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An evaluation of African eggplant fruits engineering properties in relation to robotic harvesting

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ABSTRACT: The construction and application of eggplant harvesting robot required some basic physical characteristics and mechanical properties of the eggplant fruit. The physical characteristics (geometric mean diameter, surface area, volume, sphericity, and weight), and mechanical properties (failure energy, failure force, deformation, shear resistance, and shear force) of the Africa beauty eggplant fruits, were evaluated at three different maturity stages in this study. The maturity stages adopted in this study were 21 days after peak anthesis (DAPA), 28 DAPA, and 35 DAPA. The results obtained showed that the maturity stage resulted in a significant effect ($p<0.05$) on the mechanical properties of the eggplant fruits. The geometric mean diameter, surface area, volume, sphericity, and weight of the fruits significantly increased as the fruits matured from 21 DAPA to 35 DAPA ($p<0.05$). The failure energy, failure force, shear resistance, and shear force of the fruits were fluctuating during maturity; fruits harvested at 21 DAPA recorded the lowest values, while those harvested at 28 DAPA recorded the highest values. In addition, the study revealed that the loading position had a significant effect on the mechanical properties of the fruits ($p<0.05$). The best eggplant harvesting robot properties obtained in this study was at 28 days after peak anthesis (DAPA). The physical characteristics and mechanical properties results of eggplant fruit, obtained in this study will be useful information for the application in the design and construction of eggplant fruits robot harvesting.

Keywords: Africa beauty, artificial intelligence, eggplant, harvesting robot, mechanical properties, physical characteristics.

INTRODUCTION

Eggplant (*Solanumm elongena L*) belonging to the *Solanaceae* family, is one widely consumed vegetable plant, cultivated in the tropical and subtropical regions of the world. It thrives well in a well-drained but fertile soil. Food and Agriculture Organization (FAO), an organ of the United Nations stated that eggplant is the fifth most cultivated - *solanaceous* crop in the world (Uthumporn *et al*., 2016; Akpokodje and Uguru, 2019). Eggplant is increasingly gaining popularity in the world compared to other vegetable species due to its enormous morphological diversity (Ranil *et al*., 2017). In tropical Africa, eggplant is the third most commonly consumed fruit vegetable in quantity and value (Omotesho *et al*., 2017). Globally, eggplant fruit production is around 50 million tons per annum. The economic importance of the eggplant is better explained by the net value record of US$10 billion per year associated with eggplant production (FAO, 2014). The general global trend towards diversity in diets and increasingly greater reliance on vegetables has resulted in enigmatic eggplant production (National Research Council, 2006). Eggplant fruits are a rich source of essential minerals and vitamins, which help to decrease the low-density lipid (LDL) concentration in the blood, prevent glaucoma, subdue hydroxyl radical production within the human body, etc. (Noda *et al*., 2000; Kashyap *et al*., 2003; Harish *et al*., 2008; Ozobia *et al*., 2013). USDA

(2009) listed some of the essential nutrients contained in eggplant fruits as: dietary fiber, ascorbic acid, folate, vitamin K, vitamin B6, niacin, pantothenic acid, iron, potassium, manganese, magnesium, copper, and phosphorus.

Furthermore, pre-harvest and harvesting labours are some of the main constraints encountered by farmers during eggplant production, costing about 60% of the total cost of production (Grubben and Denton, 2004; Nwaiwu *et al*., 2012; Ekruyota and Uguru, 2021). Eggplant starts producing fruits 11 weeks after generation and had a production period of about 8 weeks. Generally, the eggplant fruit's skin in the third week after flowering is tender, glossy, firm, and sufficiently edible (Nwanze and Uguru, 2020). Eggplant fruit harvesting is carried out through manual handpicking or through the use of a pruning knife to cut off the fruits from the plant. The speedy browning colouration of the eggplant fruit after harvesting is a result of mechanical damage; thus, eggplant fruits need careful handling during harvesting and handling operations, though it will slow down the speed of the harvesting and handling operations (National Research Council, 2006; Umurhurhu and Uguru, 2019). Delaying the harvesting of eggplant fruits can lead to over maturity of the fruits, which will result in the production of fruits with - spongy flesh, dull colour skin, hardening of the seeds, amongst others. These negative impacts of over-matured eggplant fruits necessitate prompt harvest of the eggplant fruits, mostly when they have developed to full size and firm to touch, in order to achieve optimum viability and strength of the fruit (National Research Council, 2006; Nwanze and Uguru, 2020). Though the exact quantity of fruits and vegetables lost between the harvest and the consumption is not ascertainable (Ibeawuchi *et al*., 2015), it is necessary to develop an automatic system that will help better harvesting and stable production to boost food security.

