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Full-Length Research Paper

Evaluation of the mechanical properties of tomato (Cv. Roma) fruits as related to the design of harvesting and packaging autonomous system

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ABSTRACT: The world is currently facing a high food price index as a result of global food security deterioration. The automation of agricultural operations will increase food production by conserving power and energy. The purpose of this study was to evaluate some mechanical properties of tomato fruits that are required for the development and optimization of a tomato fruit harvesting robot. The Roma tomato seeds were planted using three different farming methods: organic, inorganic, and combined. Compost manure was used as a soil amendment in the organic method; NPK 15:15:15 fertilizer was used as a soil amendment in the organic method; and a 5:5 mixture of compost manure and NPK 15:15:15 fertilizer was used as a soil amendment in the organic method. Fruits from these farming methods were harvested at two maturity stages (pink and red ripe) and their compression parameters were tested in accordance with ASABE recommended procedures. The compression test results showed that farming method and maturity stage had a significant (p 0.05) effect on the failure force, failure energy, and compressibility of tomato fruits. Regardless of farming method, the fruits harvested at the pink maturity stage had higher failure force and failure energy than the fruits harvested at the red maturity stage. Similarly, regardless of maturity stage, fruits produced with the combined treatment developed the highest compressive parameters, while control fruits developed the lowest compressive parameters. The failure parameters of the tomato fruits revealed the maximum pressure that a robotic system should apply to a tomato fruit in order to minimize mechanical damage to the fruit. The study's findings can be used by robotic engineers and software developers to create and optimize a robotic system for tomato fruit production.

Keywords: Food security, robotic system, tomato fruit, maturity stage, mechanical properties

INTRODUCTION

Food insecurity is currently on the rise as a result of harsh climatic conditions and a labor shortage. As a result, agricultural robots have emerged as a critical factor in improving global food security (FAO, 2016; Vasconeza et al., 2019). Because of their ability to perform autonomous tasks, robots are now widely used in agricultural operations. Planting, weeding, fertilization, harvesting, disease detection, sorting, and packaging operations are some of the agricultural operations where robotic technology excels (Fountas et al., 2020). Mechanized farming can be fully automated by connecting chains of robots and autonomous vehicles into a flexible system that performs all farming operations. Burke et al. (2017) declare that the smart farming concept makes use of autonomous flexible systems and decision making to optimize the performance of farming operations Intelligent farming ensures set efficiency, improves product quality and safety, environmental sustainability, lowers production costs and increases profitability, reduces consumer delivery time, and so on (Robert et al. 2016; Gonzalez-de-Santosm et al., 2020). Due to the non-homogeneous and isotropic nature of agricultural products, agricultural robots must be robust and dynamic in order to perform in complex and unstructured environments (Hiremath et al., 2014). According to Eizicovits and Berman (2014), fruits and vegetables are typically soft, vary widely in shape and size, and are extremely sensitive to environmental physical conditions; thus, harvesting and handling machines must be designed to accommodate these anomalies without causing irreversible damage to the products (Ekruyota and Uguru, 2021). Gonzalez-de-Santosm et al. (2020) went on to say that industrial objects (non-bio-materials) typically have uniform shapes, sizes, and other mechanical properties, whereas crops have a wide range of physical and mechanical properties. To handle the variability of agricultural products, special robotic arms equipped with sophisticated sensors are required. Agricultural robots are currently being modified by robotics companies to improve their performance in the field. This includes the development of dual-robotic arm robots that can easily handle fragile products while causing minimal mechanical stress to the products (Nirmala et al., 2017; Motoman, 2018). Numerous scientists (Yaghoubi et al., 2013; Bac et al., 2014; Akbar et al., 2016; Moreno et al., 2013) have successfully developed advanced robots for agricultural operations, reducing labor workforce demand and optimizing food production. Several studies have found that agricultural products' mechanical properties aid in the design and performance of agricultural robots. According to Ashtiani *et al.* (2016) and Nwanze and Uguru (2020), the knowledge of the engineering properties of eggplant fruits is essential during the design and development of autonomous machines for their harvesting, handling and processing operations. Idama and Uguru H (2021) reported that the mechanical properties of tomato (cv. UC82B) fruits will helped to optimize the performance of their automated harvesting system. Similarly, Li *et al.* (2011) investigated some engineering properties of tomato (cv. Fenguan906 and Jinguang28) fruits, which will enhanced the performance of their harvesting robots. Roma is one of many tomato cultivars (Solanum lycopersicum) that are widely grown throughout the world, particularly in Nigeria. It is a high-yielding tomato cultivar that is used to make paste and sauce (Tomato, 2020). As an agricultural material, the engineering properties of tomato fruit are influenced by climatic conditions, maturity, harvesting period, farming methods, soil type, and so on (Eboibi et al., 2019). Although several studies on tomato fruits have been conducted, little is known about the effect of farming methods on the physical and mechanical properties of tomato (cv. Roma) fruits as they relate to robotic design. As a result, there is a knowledge gap between the engineering properties studied by previous researchers and the data required to design and develop an agricultural robot for Roma tomato fruits. As a result, the goal of this research is to assess the impact of farming methods on the physical and mechanical properties of tomato (cv. Roma) fruits, which will aid in the development of tomato harvesting and handling robots.

