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Research Article

Mechanical Properties of Bell Pepper Fruits, as Related to the Development of its Harvesting Robot

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ABSTRACT

Adequate knowledge of the mechanical properties of fruits is required for the optimization of fruits harvesting robots. This study was carried out to evaluate some physical and mechanical properties of bell pepper fruits, which will be useful for the design and utilization of bell pepper fruits harvesting robots. Some mechanical properties (failure force, failure energy and compressibility) of matured bell pepper fruits were evaluated at three different dimension sizes and two fruit orientations, according to the American Society of Agricultural and Biological Engineers (ASABE) approved procedure. Results obtained from this study revealed that the fruit size and orientation had significant ($p \leq 0.05$) effect on the mechanical properties of the bell pepper fruits. The failure force and failure energy of the fruit increased significantly ($p \leq 0.05$) as the fruit locule number increases from 3 to 4. Relatively, the results revealed that the failure force and failure energy of the fruit increased significantly ($p \leq 0.05$) as the fruit size increased from small to large size. As portrayed by this study results, the failure force and failure energy of the fruit when loaded in the natural position was higher than values obtained, when the fruit was compressed at the vertical position; irrespective of the fruit size. This revealed that the fruit at the natural position absorbed higher compressive force (pressure) and compressive energy, regardless of the fruit locule number. Results obtained from this study will present useful information for the design, programming and optimization of bell pepper harvesting and handling robots.

RESEARCH ARTICLE

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- Compression test,
- Fruit harvesting robot
- Locule number
- Optimization

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INTRODUCTION

There is a global increment in food demand, due to the growing world human population. This has necessitated increase in food production through modern farming techniques. Pepper (genus Capsicum) is a berry fruits bearing plant belonging to the nightshade family, which is extensively cultivated for its edible and medicinal value. The fruits are used as vegetables and relishes, and may be pickled, or ground into a fine powder for use as spices (Britannica, 2020). There is sharp increment in pepper fruit production globally between 2012 and 2019. According to the Food and Agriculture Organization (FAO) portal, global pepper fruits produced increased from 30.964 million tons to 38.027 million tons, between 2012 and 2019 (FAOSTAT, 2019). Bell pepper (*Capsicum annuum*), which is one of the genus of *Capsicum* is widely cultivated in Nigeria due to its flavor, medicinal and nutritional qualities. Bell pepper is susceptible to pests and diseases, mostly the viral diseases, although some cultivars (e.g. cv. Goliath) are resistant to some of these pests and diseases. Bell pepper can thrive well in dry, sub-arid, sub-humid and humid regions, if well managed (Madagascar Catalogue, 2014; CABI, 2017).

According to Gallardo *et al.* (2010), harvesting of fruits and vegetable which are susceptible to damage is highly cost intensive, due to the dwindling skilled labor force. Poor labor supply can lead to delay in crop harvesting, which will then lead to food wastage (FAO, 2011). According to Młotek *et al.* (2015), manual fruits harvesting can lower the nutritional status of the fruits, and at the same time expose the workers to some health challenges. For instance, the juice or fluids produced by some crops (e.g. cashew fruit) are toxic to the human skin. Grubben and Denton (2004) reported that labor alone amounts to about 50% of the total cost of crop production; therefore, full automation of the agricultural sector has become inevitable. This is because, automated fruit harvesting system will augment the increasing labor demand, while decreasing the labor time, energy, and cost, which is profitable to both producers and consumers (Fennimore and Doohan, 2008; Gongal *et al.*, 2015). Although, the exact amount of agricultural products lost due to delay harvest and processing is not ascertainable; it is necessary to develop an automation system that will help crop harvesting; thus preventing food waste and improving food security (Ibeawuchi *et al.*, 2015)