Fruits harvesting and post-harvest unit operations have a lot of complications and stress, in conjunction with the shortfall in human capacity. Accordingly, there is an urgent need for extra effort in the production process, which can be addressed by using artificial intelligence. The design and fabrication of artificial intelligence (AI) machines (robots) has helped to replace human labour as manual handlings. The main advantages of AI machines in most production systems (farming inclusive) are time and energy conservation. In fruit harvesting automation, a pre-programmed machine emulates human judgment and initiative to harvest the targeted fruits at a preferred maturity stage is required (Hayashi *et al*., 2002; Ekruyota and Uguru, 2021). In fruit harvesting automation, the following processes are involved; detecting the fruit through the aid of a sensor, directing the robot grippers to the fruit's location; gripping the fruit, and plucking it using the end effector. These processes should be done without causing significant mechanical damage to the targeted fruit (Onishi *et al*., 2019; Ekruyota and Uguru, 2021). Li *et al*. (2011) pointed out that fruits mechanical damage is one of the major challenges encountered during robotic fruit harvesting and handling if the fruit's engineering properties are not taken into consideration during the design and programming of the machine. Adequate knowledge of fruit's relevant optical and mechanical properties can cause substantial achievement in time conservation and operational output in automated agricultural machines (Arima *et al*., 2001). Another area of fruit farming where robots have taken advantage is in the apple fruits harvesting (Rakun *et al*., 2011) the guiding principles followed in this development was the use of the textural attributes of apple fruits.

The mechanical damage caused to fruit during automated harvesting, is mainly from the robot excessive grippers' pressure on the fruit. Hence, it is crucial factor to have the knowledge of the agricultural products' mechanical properties, during the design, construction, and applications of agricultural robots (Ekruyota and Uguru, 2021; Uguru and Akpenyi-Aboh, 2021). Relevant data on the physic-mechanical and textural properties of fruits are vital tool in the workout plan of better robot grippers, for optimum area gripped by the robot on the fruit's surface (Ashtiani *et al*., 2016). Areas found in the research literature where the physical and the mechanical properties has been applied is in two tomato cultivars used for the design and utilization of tomato fruit harvesting robot (Li *et al*., 2011). Physical and micromechanical properties of tomato fruit's epicarp and mesocarp, which are useful in the production of harvest and post-harvest unit operations robots, were studied by Arazuri *et al*. (2007) and Gladyszewska and Ciupak (2009). Ashtiani *et al*. (2016) investigated some engineering properties of eggplant (cv. Siah-e-Mashhad) fruits, concerning the fruit's region (part) and orientation, which are essential in the design and applications of robots. Apart from fruits' harvesting, knowledge of the engineering properties of fruits is also vital during the automation design of fruits' peeling, cutting, and packaging systems.

Although there had been several studies on some basic engineering properties of plant materials, which are relevant to robot development; information related to the effect of maturation and loading position on mechanical responses of Nigerian grown eggplant tissues is lacking. Therefore, this study aimed at determining the physical characteristics and mechanical properties of eggplant (*African Beauty*) fruits at their maturity stages, as related to the design and control of harvesting and processing robots.

MATERIALS AND METHODS

Steps taken in the achievement of the objective of this study are presented in Figure 1.

