential of 3D-printed, force-sensing grabbers for robotic pineapple harvesting. By analyzing the frictional properties and compressive characteristics of two pineapple cultivars, we were able to identify a safe gripping force range that minimizes the risk of fruit damage. Our findings highlight the importance of understanding the delicate balance between secure gripping and excessive force during automated harvesting.

The development of a customizable and adaptable 3D-printed grabber equipped with a force sensor offers a promising solution for delicate fruit handling. The ability to rapidly prototype and iterate designs allows for tailoring the gripping mechanism to specific fruit characteristics, while force sensing provides real-time feedback to optimize gripping strategies and prevent damage.

This research has significant implications for advancing robotic and semi-automatic harvesting systems, not only for pineapples but also for a wide range of fruits and vegetables. By incorporating force sensing and customizable gripping mechanisms, robotic harvesters can operate with greater precision and delicacy, reducing fruit damage, improving efficiency, and potentially even enabling selective harvesting based on ripeness. Furthermore, the insights gained from this study extend beyond harvesting to encompass broader postharvest handling practices. By understanding the relationship between mechanical forces and fruit damage, we can develop gentler handling equipment and protocols throughout the supply chain, ultimately reducing food waste and enhancing product quality. This research underscores the promising potential of combining innovative technologies with a deeper understanding of fruit mechanics to create a more sustainable and efficient agricultural industry.

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REFERENCES

[1] Anh, N. P. T., S. Hoang, D. Van Tai, and B. L. C. Quoc. 2020. "Developing Robotic System for Harvesting Pineapples." Pp. 39–44 in *2020 International Conference on Advanced Mechatronic Systems (ICAMechS)*.

[2] Anjali, A. V., P. K. Anjitha, K. P. Neethu, A. Arunkrishnan, P. Abdul Vahid, and Santhi Mary Mathew. 2019. "Development and Performance Evaluation of A Semi-Automatic Pineapple Peeling Machine." *International Journal of Current Microbiology and Applied Sciences* 8(11):325–32. doi: 10.20546/ijcmas.2019.811.041.

[3] Benos, Lefteris, Dimitrios Tsaopoulos, and Dionysis Bochtis. 2020. "A Review on Ergonomics in Agriculture. Part I: Manual Operations." *Applied Sciences (Switzerland)* 10(6):1–21.

[4] Bhat, Krishnamurthy, and C. L. Chayalakshmi. 2021. "Microcontroller-Based Semiautomated Pineapple Harvesting System." Pp. 383–92 in *International Conference on Mobile Computing and Sustainable Informatics: ICMCSI 2020*. Springer.

[5] Crisostomo, Jan Lloyd Buenaventura, and John Ryan Cortez Dizon. 2021. "3D Printing Applications in Agriculture, Food Processing, and Environmental Protection and Monitoring." *Advance Sustainable Science, Engineering and Technology* 3(2):372312.

[6] Du, Xinwu, Xulong Yang, Jiangtao Ji, Xin Jin, and Lei Chen. 2019. "Design and Test of a Pineapple Picking End-Effector." *Applied Engineering in Agriculture* 35(6):1045–55. doi: 10.13031/aea.13405.

[7] Elfferich, Johannes F., Ebrahim Shahabi, Cosimo Della Santina, and Dimitra Dodou. 2024. "Berry Twist: A Twisting-Tube Soft Robotic Gripper for Blackberry Harvesting." *ArXiv Preprint ArXiv:2403.17099*.

[8] Farid Hossain, Md. 2015. "Nutritional Value and Medicinal Benefits of Pineapple." *International Journal of Nutrition and Food Sciences* 4(1):84. doi: 10.11648/j.ijnfs.20150401.22.

[9] Fathallah, Fadi A. 2010. "Musculoskeletal Disorders in Labor-Intensive Agriculture." *Applied Ergonomics* 41(6):738–43. doi: 10.1016/j.apergo.2010.03.003.

[10] Feng, Qingchun. 2021. "End-Effector Technologies." Pp. 191–212 in *Fundamentals of Agricultural and Field Robotics*, edited by M. Karkee and Q. Zhang. Cham: Springer International Publishing.

[11] Gunderman, Anthony L., Jeremy A. Collins, Andrea L. Myers, Renee T. Threlfall, and Yue Chen. 2022. "Tendon-Driven Soft Robotic Gripper for Blackberry Harvesting." *IEEE Robotics and Automation Letters* 7(2):2652–59.

[12] Guo, A. F., J. Li, L. Q. Guo, T. Jiang, and Y. P. Zhao. 2021. "Structural Design and Analysis of an Automatic Pineapple Picking and Collecting Straddle Machine." in *Journal of Physics: Conference Series*. Vol. 1777. IOP Publishing Ltd.

