Design and development of a tomato-packaging container using Acrilonitrile-Butadiene-Styrene (ABS) plastic sheets

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Abstract. Tomato (Solanum lycopersicum L.) is a vegetable crop reported as one of the most popular crops in the world. Producing tomatoes in many developing African countries is plagued with numerous postharvest challenges. Handling and packaging of harvested tomatoes is one of the main challenges faced in Africa. Packaging provides a means of ensuring safe delivery of a product to the ultimate user in a sound condition, at a minimum overall cost. In order to reduce post-harvest losses resulting from packaging and transportation of fresh tomato fruits, an alternative tomato-packaging container using Acrilonitrile-Butadiene-Styrene (ABS) plastic sheet was developed. The drawing was produced using automated computer aided design (AUTO-CAD). The drawing was simulated using 3-dimensional solid works software. The Finite Element Analysis (FEA) was run on the software to determine the tolerable stresses on the base and handles, drop test, buckling test and stack test. Also, design calculations were done for aerodynamics requirement, heat stress, container thickness, packaging ventilations and ergonomics. The container was developed using vacuum forming method from ABS sheet. A compression test was carried out in the strength of materials laboratory. Results revealed that the packaging container can accommodate a maximum load of 0.903 kN, implying that 3 containers when filled with fresh tomato fruits can be stacked on one another. The developed tomato-packaging container is collapsible and easy to maintain by cleaning with water. Ultimately, the tendency of the plastic packaging container to be stacked on top of one another makes it better than the conventional baskets currently used for packaging and transporting fresh tomato fruits.

1. Introduction

Tomato (Solanum lycopersicum L.) is a vegetable crop reported as one of the most popular crops in the world [1]. Tomatoes production accounts for about 4.8 million hectares of harvested land area globally with an estimated production of 162 million tonnes [2] Similarly, Álvaro et al. [3] put the
global production at around 130 million tons in a year, of which around 42 million tons/year are processed. Producing tomatoes in many developing countries, Africa in particular is plagued with numerous challenges. Few among these challenges are harvesting, handling and marketing. Handling, which is mainly packaging of harvested tomatoes, is the main challenge faced in Africa. Packaging in postharvest management of fresh produce is to protect the product from extrinsic factors such as gas composition, spoilage by microorganisms, contaminations, mechanical damage, and to provide consumers with nutritional and ingredient information [4]. Packaging therefore provides a means of ensuring safe delivery of a product to the ultimate user in a sound condition, at a minimum overall cost. In order to reduce post-harvest losses resulting from packaging and transportation of fresh tomato fruits with the woven basket containers, this study developed an alternative tomato-packaging container using Acrilonitrile-Butadiene-Styrene (ABS) plastic sheet.

2. Materials and Methods

2.1 Material selections

Materials used for the development of the tomato-packaging container was carefully selected to ensure that the quality and freshness of the product is maintained through the distribution chain. Numerous packaging materials are suitable for horticultural products, which include glass, metals, and paperboard which are the predominantly used. However, a step was taken further to use plastic, precisely Acrilonitrile-Butadiene-Styrene (ABS).

2.1.1 Development and Simulation of the Drawing. A drawing of the packaging container was developed using Automated Computer Aided Design (AUTO-CAD). The drawing was then simulated with a 3-Dimensional solid works software and run the Finite Element Analysis (FEA) to determine the stresses on the base, handles, drop test, buckling test and stack test. The design calculations were done accordingly.

2.2 Design calculations

2.2.1 Aerodynamic considerations. Forces acting on an object moving through fluid (air) are mostly characterized by drag and lift force. Lift and drag force are usually quantified by defining a coefficient of lift CL and a coefficient of drag CD for the object, and then using the formulae [5]

\[ F_L = \left( \frac{1}{2} \rho V^2 \right) C_L A_L \]
\[ F_D = \left( \frac{1}{2} \rho V^2 \right) C_D A_D \]

Where, \( \rho \) is the air or fluid density, \( V \) is the speed of the fluid, and \( A_L \) and \( A_D \) are measures of the area of the objects.