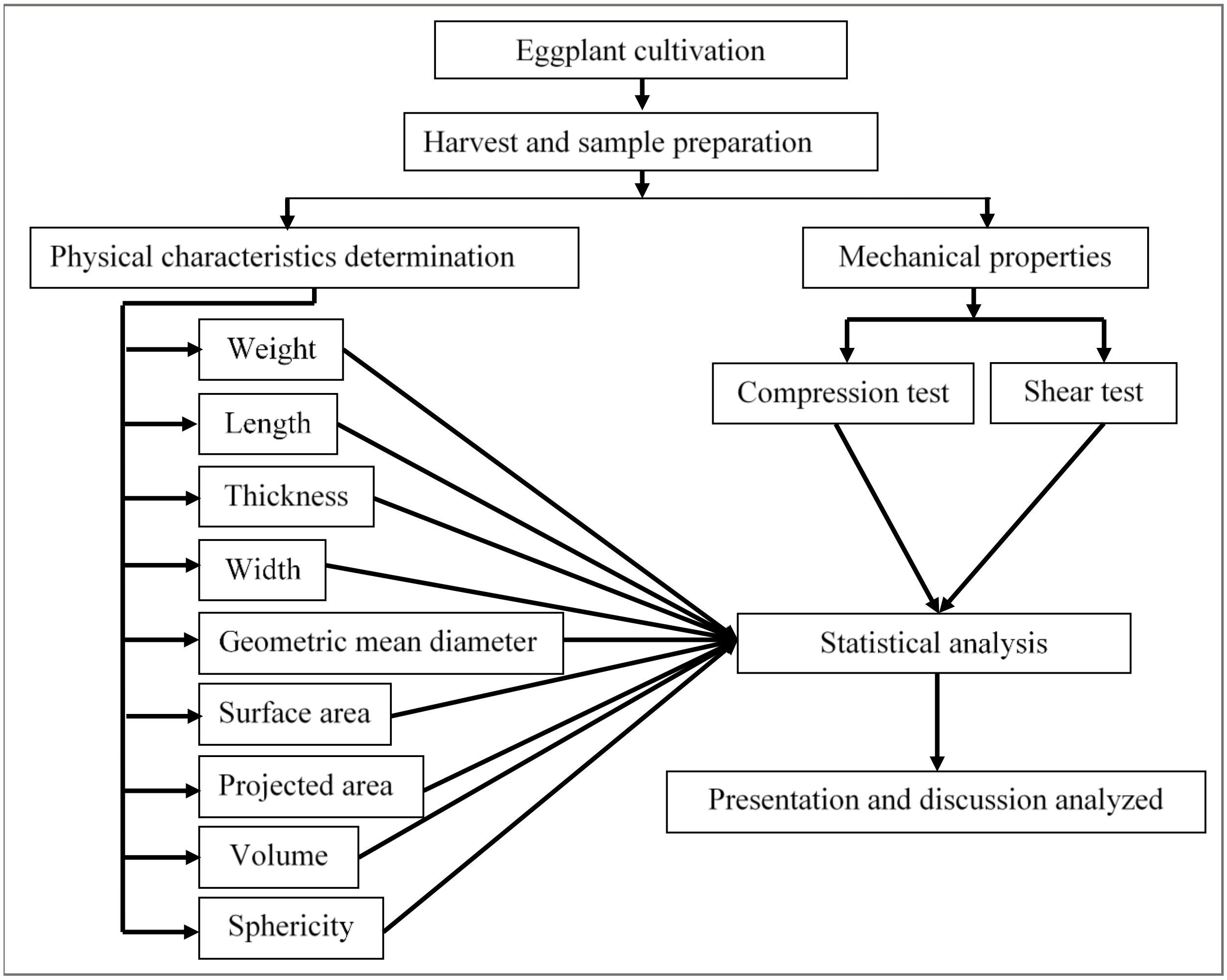

Figure 1. Framework model for this study.

Eggplant cultivation

The African beauty eggplant used for the analysis in this study was cultivated at the experimental farm of Delta State University of Science and Technology Ozoro, Nigeria. Organic farming method was adopted, as it is of benefit to the environment by reducing pollution, improving soil conservation, and water quality.

Eggplant fruits harvest and preparation

The eggplant fruits were harvested at three maturity stages from the farm using a random sampling technique. The physical characteristics and the mechanical properties of eggplant fruit analysis involved in the three maturity stages were based on the number of days after peak anthesis (DAPA). The three maturity stages were 21 DAPA (Stage 1), 28 DAPA (Stage 2), and 35 DAPA (Stage 3). For each of the three assessment stages, forty eggplant fruits were harvested and used. The eggplant fruit selected and used for the analysis had no mechanical damage or visible defect. The total number of eggplant fruit analyzed was one hundred and twenty (120).