MATERIALS AND METHODS

The methodology taken to achieve the aim of this study is given in (Figure 1).

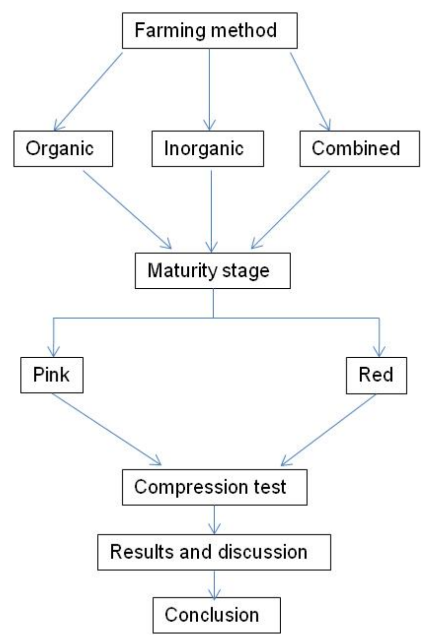

Figure 1: Research methodology flowchart

Compost manure formation

The compost manure was formulated from the mixture of oil palm bunch waste, lawn grasses, poultry waste and cassava peelings; mixed at the ratio of 3:2:4:1 (by weight).

Experimental design

The land was prepared into plots, each measuring 2 m^2. The compost manure was applied at the rate of 3 kg per plot; the NPK 15:15:15was applied at the rate of200 g per plot; while the combined treatment (prepared by mixing

compost manure and NPK 15:15:15 fertilizer at the ratio of 5:5 [by weight]), was applied at the rate of 3 kg per plot. The treatments were incorporated into the soil at a depth of 20 cm, and were done two weeks before the transplanting of the tomato seedlings; and were retreated in the form of ring manure application method, four weeks after transplanting. Each of the treatment was experimented with three replications. Every other variable (e.g. irrigation method, weed and pests control method, climatic conditions) was the same for all treatments.
The treatments were coded as follow:

T1 = Control (zero treatment)
T2 = Compost manure
T3 = NPK 15:15:15 fertilizer
T4 = Combined treatment.

Tomato fruits collection

The tomato fruits were harvested at two maturity stages; the pink and red maturity stages. The fruits were harvested manually, cleaned and sorted to remove deformed fruits. All the sorted fruits were washed under running water and dried with paper towel to remove the field heat.