This design considers drag force as the configuration of the arrangements in the vehicle does not give room for lift.

A simple model to describe the drag force [5] is:

\[ F_D = bV + CV^2 \]  

(2)

b and c are constant that depend upon the properties of the fluid and shape of the object.

bV^2 dominates at low speeds (Small Re) – Laminar
CV^2 dominates at high speeds (Large Re) – Turbulent; which is the case in this study

\[ F_D = CV^2 \] - applies to objects like cars, planes initially travelling faster than their terminal velocities are slowed down to terminal velocity by the drag force hence,

\[ F_D = \frac{1}{2} \rho AC_D V^2 \]  

(3)

Where,
\[ \rho = \text{density of fluid (air)} = 0.9 \text{ kg/m}^3 \]

\[ A = \text{maximum cross sectional area presented by moving objects.} \]

The container shape assumes a frustum, hence, area of frustum is

\[
A = \frac{\left[(r_1 + r_2)l + r_1^2 + r_2^2\right]}{2} 
\]

Total surface area =

\[
l = \sqrt{h^2 + (r_1 - r_2)^2} 
\]

\[ r_1 = 0.22m, r_2 = 0.175m, h = 0.25m \]

\[ A = 0.566m^2 \]

\[ C_D = \text{drag coefficient} – \text{dimensionless number depending on shape of objects; 0.3 – 1.2} \]

\[ V = \text{Speed of truck} = \text{speed of fluid (air)} = 56 \text{ km/hr.} \]

\[ F_D = \frac{1}{2} x 0.9 x 0.566 x 1.2 \times 56 \]

\[ F_D = 17.12N \]

The drag force is less than the total weight of the packaging container when loaded with tomato, hence, the design is safe during transportation.

### 2.2.2 Heat stress

The heat stress is the maximum heat fresh tomato fruits can withstand without causing damage to them. The peak respiration temperature suitable for tomato fruits as revealed in literatures is 37 °C, found to be the same as the environmental temperature of Nigeria. The O\(_2\) level is at 3% and tomato respiration rate will be at

\[ 20^\circ C \rightarrow 30 \text{ mg/kg.h CO}_2 \]

It is therefore expected that a normal tomato fruit at

\[ 20^\circ C \rightarrow 30\text{mg/kg.h CO}_2 \]

\[ 37^\circ C \rightarrow x, \text{ and } x = \frac{37 x 30}{20} = 55.5 \text{ mg/kg.h CO}_2 \]

will respire at 55.5 mg/kg.h CO\(_2\)

Transportation of tomato from the north to the western part of Nigeria usually takes a day (NSPRI, 1986) but due to continuous road deterioration, a day and a half was considered in this study. The permissible radius of a road is 10.7 m [6].

Heat produced in 36 hours at 55.5 mg/kg.h respiration will be

\[ 55.5 \times 10.7 \times 24 = 14,252.4 \text{ J/kg} = 14.25 \text{ kJ/kg through the entire journey} \]

The container is designed to accommodate 23 kg tomato

Total heat produced/package = 23 x 14.25 = 327 kJ/entire journey

Temperature rise in the package [7]

\[ Q = mc_p \delta t \]

\[ Q = \text{total heat produced by the tomato (sensible), J} \]

\[ C_p = \text{Specific heat of tomato} – \text{J/kg}^\circ \text{C} \]

\[ \delta t = \text{Temperature rise} – ^\circ \text{C} \]

As calculated \( Q = 327 \text{ kJ}, M = 23 \text{ kg}, C_p= 3.978 \times 10^3 \text{ J/kg}^\circ \text{C} \) [8] (ASHRAE, 2016)

\[ \delta t = \frac{Q}{mc_p} = \frac{327000}{23\times3.978\times10^3} = 3.5^\circ \text{C} \]