Determination of the physical characteristics of the eggplant fruits

The one hundred and twenty eggplant fruits weights were measured using an electronic weighing balance. The principal dimensions, length (L), width (W), and thickness (T), were measured with the aid of a digital Vernier calliper (Model 500-196-30, Mitutoyo, Japan), having 0.01 mm accuracy (Uguru and Nyorere, 2019). The fruit geometric mean diameter (D_g), surface area, projected area, volume, and sphericity were calculated by employing equations 1, 2, 3,4 and 5 (Mohsenin, 1986; Burubai *et al*., 2007).

The geometric mean diameter (D_g) was calculated utilizing equation1 as follows:

$$D_g = \sqrt[3]{L \times W \times T} \quad (1)$$

Where: D_g = geometric mean diameter of the eggplant fruit, L = Length, W = Width and T = Thickness

The surface area was determined using equation 2.

$$A_s = \pi D_g^2 \quad (2)$$

Where: A_s = surface area and D_g = geometric mean diameter

The calculation of the projected area was done using equation 3.

$$A_p = \frac{\pi L W}{4} \quad (3)$$

Where: A_p = Projected area, L = Length and W = Width

The volume of the eggplant fruit was calculated using equation 4.

$$V = \frac{\pi X L X W X T}{6} \quad (4)$$

Where: V = Volume, L = Length, W = Width and T = Thickness

The sphericity was obtained using the expression at stated by equation 5.

$$f = \frac{D_g}{L} \times 100 \quad (5)$$

Where: f = Sphericity and D_g= geometric mean diameter

Mechanical properties

Compression test of the intact eggplant fruit

The intact eggplant fruit was subjected to a compression test, by using a Universal Testing Machine (UTM) (Testometric M500 100AT, England). The machine has two cells; a fixed bottom cell, and a mobile upper cell which can be pre-set at various loading speeds. For each test, an eggplant fruit sample was placed in the machine and loaded uniaxially at a compression speed of 20 mm/min, in accordance with ASABE recommendations (Sirisomboon *et al*., 2012).

Eggplant fruit has a mechanically complex and heterogeneous structure, which is anisotropic in nature (Li *et al*., 2013); hence, its shape and size changes continuously during compression. Bio-yield and rupture point concepts were used to address the difficulty of the characterization of the eggplant fruit for a simple constants value due to the continuous changes in the shape and size of the axial load (Mohsenin, 1986). The rupture force, rupture energy, and deformation at rupture points were extracted from the readings produced by the machine. Steffe (1996) stated that the rupture point of a fruit correlates to its macroscopic failure (Breaking point).

Shear test of the eggplant fruit stalk

The Warnere Bratzler device was used for the shear test. A 30^o V-notch 1 mm thick stainless steel blade was attached to the device, which was then attached to the Universal Testing Machine. The eggplant fruit stalk was placed into the device and sheared at a speed of 1 mm/s until it fractured. During the test, a shear force-deformation curve was plotted automatically by the machine. From the curve, the shear force and shear energy of the eggplant stalk were calculated electronically by the machine.

Shear test of the eggplant intact fruit

The UTM was used for this test. A 30^0 V-notch 1 mm thick stainless steel blade was attached to the UTM. The UTM was pre-set with the following information: Pre-test speed, 5 mm/s; loading force, 500 N; testing speed 1 mm/s; post-test speed 1 mm/s. For each shear test, an individual fruit was placed on its transverse position on the platform of the machine and loaded axially until the fruit cuts into two parts. The shear force and shear resistance were determined electronically by the UTM and displayed on the computer attached to the machine.

All the laboratory tests were replicated 20 times in accordance with ASABE recommendations (2008), and the mean values were recorded.

Statistical evaluation of the data obtained

Statistical analyses were carried out on the results obtained from the physical characteristics and mechanical properties of the eggplant fruit. The analyses were done using the SPSS (version 20.0) software. The means were separated and compared with the Duncan Multiple Range Test ($p<0.05$).

RESULTS AND DISCUSSION

Analysis of the eggplant fruits' physical characteristics

The analysis of variance (ANOVA) of the eggplant fruits' physical characteristics and their separated means are given in Table 1. The ANOVA result showed that fruit

Table 1. ANOVA of physical characteristics of the eggplant fruits.