Several scientists have designed and developed agricultural robots, which operate based on the engineering properties of agricultural products. Lehnert *et al.* (2017) designed sweet pepper harvesting robots, which can be utilized in a farming method where the plants are grown on planar trellis structures. Under performance of the sensing skills of a robot, which is caused by inadequate engineering information about the targeted crop, is one of the main hindrances during the application of intelligent automated crop management systems. Out of all the engineering properties of agricultural products, mechanical properties are some of the major obstacles in the optimization of agricultural robots (Tanigaki *et al.*, 2008). Li *et al.* (2011) stated that mechanical damage occurring to agricultural products, during robotic harvesting and handling operations is a major hindrance in the robotization of the agricultural sector. This is due to shortfall in the adequate knowledge of the mechanical properties of the targeted crop, during the design, programming and operation of the robot. According to Myhan *et al.* (2012), during the automatized harvesting and handling operations of agricultural products, they are often subjected to several mechanical forces. If these forces are above the bearing capacity of the targeted product, they cause internal mechanical damage to the products. Since agricultural products are non-homogeneous, their mechanical properties vary widely along their dimension and orientation. Thus, adequate information on the mechanical properties of agricultural products in this regard is necessary for the optimization of harvesting robots (Idama and Uguru, 2021). Onishi *et al* (2019) stated that accurate information on the targeted crop is crucial, during the design and programming of agricultural robot, with the purpose of minimizing the rate of mechanical damage inflicted on the target crop, by the robot's grippers and its accessories.

Several researches have been done analysis in fruit detection and harvesting operations. Kurtulmus *et al.* (2011) investigated the application of texture analysis to segment green citrus fruits, and they observed a 75.3% true fruit identification and 27.3% false fruits detection. Despite breakthroughs made in the field of automation in the agricultural sector, through the application of computer-assisted technologies, total robotization of the agricultural sector is still in the infancy stage (Barth *et al.*, 2018). This is mainly due to the lack of detailed and clear engineering data of the various crops, that are necessary to produce automated crop management systems which is caused by genetic, structural and morphological differences, farming method, prevailing climatic conduction, etc. (Gongal et al., 2015; Iweka and Uguru, 2019). Sistler (1987) stated that lack of clear direction for agricultural automation and robotics; variable environmental conditions; and complex plant structure, including its shape and size are some of the challenges hindering the optimization of agricultural robots. Therefore, the objective of this present study was to evaluate the mechanical properties of bell pepper (cv. Goliath) fruits, cultivated under Nigerian climatic conditions; which will be useful during the design, programming and optimization of bell pepper harvesting and handling robots.

MATERIALS AND METHODS

The steps to be taken in order to achieve the objectives of this study are presented in Figure 1.

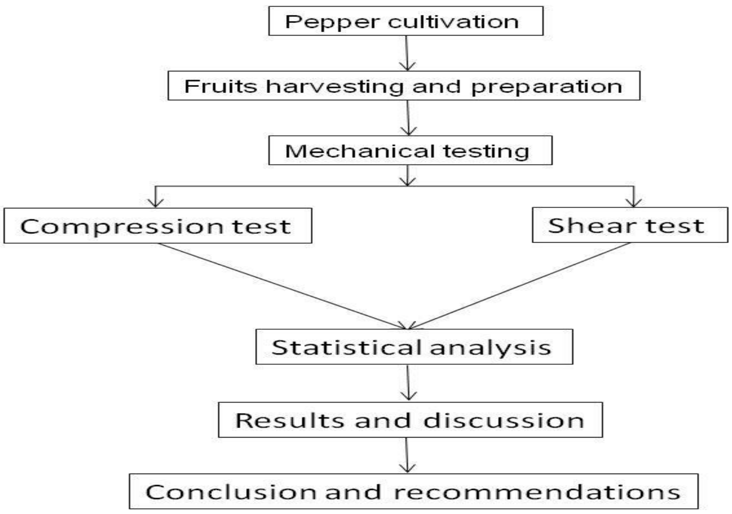

Figure 1. Flowchart of how the study objectives will be accomplished.

Pepper Cultivation

The bell pepper (*Capsicum annuum* L., cultivar Goliath F1) was cultivated at the research station of Delta State Polytechnic, Ozoro, Nigeria. Pure organic farming method was adopted; compost manure at the rate of 3 tons ha^{-1} was used for soil amendment, while neem seeds extract was used as the insecticide. Sprinkler irrigation was used as the irrigation method, while weeding was done manually throughout the experimental period.