### 2.2.3 Ventilation of the package

The Anaerobic compensation point (ACP) of tomato as reported by Abubakar [6] from CIGR [9] ranges between 1 and 3% O\(_2\). The highest value is chosen to maintain the organoleptic properties of tomato.
Also,
The Oxygen (O\textsubscript{2}) in air = 21%.
If 100% air passes through the packaging container, it is expected to have 21% O\textsubscript{2}.
At ACP, X\% pass of air through the container will give 3\% O\textsubscript{2}.
If mathematically expressed,
\[ X = \frac{3 \times 100}{21} = 14\% \] (10)
For adequate ventilation of the packaging container, 14\% porosity was adopted for the development.
For plastic materials, circular surface holes diameter of 6 mm was used for the ventilation [6].
To determine the number of holes required for adequate ventilation of the packaging container, the expression;
14\% ventilation \times Area of circular hole [10]
But
\[ \text{Area of circular hole} = \frac{\pi d^2}{4} = 9\pi \text{mm}^2 \] (11)
Number of holes on the bottom surface
\[ \text{= Area of bottom} = 5,655 \text{ mm}^2 \]
No. of hole at bottom side\[ \frac{0.14 \times 5,665}{9\pi} = 28 \]
Number of holes on the body
\[ \text{= Area of container} = 56,600 \text{ mm}^2 \]
No. of holes on the body\[ \frac{0.14 \times 56,600}{9\pi} = 280 \] (12)

2.2.4. Design of container thickness. Wall thickness is typically determined when structural strength requirements, aesthetics, and economics (including material and production costs) are considered.
INEOS [11] advised that wall thickness should be kept uniform and avoid abrupt thickness changes.

Allowable working stress/hoop’s stress (\(\sigma\)) [12]
Yield stress of materials i.e. plastic (\(\sigma\))
n = factor of safety
\[ \sigma_1 = \frac{\sigma}{n} \] (13)
Factor of safety n that includes impact and vibration is within the range of 1.5 – 5.
For ABS material:
Yield stress \(\sigma\) = 29 N/mm\textsuperscript{2}, density of 1040 kg/m\textsuperscript{3}
\[ \sigma_1 = \frac{29}{5} = 5.8 \text{ N/mm} \]
Material thickness is expressed with the equation [13]
\[ t = \frac{P_t d}{2\sigma_1} \] (14)
Where
\( t \) = thickness
$P_T = \text{maximum expected pressure}, \quad = 20 \times 9.81 = 196.2 \text{ N/m}^2$

d = \text{diameter i.e. base diameter} = 350 \text{ mm} = 0.35 \text{ m}

\[ t = \frac{P_T \times 0.35}{2 \times 5.8} = \frac{196.2 \times 0.35}{2 \times 5.8} = 0.59 \text{ mm} \]

Thickness = 0.59 mm

2.2.5 Ergonomic factors. Tomatoes require careful handling, hence, packaging containers are mostly lifted manually. As a result, the ergonomic factor considered was purely the derivation of lifting equation that ensures the safety of the person that will load and off-load tomatoes with the developed packaging container.

2.2.6. Derivation of lifting factors. The most important lifting equation is the Recommended Weight Limit (RWL) as developed by the National Institute of Safety Health (NIOSH) [14]. The RWL for a task represents a load value that almost all healthy workers could perform over a substantial period of time mostly, up to 8 hours without an increased risk of developing lifting-related aches.

Recommended Weight Limit (RWL) = LC x HM x VM x DM x AM x FM x CM \quad (15)

Where

LC = Load Constant, HM = Horizontal Multiplier, VM = vertical Multiplier, DM = Distance Multiplier, AM = Asymmetry Multiplier, FM = Frequency Multiplier, CM = Coupling Multiplier, [15]

RWL = 4.57

The Lifting Index is a ratio or comparison between the actual weights lifted (L) and the recommended weight limit (RWL). It is a relative index of physical stress expressed as:

\[ LI = \frac{\text{Load weight}}{\text{RWL}} = \frac{23}{4.57} = 5.03 \]

The Load Index is 5.03 which is within the recommended safe load by NIOSH.