Mechanical properties determination

With the help of the Universal Testing Machine, the tomato fruit was compressed (Testometric model). In each test, a tomato fruit sample was loaded into the machine and compressed uniaxially at a compression speed of 15 mm/min, as recommended by ASABE (Sirisomboon et al., 2012). The failure force, failure energy, and deformation at the failure point were extracted from the readings produced by the machine's microprocessor at the end of each compression test. Tomato fruit, like other agricultural materials, has an anisotropic and heterogeneous structure; thus, its size changes continuously during compression as a result of the amount of compressive force applied to it (Li et al., 2013; Uguru et al., 2020). As a result of the continuous changes in size during axial loading, failure (bio-yield) and rupture points are common concepts used to address the characterization of tomato fruit (Mohsenin, 1986; Steffe, 1996). Steffe (1996) stated that the failure point of a fruit correlates to its microscopic failure (bio-yield point). The compression test was replicated 20 times in accordance with ASABE recommendations (ASABE, 2008), and the mean values recorded.

Statistical analysis

Results obtained from the mechanical test was analyzed using the Statistical Package for Social Statistics (SPSS version 20.0), to evaluate the effect of treatment option on the mechanical properties of tomato fruit. Then the means were separated and compared by using the Duncan's Multiple Range Test (DMRT) at 95% confidence level.

RESULTS AND DISCUSSION

The analysis of variance (ANOVA) results of the effect of farming method and maturity stage on the mechanical properties of tomato (cv. Roma) fruits are presented in (Table 1). According to the ANOVA results, farming method and maturity stage had a significant (p 0.05) effect on the mechanical properties of the tomato fruit. Similarly, the interaction of farming method and maturity stage had a significant (p 0.05) effect on tomato fruit compressibility. The interaction of farming method and maturity stage, on the other hand, had no significant (p 0.05) effect on the failure force and failure energy of tomato fruit.

The fruit mechanical properties

Tomatoes are primarily harvested at the pick maturity stage because they are a climacteric and highly perishable fruit. This allows the ripening process to continue to the red ripe stage during the postharvest period, reducing deterioration and food waste (Moneruzzaman et al., 2009). The parameters of tomato fruit failure were the focus of this study. This is because the primary goal of robotic fruit harvesting is to improve food security by reducing food waste. According to Idama and Uguru (2021), once fruit has reached its failure point, it is extremely susceptible to deterioration, resulting in food waste. The results of the mechanical properties of tomato fruit are shown in (Table 2). According to (Table 2), regardless of maturity stage, fruits produced with combined treatment had the highest failure force, failure energy, and compressibility, while control fruits had the lowest failure force, failure energy, and compressibility. At T4, the pink and red tomato fruits had fruit failure forces of 99.07N and 89.87N, respectively; failure energies of 26.60 Nmm and 21.50 Nmm, respectively; and compressibility of 53.59 mm and 92.30 mm, respectively. The failure force in T1 fruits was 81.40 N and 71.80 N for pink and red tomato fruits, respectively; the failure energy was 14.47 Nmm and 10.33 Nmm for pink and red tomato fruits, respectively; and the compressibility was 37.72 mm and 47.72 mm for pink and red tomato fruits, respectively. Similarly, the failure force, failure energy, and compressibility of fruits produced with compost manure were significantly (p 0.05) higher than those produced with NPK 15:15:15 fertilizer. The higher compression

Table 1: ANOVA results of the effect of farming method and maturity stage on the mechanical properties of tomato fruit.

Source	Parameter	df	F Stat	P-value
Treatment	Failure force	3	317.24	1.85E-14*
	Failure energy	3	354.36	7.75E-15*
	Compressibility	3	723.95	2.72E-17*
Maturity	Failure force	1	616.40	3.34E-14*
	Failure energy	1	237.93	5.02E-11*
	Compressibility	1	3445.25	4.10E-20*
Treatment x Maturity	Failure force	3	3.90	0.0287^{ns}
	Failure energy	3	0.95	0.43802^{ns}
	Compressibility	3	175.99	1.84E-12*

* = significant at p ≤ 0.05; ns = not significant

Table 2: Mechanical properties of the tomato fruit at different stages of maturity