Fruits Collection and Preparation

The pepper fruits used for this study were harvested at the deep green maturity stage. The fruits were manually inspected to remove damage, deformed and pests infected fruits, before they were taken to the laboratory for storage and mechanical analysis. After which, the fruits were further sorted based on the numbers of locule (Figure 2).

Figure 2. Locule of bell pepper fruit.
A) A three locule bell pepper fruit, B) A four locule bell pepper fruit.

Fruits Size Arrangement

The two principal dimensions (Length "*L*" and Width "*W*") of the fruits were used to categorize the fruits into different sizes. Each fruit was measured with a digital vernier caliper (accuracy of 0.01 mm); and categorized into three sizes (small, medium and large) as presented in Table 1.

Table 1. Classifications of the bell pepper fruit size

	Size		
	Small	Medium	Large
Width (mm)	$W < 55$	$55 \leq W \leq 85$	$W > 85$
Length (mm)	$L < 65$	$65 \leq L \leq 95$	$L > 95$

The Mechanical Test of the Bell Pepper Fruits

The Universal Testing Machine (UTM) (Testometric M500 100AT, England), equipped with 500 N loading cell and micro-processor, was used to determine the mechanical properties of the pepper fruits. The mechanical properties of the bell pepper fruits were tested at two loading positions, which were the natural and vertical positions (as shown in Figures 3 and 4) at three fruit sizes (small, medium and large) for both the 3 locule and 4 locule fruits.

During the mechanical (compression) test, each pepper fruit was placed between the two-loading platen of the machine (Figure 3) and compressed with a compression speed of 10 mm min^{-1}, until the fruit ruptured. As the compression progressed, the deformation of the fruit was determined electronically, in relation to the force (load) applied, which was then plotted by the machine (Figure 5). Due to the heterogeneous structure of bell pepper, the fruit shape and size changed continuously during compression, as the mechanical properties of fruits are anisotropic in nature (Li *et al.*, 2013). According to Kilickan and Guner (2008) compressibility of a fruit, is related to its relative deformation, at the failure or rupture point. All the laboratory tests were replicated 8 times in accordance with ASABE recommendations (ASABE, 2008), and the mean values recorded.

Figure 3. A four locule bell pepper fruit undergoing compression test, in the natural position.

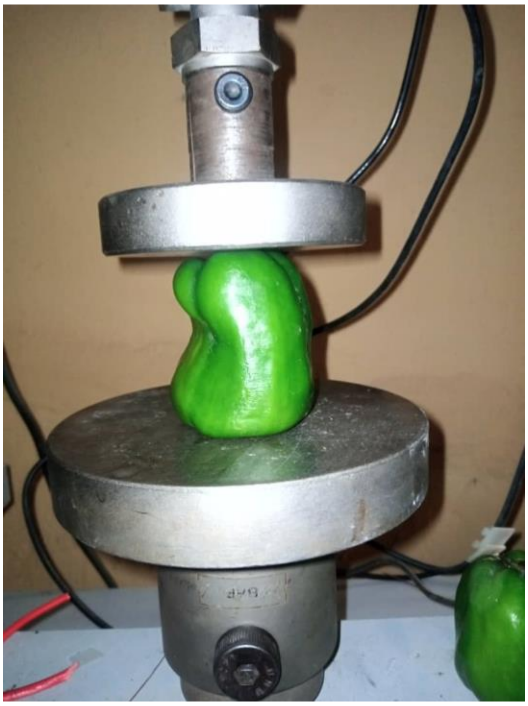

Figure 4. A three locule bell pepper fruit undergoing compression test, in the vertical position.