Parameter	Maturity stage			Duncan (*p*-value)
	Stage 1	Stage 2	Stage 3	
Weight (g)	278.00 ± 10.170	427.00 ± 16.110	434.00 ± 15.070	2.30E-03*
Length (mm)	118.62 ± 3.060	137.24 ± 4.170	141.42 ± 4.320	2.71E-05*
Width (mm)	81.28 ± 2.170	112.09 ± 2.520	117.31 ± 3.130	9.18E-05*
Thickness	79.27 ± 2.040	110.54 ± 3.210	116.37 ± 2.070	2.71E-06*
D_g (m)	0.09 ± 0.001	0.12 ± 0.003	0.12 ± 0.002	2.73E-05*
Surface area (m^2)	0.03 ± 0.006	0.04 ± 0.005	0.05 ± 0.006	1.34E-03*
Projected area (m^2)	0.01 ± 0.003	0.01 ± 0.003	0.01 ± 0.004	2.88E-04*
Volume (m^3)	0.00 ± 0.001	0.00 ± 0.001	0.00 ± 0.001	3.29E-03*
Sphericity (%)	77.07 ± 1.270	87.13 ± 1.140	88.05 ± 1.32	4.27E-05*

Mean ± standard deviation; n = 20. *Significant at 95% confidence level.

Table 2. ANOVA of the compressive properties of the eggplant fruit for the maturation stages.

Parameter	Maturity stage			df	Duncan (*p*-value)
	Stage 1	Stage 2	Stage 3		
Failure force (N)	1108.33 ± 37.00	1572.67 ± 60.07	1341.00 ± 74.91	2	2.31E-03*
Failure energy (Nm)	7.08 ± 0.26	10.11 ± 0.32	8.11 ± 0.23	2	2.69E-05*
Rupture force (N)	1341.67 ± 72.59	1819.33 ± 33.29	1607.67 ± 41.77	2	5.08E-02*
Rupture energy (N)	7.48 ± 0.09	10.28 ± 0.26	8.48 ± 0.10	2	3.16E-06*
Def. at rupture (mm)	51.31a± 1.44	42.63 ± 1.76	64.81 ± 2.55	2	5.08E-04*

Mean ± standard deviation; n = 20. *Significant at 95% confidence level.

maturation had a significant effect at p≤0.05 on the physical characteristics investigated in this study. Additionally, the study revealed that the fruits' weight, length, width, thickness, geometric mean diameter, sphericity, volume, and surface area were significantly increased at p≤0.05 during maturation. Although the maturity stage had a significant effect on the physical characteristics, the fruits harvested at stages 2 and 3, exhibited no significant difference (p≤0.05). The geometric mean diameter of the fruit varied from an average value of 0.09±0.001 to 0.12±0.002 m as the fruit matured from stage 1 to stage 3. The surface area and projected area of the fruits varied from 0.03±0.006 to 0.05±0.006 m^2 and 0.01±0.003 to 0.01±0.004 m^2 respectively. These physical characteristics are very essential when designing automated machines for eggplant fruit harvesting. Geometric mean diameter, surface area, projected area, and sphericity help in the control and gripping accuracy of the robot's grippers. Fruit mass is a factor that determines the amount of electronic support that should be given to the robot's grippers, to avoid the collapse of the system (Ekruyota and Uguru, 2021). Similar results were reported by Li *et al*. (2011) on tomato fruits, during the study to enhance the efficiency of tomato automated harvesting vehicles. According to Li *et al.* (2011), the probability of the robot causing mechanical damage to the fruit will be reduced if the fruit is grasped at the appropriate region during harvesting.

Analysis of the eggplant fruits' compressive properties

The effect of the maturity stage on the compressive properties of the intact eggplant fruits is given in Table 2. The compressive properties of the eggplant fruits showed that the maturation of the fruits had a significant effect on the compressive properties of the fruits investigated (p≤0.05). The study revealed that the failure force, failure energy, rupture force, and rupture energy of the eggplant fruits fluctuated during the maturation of the fruit. The fruits harvested at stage 2, recorded the highest failure force, failure energy, rupture force, and rupture energy. A compressive force of 1341.67±72.59 N was required to rupture the fruits at maturity stage 1. The compressive force increased to 1819.33±33.29 N at maturity stage 2 but later declined to 1607.67±41.77 N at the fruits matured into maturity stage 3. This result signified that the cellular structure of the fruits gets weaker from maturity stage 2 to stage 3. This study revealed that during robot harvesting

Table 3. ANOVA of the shear properties of the eggplant fruit for the maturation stages.