Parameter	Maturity	Treatment			
		T1	T2	T3	T4
Failure force (N)	Pink	81.40^{a}±1.31	95.20^{c}±0.79	90.23^{b}±0.38	99.07^{d}±1.36
	Red	71.80^{a}±0.60	82.33^{c}±0.45	80.17^{b}±0.87	89.87^{d}±1.68
Failure energy (Nmm)	Pink	14.47^{a}±0.31	25.23^{c}±0.74	23.37^{b}±0.45	26.60^{d}±0.75
	Red	10.33^{a}±0.47	20.80^{c}±0.96	19.57^{b}±0.70	21.50^{d}±0.89
Compressibility (mm)	Pink	37.72^{a}±0.85	51.24^{c}±2.4	48.88^{b}±0.9	53.59^{d}±1.5
	Red	47.72^{a}±0.36	89.39^{c}±2.3	82.34^{b}±1.5	92.30^{d}±1.7

Mean± standard deviation; in each row, means with the same common letter (superscript) are not significantly different at p ≤0.05, according to Duncan's Multiple Range Test.

parameters observed in T2, T3, and T4-treated fruits could be attributed to the essential nutrients present in the treatment options. According to Serrano et al. (2004) and Edafeadhe and Uguru (2018), essential soil nutrients such as nitrogen, potassium, phosphorus, calcium, and others aid in fruit development, increasing the fruit's ability to withstand mechanical stress and pressure. Similarly, regardless of the farming method used, tomato fruits harvested at the pink maturity stage had higher compressive force and compressive energy than tomato fruits harvested at the red maturity stage. These findings supported Toivonen (2007) findings that tomato fruits harvested at the red maturity stage are highly susceptible to mechanical damage during the harvesting process, resulting in massive food waste. Mechanical forces, according to Shahedy (2007), are a major cause of post-harvest food losses, which result from improper fruit harvesting and handling operations.

Application of the results in robotic design and development

The mechanical properties of tomato fruit assessed in the study will be useful in the development of agricultural robots. The compressive properties of fruits, according to Gongal et al. (2015), influence the design of the end-effect or and control system for fruit harvesting robotic systems. The proposed tomato fruit harvesting robot's flowchart is shown in (Figure 2). The robotic system will function based on the farming method used for tomato production and the maturity stage of the tomato fruit, as shown in (Figure 2). The information in (Table 2) will be used to determine the amount of pressure (compressive force) that the robot gripper will apply to each fruit in order to avoid rupturing the fruit during the harvesting operation. The robot will be programmed to abort the harvesting operation if the grippers are unable to apply the appropriate compressive force on the targeted tomato fruit, as shown in the flowchart. As a result, in order to minimize excessive damage to tomato fruits, the robot gripper must read and interpret the maturity stage of the tomato fruit, as well as the farming method used to cultivate it. Aside from the robotic gripper, the findings of this study will aid in the design of a harvesting robot fruits collection container. The failure force values will determine the number of fruits that can be stored in the collection container without causing stress and relaxation to the fruits in the bottom layer. To reduce the rate of mechanical damage to the fruits during the harvesting operation, the pressure applied to the fruit must be lower than the fruit's failure force. According to Onishi et al. (2019) and Li et al. (2011), fruits harvesting robots must