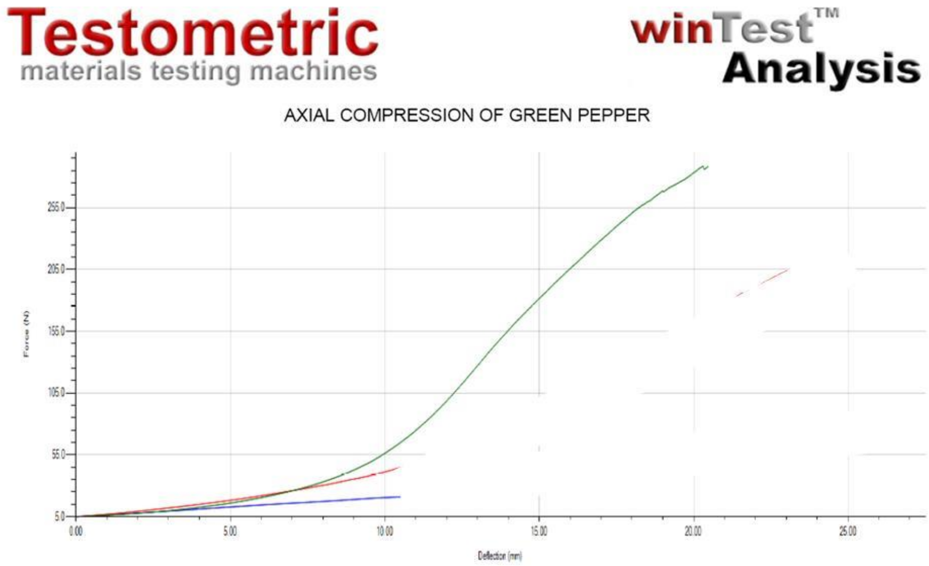

Figure 5. A force-deformation relationship of the bell pepper fruit under compression test.

Statistical Analysis

The results obtained from this study were subjected to analysis of variance (ANOVA) using SPSS 20.0 software (IBM Corporation, USA), to ascertain if the fruit size, locule number and fruit position have significant effects on the mechanical properties of bell pepper fruits. Duncan's Multiple Range Test (DMRT) was used to separate and compare the mean at 95% confidence level.

RESULTS AND DISCUSSION

The compressive parameters of the fruit at bio-yield (failure) point were considered in this study. Failure point is a crucial point to be considered during the design and development of machines for automated harvesting and handling. This is because; studies (Ince *et al.*, 2009) had shown that failed agricultural products are susceptible to microbial attacks, resulting in deterioration of their biochemical/mechanical properties during storage. According to Oghenerukewve and Uguru (2018), once an agricultural product had failed, its ability to store adequately will drop significantly, which will then lead to a shorter shelf life and high food wastage.

Effect of Locule Number and Fruit Position on the Compressive Properties of the Pepper Fruit

The statistical analysis of results presented in Table 2, revealed that the bell pepper locule number and fruit loading position had significant ($p < 0.05$) effect on the compressive properties of the pepper fruit. But in contrast, the ANOVA results showed that the interaction of locule number and loading position did not significantly ($p < 0.05$) influenced the compressive properties of the pepper fruit. The mean values and the standard deviation of failure force, failure energy and compressibility (specific deformation), as a function of the fruits locule number and fruit loading position are presented in Table 3. As portrayed in the results presented in Table 3; irrespective of the loading position, the failure force and failure energy of the fruit increased significantly ($p < 0.05$) as the locule number increases from 3 to 4; while the compressibility decreased as the locule number increases from 3 to 4. The highest failure forces (300.12 N and 277.21 N) were obtained when the 4 locule fruit and 3 locule fruit were compressed along the natural orientation respectively. This portrayed that the fruits can absorb more pressure, when compressed along with the natural orientation, compared to the vertical orientation. Similar results were obtained by Oghenerukevwe and Uguru (2018) for *Gmelina arborea* fruits, in which the mechanical properties of the fruits were also affected by the loading orientation of the fruits.