Fruit parts	Parameter	Maturity stage			Duncan (*p*-value)
		Stage 1	Stage 2	Stage 3	
Fruit stalk	Shear force (N)	318.24 ± 14.31	447.63±10.19	451.97±12.22	5.65E-04*
	Shear energy (Nm)	0.814 ± 0.05	0.942 ±0.03	0.954 ±0.06	2.34E-03*
Intact fruit	Shear force (N)	204.14 ± 9.45	318.26±11.58	305.45±11.09	6.08E-05*
	Shear energy (Nm)	0.497 ± 0.09	0.737 ± 0.05	0.722 ±0.08	4.15E-04*

Mean ± standard deviation; n = 20. *Significant at 95% confidence level.

of African beauty fruits, the maximum force (pressure) exerted by the robot grippers on the fruits was 1108.33±37.00N at maturity stage 1, 572.67±60.07 N at maturity stage 2, and 1341.00±74.91N at the maturity stage 3. The maximum exertion pressure was to avoid the internal microstructural failure of the fruits. According to Uguru and Nyorere (2019), microstructural failure in fruits causes the fruits to lose their viability; hence, becoming highly susceptible to microbial attacks during storage.

Analysis of the eggplant fruit shear properties for the maturation stages

The ANOVA results of the effect of the maturity stage on the shear properties of the eggplant fruit and their separated means are given in Table 3. The study showed that maturity stages significantly influenced all the shear properties studied $p \leq 0.05$. With regards to the eggplant fruit stalk, the force required to shear the stalk increased dramatically with the increase in the maturation of the fruit. The average means of shear force needed to cut the eggplant fruit stalk at maturity stage 1 was 318.24±14.31 N but increased to 451.97±12.22 N at maturity stage 3. The study further revealed that the shear force and shear energy of the intact fruit generally increased during the maturity of the fruit. The shear force and shear energy increasing trend recorded in the fruit stalk, the shear force of the fruit at maturity stage 2 (318.26±11.58 N), was not significantly higher than the value recorded at the maturity stage 3 (305.45±11.09 N). Likewise, the shear energy of the fruit behaves similar to the shear force. The maturity stage 2 (0.737±0.05 Nm) recorded the highest shear energy, which was not significantly higher than the shear energy of the maturity stage 3 fruits (0.722±0.08 Nm). These results are necessary for controlling robots during fruit harvesting and fresh cutting. To prevent mechanical stress on the eggplant plant, the shear force that should be applied when cutting the fruit stalk should not be less than 451.97±12.22 N the maturity stage 3, 447.63±10.19 N at maturity stage 2 and 318.24±14.31 N at the maturity stage 1. During the robot's harvesting of eggplant fruit, the first action taken by the robot was the stable grasping of the fruit, before cutting the fruit stalk. Plucking the fruit out of the plant stalk, as in the case of tomato harvesting, there is a higher tendency of mechanical damage occurring to the plant. The mechanical damage was due to the firm anchorage between the African eggplant fruit stalk and the plant.

Conclusion

This research evaluated several physical characteristics and mechanical properties of African beauty eggplant fruits, which are useful for the construction of automated harvesting and processing systems. The fruits were harvested at three maturity stages, and their properties were evaluated accordingly. Results obtained revealed that the maturation of the fruits significantly influenced the fruits' physical and mechanical properties. It was observed that the eggplant fruits' physical characteristics significantly increased during maturation ($p \leq 0.05$). Similarly, it was observed that the fruits' compressive and shear properties increased in a fluctuating manner during the maturation of the fruits; with the results obtained at maturity stage 2, relatively higher than the results obtained at maturity stage 3. This study concluded that the maturity stage 2 (28 days after peak anthesis) had the best mechanical parameters investigated which are very important for the proper design and control of eggplant fruit harvesting and processing robot, as the occurrences of mechanical damages to the fruits will be minimized. Additionally, the physical characteristics results obtained in this study are useful information for the application of robot harvesting of eggplant fruits.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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