[13] Hasan Samad, Abu, YBhg Dato, Ir Ibrahim Hussein, Ismail Bahari Lynas Sdn Bhd, Malaysia Jeffereli Shamsul Bahrin, Madya Shamsul Bahari Shamsudin, Krishna Gopal Rampal, Mohd Rafee Baharudin, Nur Dalilah Dahlan, En Fadzil Osman NIOSH, Malaysia Tn Hj Mohd Esa Baruji NIOSH, Malaysia Secretariat Ayop Salleh NIOSH, Malaysia Raemy Md Zein NIOSH, Malaysia Hajah Suhaily Amran NIOSH, Malaysia Amirrudin Abdul Aziz NIOSH, Malaysia Siti Nazhatul Marina Bt Mior Iskandar NIOSH, Malaysia Noorhasimah Bt Awang NIOSH, and Malaysia Muhammad Zaki Bin Nordin NIOSH. 2016. "Journal of Occupational Safety and Health National Institute of Occupational Safety and Health (NIOSH) Ministry of Human Resources Malaysia." *Journal of Occupational Safety and Health* 13(1).

[14] He, Fengguang, Qin Zhang, Ganran Deng, Guojie Li, Bin Yan, Dexuan Pan, Xiwen Luo, and Jiehao Li. 2024. "Research Status and Development Trend of Key Technologies for Pineapple Harvesting Equipment: A Review." *Agriculture* 14(7):975. doi: 10.3390/agriculture14070975.

[15] Hohimer, Cameron J., Heng Wang, Santosh Bhusal, John Miller, Changki Mo, and Manoj Karkee. 2019. "Design and Field Evaluation of a Robotic Apple Harvesting System with a 3D-Printed Soft-Robotic End-Effector." *Transactions of the ASABE* 62(2):405–14.

[16] Kultongkham, Asiwan, Supakit Kumnon, Tawan Thintawornkul, and Teeranoot Chanthsopeephan. 2021. "The Design of a Force Feedback Soft Gripper for Tomato Harvesting." *Journal of Agricultural Engineering* 52(1). doi: 10.4081/jae.2021.1090.

[17] Liu, Tianhu, Wei Liu, Tingjun Zeng, Yifeng Cheng, Yan Zheng, and Jian Qiu. 2022. "A Multi-Flexible-Fingered Roller Pineapple Harvesting Mechanism." *Agriculture (Switzerland)* 12(8). doi: 10.3390/agriculture12081175.

[18] Mohd Ali, Maimunah, Norhashila Hashim, Samsuzana Abd Aziz, and Ola Lasekan. 2020. "Pineapple (Ananas Comosus): A Comprehensive Review of Nutritional Values, Volatile Compounds, Health Benefits, and Potential Food Products." *Food Research International* 137.

[19] Mohd Ali, Maimunah, Norhashila Hashim, Siti Khairunniza Bejo, Mahirah Jahari, and Nurul Aqilah Shahabudin. 2023. "Innovative Non-Destructive Technologies for Quality Monitoring of Pineapples: Recent Advances and Applications." *Trends in Food Science & Technology* 133:176–88. doi: https://doi.org/10.1016/j.tifs.2023.02.005.

[20] Navas, Eduardo, Roemi Fernández, Delia Sepúlveda, Manuel Armada, and Pablo Gonzalez-De-santos. 2021. "Soft Grippers for Automatic Crop Harvesting: A Review." *Sensors* 21(8).

[21] Gao, F., Wang, Y.-S., & Wang, R.-Y. (2023). Ecological Sensitivity Assessment of Hangzhou City Based on GIS and AHP. In International Journal of Rural Development, Environment and Health Research (Vol. 7, Issue 5, pp. 115–128). AI Publications. https://doi.org/10.22161/ijreh.7.5.10

[22] Navas, Eduardo, Redmond R. Shamshiri, Volker Dworak, Cornelia Weltzien, and Roemi Fernández. 2023. "Soft Gripper for Small Fruits Harvesting and Pick and Place Operations." *Frontiers in Robotics and AI* 10. doi: 10.3389/frobt.2023.1330496.

[23] Parsa, Soran, Bappaditya Debnath, Muhammad Arshad Khan, and Amir Ghalamzan E. 2023. "Autonomous Strawberry Picking Robotic System (Robofruit)."

[24] Pi, Jie, Jun Liu, Kehong Zhou, and Mingyan Qian. 2021. "An Octopus-Inspired Bionic Flexible Gripper for Apple Grasping." *Agriculture (Switzerland)* 11(10). doi: 10.3390/agriculture11101014.

[25] Rabina, Korimayum, Dipak Kumar Bose, and Syed H. Mazhar. 2021. "Knowledge of the Pineapple Growers toward Improved Pineapple Production Practices in Imphal East District of Manipur." *International Journal of Advances in Agricultural Science and Technology* 8(8):163–69. doi: 10.47856/ijaast.2021.v08i8.017.