In terms of the failure energy of the fruits, fruits with higher locule numbers had significantly ($p \leq 0.05$) higher failure energy values, when compared to the fruits with lower locule number (Table 3). On average failure energy of 1.124 N m was obtained when the 4 locule number fruit was compressed at the natural orientation, which was higher than the average failure energy of 0.854 N m that was obtained, when fruits with a locule number of 3 were compressed along with the same natural orientation. This portrayed that during compression, the 4 locule number fruits required more energy for failure than the fruits with 3 locule number. Kilickan and Guner (2008) reported the higher rupture energy (0.3398 N m) was observed when an olive fruit was compressed along the *X*-axis; which was significantly higher ($p \leq 0.05$) than the rupture energy value (0.257 N m) recorded when the same size olive fruit was compressed at the *Y*-axis.

As presented in Table 3, irrespective of the loading position, the compressibility of the fruits decreased as the locule number increases from 3 to 4. Compressibility values of 31.37% and 37.79% were recorded when the 3 locule fruits were compressed along with the natural and vertical positions, respectively. However, it was observed from the results that the compressibility of the fruits declined to 24.41% and 29.28%, as the 4 locule fruits were compressed along with the natural and vertical positions, respectively. The differences in the compressibility and other mechanical properties of the fruits, across the locule numbers line, could be attributed to the difference in the internal structure of the green pepper fruit, as shown in Figure 2. According to Li *et al.* (2011), when fruits are loaded along with the natural orientation, they tend to have lower compressibility than those compressed in other orientations. This is because, the tissues arrangement of the fruit in the natural position gives the fruit a lower compression resistance. Additionally, the lower compressibility observed in the 4 locule fruit, regardless of the fruit loading orientation, could be ascribed to the better resistance offered by the fruit cross wall tissues (Li *et al.* 2011).

Table 2. ANOVA results of the effect of locule number and compression position on the failure properties of bell pepper fruit.

Source		df	MSS	F Sat	P-value
Locule	Failure force	1	6894.41	5.35	2.29E-03*
	Failure energy	1	1.22	71.59	3.91E-13*
	Compressibility	1	123.39	3.26	7.39E-03*
Position	Failure force	1	635947.28	493.15	9.88E-39*
	Failure energy	1	8.69	515.73	1.72E-39*
	Compressibility	1	765.42	20.27	1.96E-05*
locule * position	Failure force	1	852.58	0.661	0.4182^{ns}
	Failure energy	1	0.05	2.975	0.0878^{ns}
	Compressibility	1	14.56	0.385	0.536^{ns}

MSS: mean sum of square, *: significant at Duncan $p \leq 0.05$ according to Duncan's Multiple Range Test,
^{ns}: not significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test.

Table 3. Means and standard deviations of the mechanical properties of bell pepper fruit as a function of locule number and compression position.

Parameter	Position	Locule number	
		3 locule	4 locule
Failure force (N)	Natural	277.21±47.48	300.12±43.86
	Vertical	120.39±19.02	131.38±24.87
Failure energy (Nm)	Natural	0.854±0.17	1.124±0.15
	Vertical	0.298±0.07	0.476±0.10
Compressibility (%)	Natural	31.37±4.66	24.41±5.08
	Vertical	37.79±7.27	29.28±7.11

Mean± standard deviation; n: 8

Effect of Fruit Size and Fruit Position on the Compressive Properties of the Pepper Fruit

The ANOVA analysis results presented in Table 4, showed that the pepper fruit size and fruit loading position had significant ($p < 0.05$) effect on the failure parameters of the pepper fruit. In addition, an interaction of the fruit size and loading position significantly ($p < 0.05$) influenced the failure force of the pepper fruit, but the interaction of the fruit size and loading position, did not exhibit any significant ($p < 0.05$) effect on the failure energy and compressibility of the pepper fruit. As reflected by the results (Table 5), the large bell pepper fruits had better failure parameters than the medium and small bell pepper fruits, regardless of the loading position (Table 5). As presented in Table 5, regardless of the loading position, the failure force of the pepper increased significantly ($p < 0.05$), as the fruit size increases from small to large. As seen in the results given in Table 5, there was a drastic increment in the failure force of the fruits, as the size increased from small to large.