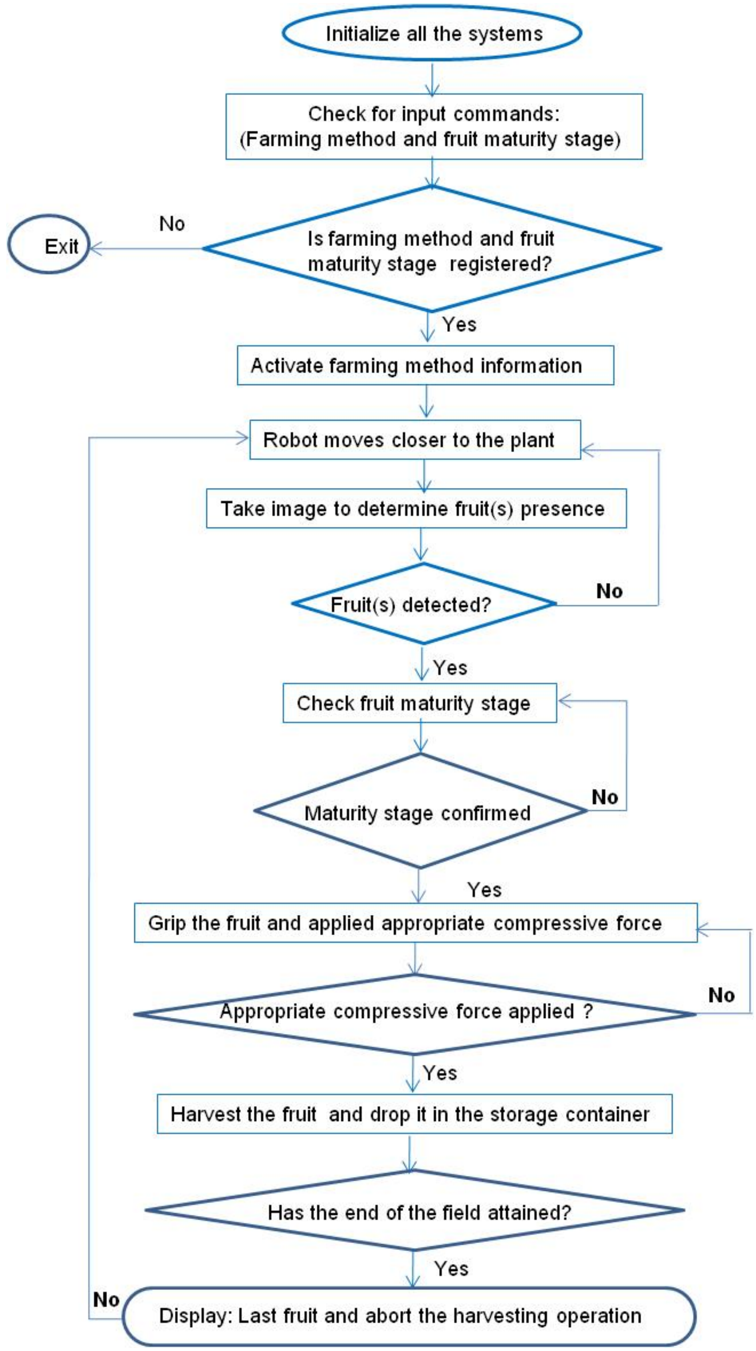

Figure 2: A flowchart of a harvesting robot for tomato fruit.

be designed and programmed in such a way that mechanical damage to the harvested fruits is minimized. The findings of this study, in conjunction with previous (Li et al., 2011; Jahanbakhshi and Kheiralipour, 2019; Edafeadhe and Uguru, 2020; Idama and Uguru, 2021), can be used to design and develop harvesting robots for various tomato cultivars grown using various farming methods. Because agricultural materials are complex and fragile in nature, Ekruyota and Uguru (2021b) believe that robust information is required to develop their harvesting robots. Similarly, Hua et al. (2019) and Idama et al. (2021) stated that the development of an effective agricultural robot requires collaboration among agricultural engineers, mechanical engineers, computer engineers, instrumentation experts, software developers, system integration specialists, and others.

Conclusion

This study was carried out to evaluate some mechanical properties of tomato fruits, which will aid in the development of tomato fruit harvesting robots. The fruits were grown using one of three farming methods: organic, inorganic, or a combination of the two. Tomato fruits from each farming method were harvested at two stages of maturity and their mechanical properties were tested using ASABE methods. The study's findings revealed that farming method and maturity stage had a significant (p 0.05) effect on the compressive properties of tomato fruits. The results showed that fruits harvested at the pink maturity stage had higher failure force and failure energy than fruits harvested at the red ripe maturity stage, regardless of farming method. Furthermore, regardless of maturity stage, the fruits produced with combined treatment had the highest compressive parameters, while the control fruits had the lowest compressive parameters. Similarly, the results showed that fruits produced using organic farming methods had higher compressive parameters than fruits produced using inorganic farming methods. These findings will be useful in the development of agricultural robots for the harvesting of tomato fruits. The force applied by the robotic system on the Roma tomato fruit during robotic harvesting should be within the permissible limit of the failure parameters stated in this study.

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