[26] Reinhardt, Domingo Haroldo, D. Uriza, Alain Soler, G. Sanewski, and E. C. Rabie. 2017. "Limitations for Pineapple Production and Commercialization and International Research towards Solutions." Pp. 51–64 in *IX International Pineapple Symposium 1239*.

[27] Bin Salleh, Ayop, Abu Hasan Samad, Ismail Bahari, Lynas Sdn Bhd, Malaysia Jefferelli Shamsul Bahrin, Basf Asia-Pacific Services SdnBhd, Malaysia Krishna Gopal Rampal, Mohd Rafee Baharudin, Nur Dalilah Dahlan, Fadzil Osman NIOSH, Malaysia Mohd Esa Baruji, Secretariat Hanif Maidin NIOSH, Malaysia Amirudin Abdul Aziz NIOSH, Malaysia Raemy Md Zein NIOSH, Malaysia Mohd Norhafsam Maghpor NIOSH, Malaysia Abu Hanifah Mohd Kamal NIOSH, Malaysia Muhammad Syaidan Abdullah NIOSH, Malaysia Noorhasimah Awang NIOSH, Malaysia M. Hamzah Jamaludin NIOSH, and Malaysia Muhammad Zaki Nordin. 2018. *Journal of Occupational Safety and Health Editor-in-Chief*. Vol. 15.

[28] Salleh, N. F. M., E. H. Sukadarin, N. K. Khamis, and R. Ramli. 2019. "Pattern of Muscle Contraction in Different Postures among Malaysia Pineapple Plantation Workers." in *IOP Conference Series: Materials Science and Engineering*. Vol. 469. Institute of Physics Publishing.

[29] Singh, Hijam Jiten, and Sougata Karmakar. 2022. "Socio-Demography, Working Conditions, and Musculoskeletal Ailments among Pineapple Farmers in Northeast India." *Journal of Agromedicine* 27(2):245–57. doi: 10.1080/1059924X.2021.1920529.

[30] Thakar, Chetan M., Shailesh S. Parkhe, Ankit Jain, Khongdet Phasinam, G. Murugesan, and Randy Joy Magno Ventayen. 2022. "3d Printing: Basic Principles and Applications." *Materials Today: Proceedings* 51:842–49.

[31] Venter, D., and S. Dirven. 2017. "Self Morphing Soft-Robotic Gripper for Handling and Manipulation of Delicate Produce in Horticultural Applications." Pp. 1–6 in *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*.

[32] Vrochidou, Eleni, Konstantinos Tziridis, Alexandros Nikolaou, Theofanis Kalampokas, George A. Papakostas, Theodore P. Pachidis, Spyridon Mamalis, Stefanos Koundouras, and Vassilis G. Kaburlasos. 2021. "An Autonomous Grape-harvester Robot: Integrated System Architecture." *Electronics (Switzerland)* 10(9). doi: 10.3390/electronics10091056.

[33] Wahab, Nur Farhanawati, and Fatin Khairuddin. 2020. "Risk Identification of Postharvest Handling in Pineapple Crop That That Affecting the Fruit Quality." *International Journal of Academic Research in Business and Social Sciences* 10(9):671–80.

[34] Abba, A., Halliru, M., Ubale, S., Mustapha, A., Lawan, A. M., Rano, N. B., Idris, A., Ladi, H., & Bello, M. M. (2022). Analysis of Household Food and Nutrition Security Status in Sudano Sahelian Region of Northern Nigeria. In International Journal of Environment, Agriculture and Biotechnology (Vol. 7, Issue 3, pp. 001–012). AI Publications. https://doi.org/10.22161/ijeab.73.1

[35] Wang, Haifeng, Bin Li, Guangyu Liu, and Liming Xu. 2012. "Design and Test of Pineapple Harvesting Manipulator." *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering* 28(SUPPL. 2):42–46. doi: 10.3969/j.issn.1002-6819.2012.z2.008.

[36] Wang, Xing, Hanwen Kang, Hongyu Zhou, Wesley Au, Michael Yu Wang, and Chao Chen. 2023. "Development and Evaluation of a Robust Soft Robotic Gripper for Apple Harvesting." *Computers and Electronics in Agriculture* 204:107552. doi: https://doi.org/10.1016/j.compag.2022.107552.

[37] Zhang, Lianzhao, Shuo Tang, Ping Li, Shuang Cui, Hongli Guo, and Fangchao Wang. 2018. "Structure Design of A Semi-Automatic Pineapple Picking Machine." in *IOP Conference Series: Materials Science and Engineering*. Vol. 452. Institute of Physics Publishing.

[38] Zhou, Hongyu, Xing Wang, Wesley Au, Hanwen Kang, and Chao Chen. 2022. "Intelligent Robots for Fruit Harvesting: Recent Developments and Future Challenges." *Precision Agriculture* 23(5):1856–1907.