This result of the study further clarified that, regardless of the fruit size, the failure forces recorded when the fruits were loaded at the natural orientation, were higher than the failure forces recorded when the fruit was loaded in the vertical orientation. As revealed by the results, when the fruit was compressed at the natural orientation, failure forces of 251.63 N, 272.92 N and 341.45 N, were recorded for the small, medium and large fruits size, respectively. These were superior in magnitude, when compared to the failure force values of 108.39 N, 116.33 N and 152.95 N obtained when the small, medium and large fruits size were compressed at the vertical orientation. Similar results were reported by Nyorere and Uguru (2018), in which the failure force of gmelina seed increased from 427.71 N to 657.64 N, as the gmelina seed size increases from small to large size. Likewise, Khazaei *et al.* (2004) stated that the failure force of chickpea, regardless of the variety is highly influenced by the pea orientation and size.

Table 5 revealed that regardless of this loading position, the failure energy of the pepper fruits increased gradually, as the fruit size increases from small to large size. In terms of the fruit loading positions, it was also observed from the results that failure energy varied significantly ($p \leq 0.05$) across the two-fruit loading orientation considered. The rupture energy recorded at the natural orientation was higher than the rupture energy recorded at the Vertical orientation. At the vertical loading position, failure energies of 0.348 N m, 0.352 N m and 0.460 N m, respectively, were recorded for the small, medium and large fruits. While at the natural loading position, failure energies of 0.872 N m, 0.941 N m and 1.153 N m, respectively, were recorded for the small, medium and large fruits. These results are in conformity with previous research results of Kilickan and Guner (2008), which stated that the rupture energy of olive fruits increased as the fruit size increased from 10 mm to 30 mm. In addition, Saiedirad *et al.*

(2008) reported that the failure energy of cumin seed increased with an increment in the seed size. This depicted that as the fruit size increases, the energy absorbed by the fruit increases, probably due to increase in the body mass of the fruit.

In terms of the fruit compressibility, the compressibility of the fruits increased with increment of the fruit size (Table 5). As shown in Table 5, regardless of the loading position, the small fruits had the least compressibility while the large fruits had the highest compressibility. In all cases, the highest compressibility of 33.44%, 36.04% and 44.46% was observed when the small, medium and large fruits were compressed at the natural orientation. According to Li *et al.* (2011) compressibility of tomato fruits decreased slowly as the locule increases from 3 to 4, and it is attributed to the better deformation resistance offered by the 4 locule tomato fruits. This portrayed that the larger fruits experience more deformation and higher modulus of elasticity, during compression when compared to smaller fruits (Oghenerukevwe and Uguru, 2018).

Table 4. ANOVA results of the effect of fruit size and compression position on the failure properties of bell pepper fruit.

Source		df	MSS	F. Stat	p-value
Position	Failure force	1	635947.27	1513.71	4.42E-58*
	Failure energy	1	8.69	392.22	1.45E-34*
	Compressibility	1	765.42	57.67	2.77E-11*
Size	Failure force	2	39960.75	95.11	6.35E-23*
	Failure energy	2	0.34	15.71	1.39E-06*
	Compressibility	2	1190.66	89.72	3.72E-22*
Position * size	Failure force	2	4326.66	10.29	9.39E-05*
	Failure energy	2	0.058	2.62	0.07819[ns]
	Compressibility	2	17.79	1.34	0.26685[ns]

MSS = mean sum of square, * = significant at Duncan $p \leq 0.05$ according to Duncan's Multiple Range Test, ns = not significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test.

Table 5. Means and standard deviations of the mechanical properties of bell pepper fruit as a function of fruit size and compression position.

Parameter	Size	Position	
		Natural	Vertical
Failure force (N)	Small	251.63±24.57	108.39±7.15
	Medium	272.92±27.14	116.33±10.51
	Large	341.45±28.04	152.95±15.24
Failure energy (N m)	Small	0.872±0.18	0.348±0.11
	Medium	0.941±0.18	0.352±0.12
	Large	1.153±0.16	0.460±0.11
Compressibility (%)	Small	33.44±2.61	33.60±4.35
	Medium	36.04±2.59	35.67±5.07
	Large	44.46±4.10	46.35±4.01