2.2.7. Plastic Packaging Container Production. The ABS sheet was cut and fixed to the holder using bolts and nuts. The ABS holder was placed on top of the oven as presented in Plate 1. The oven was then plugged and allowed to heat the ABS sheet till it becomes soft that sagging was noticed. When the sheet got hot, the mould was placed on top of the vacuum unit (Plate 2). The heated ABS sheet was hurriedly placed on top of the mould and the vacuum pump switched on to suck the ABS sheet until it takes the shape of the mould as seen in Plate 3.
Plate 1. Heating of ABS sheet
Plate 2. Mould of the container
Plate 3. Mould of the cover

Plate 4. Vacuum formed plastic container and cover
The same procedure was repeated to produce the cover. After producing the container and cover, the excess sheet was carefully and neatly trimmed to bring out the container brim. The container and the cover were then drilled with a 2 mm hand held drill bit at the sides, bottom and cover as seen in Plates 5.
2.3 Performance evaluation

A compression test was carried out on the developed plastic container in the Strength of Materials laboratory, Mechanical Engineering Department, Ahmadu Bello University, Zaria. A Dennison Universal Testing Machine (UTM) was used to apply gradual load on the developed basket. The applied load (kN), and drop height (cm) were recorded. The values were then compared with the results of the computer simulation done with Solid works software.

3. Results and Discussion

Results of the computer simulation tests carried out is presented in Figure 1. The stack-ability test was selected. This was important to determine the strength of the developed container, the maximum load it can bear when stacked on each other in reality. The values recorded were presented in Table 1.

![Plate 5. Finished Packaging container](image)

![Figure 1. Stack ability test (Stack of 10)](image)

| Stack Ability Test (Stack of 10) |
|----------------------------------|
| **Result of the Compression test** |
| S/No. | Applied Force (kN) | Distance (cm) |
|-------|-------------------|--------------|
| 1.    | 0.406             | 0            |
| 2.    | 0.432             | 5            |
| 3.    | 0.532             | 7            |
| 4.    | 0.679             | 10           |
| 5.    | 0.752             | 15           |
| 6.    | 0.841             | 19           |
| 7.    | 0.892             | 25           |
| 8.    | 0.903             | 35           |
| 9.    | 0.904             | 38           |
| 10.   | 0.904             | 42           |

The simulation result revealed that the base of the first seven containers from below were stressed between $1.149 \times 10^6 N/m^2$ to $1.263 \times 10^6 N/m^2$, a relatively smaller stress when compared with studies conducted by Babarinsa and Ige [16]. The first three containers at the bottom bear the highest stress while the top three containers were least stressed. Stresses on the bottom containers were basically as a result of the collective dead and applied load when stacked on top of one another [17]; [18] and Girja et al., 2009 [19]. It is normal for the bottom most container to bear the highest stress during stacking, however, it is recommended that the stack height should be five containers. This is to maintain the minimum allowable stress and ensure longevity of the packaging container [19].

As seen from Table 1, results of the compression tests indicated that the plastic container gradually bear increase in load as applied until it gets to its threshold of 0.903 kN (92 kg). At this load, the packaging container burst and the applied load became uniform despite the increase in the distance. This phenomenon was found to correspond to Hook’s law, indicating that the maximum weight the plastic packaging container can bear is 92 kg i.e. was found to be able to accommodate 3 more stacks on top than baskets as found in the simulation result.

4. Conclusion

The packaging container developed using ABS plastic sheets was designed to specificity. Results of both the simulation test and laboratory test revealed that the developed baskets can accommodate a maximum load of 0.903 kN. A maximum allowable stress of $1.263 \times 10^6 N/m^2$ can be loaded on the container and a maximum compression force of 904 N can be accommodated by the basket. This implies that not less than three baskets can be stacked on top of one another without damaging the fresh tomato fruits packaged inside these baskets. The developed tomato packaging container allows air to circulate around it when loaded in the truck. It is collapsible allowing space in the truck when not filled with tomato fruits and easy to maintain by cleaning with water. Ultimately, the tendency of the plastic packaging container to be stacked on top of one another makes it better than the conventional baskets currently used for packaging and transporting fresh tomato fruits.
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