Mean± standard deviation, n=8

Engineering Applications of the Results in Agricultural Robot's Design

Information obtained from this present study is essential for the design, development, programming and utilization of bell pepper harvesting robot. According to Li *et al.* (2011) and Gongal *et al.* (2015), the mechanical forces that a harvesting robot applies on the targeted fruit, is a crucial factor to be considered during the design of harvesting robots and associated storage accessories. Thus, the mechanical properties of the fruit affect the mechanical design of the end-effector and its control system, which affects the overall performance of the fruit harvesting robot. Hence compressive failure parameters of bell pepper fruits are critical factors to be considered, during the design, programming and utilization of bell pepper fruits automated harvesters.

Therefore, to avert mechanical damage been done to the bell pepper fruits during automated harvesting operations, the force and energy applied by the robot grippers and suction tubes, must be within the permissible limits of the failure parameters of the bell pepper fruits. As depicted by the study's results, the force and energy to be exacted on a fruit, by the harvesting robot grippers and other accessories, should not exceed the values stated in Tables 3 and 5, in order to minimize the rate of mechanical damages and wastage of the harvested bell pepper fruits. Furthermore, to prevent excessive mechanical damages to the pepper fruits, the robot gripper must first read and interprets the size parameters of the bell pepper fruits. According to the analysis of the results, the small pepper fruit swiftly attained its failure point, when compared to the large pepper fruit.

Additionally, to prevent the robot causing excessive mechanical damages to the pepper fruits, the robot must read and interpret the size, numbers of locule and orientation of the bell pepper fruit. This is because, as shown by this study, the smaller and 3 locule fruits swiftly attained its failure point, when compared to the larger and 4 locule fruits. Similarly, the analysis of the results revealed that the pepper fruit will withstand higher failure force when the robot's grippers grasped it at the natural position. Results obtained from this study will be helpful in addressing some of the major challenges in agricultural robots production and utilization with respect to bell pepper mechanization, which include: fruit orientation detection, gripper's pressure and manipulation, fruit picking orientation and method. This will help to improve the optimization of the fruit harvesting robots; hence, minimizing the effect of occlusions as earlier stated by Lehnert *et al.* (2017).

Figure 6 shows a simple flowchart of how the results obtained from this study, can be used to design and programme a bell pepper harvesting robot, for effective applications in the field. As shown in the flowchart, if the fruit is considered matured through a digital imaging system, but the appropriate fruits size, locule number and position are not detected by the robot sensors, the system will abort the operation. This study results and its potential applications, also affirmed the conclusions of a previous report by Hua *et al.* (2019). Hua *et al.* (2019) stated that the development of agricultural robots, requires the services of agricultural engineers, computer engineers, horticulturists, mechanical engineers, software developers, system integration specialists, structural engineers, etc.

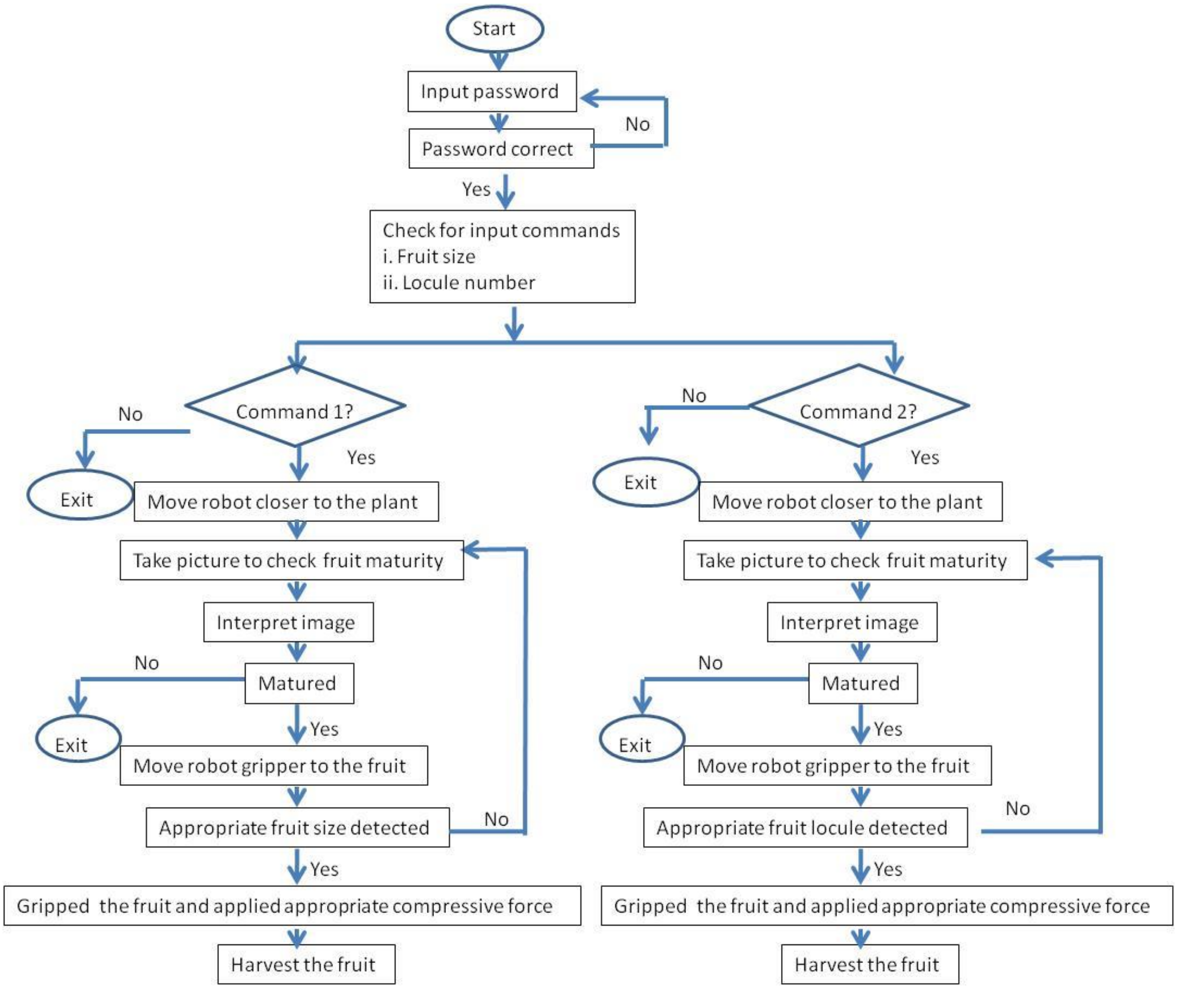

Figure 6. A simple flowchart of the proposed bell pepper harvesting robot.

CONCLUSION

In this research, some mechanical properties of bell pepper fruits were evaluated for the purpose of enhancing the efficiency of bell pepper harvesting robots. The failure force, failure energy and compressibility of matured bell pepper fruit, were tested at three fruit size levels, two locule levels and two fruit orientations levels, in according with ASABE recommended standards. Results of the tests showed that the revealed locule number, fruit size, and fruit loading position had significant ($p \leq 0.05$) effect on the compressive properties of the bell pepper fruits tested. The highest failure forces and energies were obtained when the 4 locule fruit and 3 locule fruit were compressed along their natural orientation. The results further revealed that large size bell pepper fruits required the highest failure forces and failure energies, irrespective of the fruit positions and the locule number. Similarly, analysis of the results indicates that, the pepper fruit will withstand a higher failure force, when the robot's grippers grasped it at the natural position. During robotic harvesting of matured bell pepper fruits, it is proposed that the pressure applied by the robot's accessories, should best fall within the permissible limit of the failure parameters of the bell pepper fruit, as determined by this report. This will help to reduce the occurrences of mechanical damages, and improve the efficiency of harvesting robots, particularly in Nigeria.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

The authors declared that the following contributions are correct.
Hilary Uguru: Data analysis and review of the original draft.
Ovie Isaac Akpokodje: Edited the manuscript.
Omokaro Idama: Designed the research and writing the original draft.

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