Development and Performance Evaluation of a Tomato Packaging Container using Acrilonitrile-Butadiene-Styrene Plastic Sheets

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Abstract- Tomato (Solanum lycopersicum L.) is one of the world’s major fresh and processed fruit and is the second most important vegetable crop after potato worldwide. Manual harvesting is commonly done which results in poor handling and huge postharvest losses. To reduce postharvest losses, an alternative tomato packaging container was developed using Acrilonitrile-Butadiene-Styrene (ABS) plastic sheet, and its performance was evaluated. The ABS plastic sheet was cut, fixed to the plastic holder, placed on top of the oven, and heated to soften. The softened plastic was then gently placed on the mould, and a vacuum pump was switched on till the plastic takes the shape of the mould. The container was subjected to a compression test using Dennison Universal Testing Machine (UTM) to determine the maximum bearable load. The containers were filled with fresh tomato fruits, and the farm gate weight, market weight, damaged weight, transit weight loss was measured using a weighing scale while the bruised area was measured using mathematical expressions. Results revealed that the developed baskets could accommodate a maximum compression force of 904 N, which implies that five baskets of fresh tomato fruits can be stacked on top of one another with minimal bruise damage and percentage damaged weight of 20 cm² and 5% respectively. The tendency of the plastic packaging container to be stacked on top of one another with minimal postharvest losses makes it better than the conventional baskets currently used for packaging and transporting fresh tomato fruits.

Keywords - Tomato, postharvest losses, packaging container, bruise area

1 INTRODUCTION

Tomato is one of the world’s major fresh and processed fruit and is the second most important vegetable crop after potato worldwide (Isaac et al., 2015). Tomato belongs to the Solanaceae (nightshade family), genus Solanum, section Lycopersicon. The popularity of tomatoes relates to the fact that it can be eaten in multiple forms, either fresh or processed which are whole peeled tomatoes, tomato pulp and juice, tomato puree, pickled tomato, tomato paste, tomato powder, tomato flakes, dried tomato fruits, tomato soup, tomato sauces, chili sauce and ketchup (Vitale et al., 2014 and Solanke and Kumar, 2013). Tomato production occurs either in an open field or under greenhouses. Global tomato production (fresh and processed) has sharply increased in the past five decades. In 1961, production was 27.6 million tonnes, in 2002 this was 116.5 million, and in 2014 it was estimated at 171 million tonnes. China, the European Union (EU), India, the USA, and Turkey accounted for almost 70% of global production in 2014 (FAOSTAT, 2014; Álvaro et al., 2018).

Tomato harvesting is commonly done manually in Africa, which results in significant postharvest losses. Postharvest losses in tomato are prominent in handling, mainly packaging and transportation. Contamination, micro-organisms spoilage, mechanical damage are common postharvest losses incurred due to inappropriate and inefficient packaging containers.

Babalis et al. (2013) studied design and development of innovative packaging for agricultural products considering local products like olive tree pruning, wood, wood wastes, glass and ecological glues suitable for reuse, ease of assembly and disassembly (separation) of materials. The shortcoming of the study was that it was localized to Greek products and not generalized for worldwide use. Girja et al. (2009) developed corrugated fibreboard cartons for long distance transport in India. The strength and weakness of the carton was tested by subjecting it to compression-drop and vibration tests. Tests revealed that about 7% produce damage was registered at 12 straight drops while 13.5 % produce damage within 60 minutes equivalent to 1000 km on road at a frequency of 3 Hz was recorded. Vibration test revealed that damage to produce increase with increase in time; an expected package failure experienced after 33 to 55 minutes. It has a deficiency to use during rain resulting in use of special vehicle for transporting products in covered van.

Batu and Thompson (1998) studied the effects of modified atmosphere packaging on postharvest qualities of pink tomatoes. A retail plastic packaging system within sealed packs containing tomato fruits was used. A range of plastic films with different permeability properties were tested to study changes in postharvest qualities of tomatoes harvested at the pink stage of maturity stored at 13°C for 60 days. Results revealed that all unwrapped tomatoes became overripe and soft after 30 days. Tomatoes sealed within PE 50 and PP films were reported to have the lowest weight loss and the highest soluble solids after 60 days of storage. It is applicable to domestic storage at small quantity. Saeed et al. (2010) researched on the effects of packing materials on storage of tomato considering fruit firmness on packing materials like wooden crates, corrugated card board boxes with separate cells and holes made in the boundary walls and nylon mesh bag for 12 days at 20°C room temperature. Fruits placed in corrugated cardboard box showed 69.00 kg fresh and 11.05 g dry weight. Open container and mesh bags have accelerated fruit decay frequency (complex
infection) due to faster fungal sporulation and mycelial spread. They concluded that fruit quality seems to be linked with air circulation and firmness of the tomato. Moreover, Fathare et al. (2012) reviewed the design of packaging vents for cooling fresh horticultural produce. Focus of the review was on vent designs to obtain fundamental understanding of the mechanisms by which different parameters affect the rate and homogeneity of the airflow and the cooling process. Studies revealed that total opening area and opening size and position show a significant effect on pressure drop, air distribution uniformity and cooling efficiency.

Babarinsa and Ige (2012b) postulated that the forms of mechanical damage, which progressively lead to complete failure, can be controlled remarkably by designing packaging systems with due consideration for the breaking strength of the fruit. Tomatoes sold in the domestic market are packed in a diversity of container types. However, the packaging containers are expected to be well-ventilated, strong, and capable of being stacked without damaging the fruits. They are expected to have smooth inner walls that prevents abrasion of the tomato fruits. Ideally, packaging containers are expected to be wide, shallow and stackable to avoid excessive weight and bruising of tomato fruits, a well-ventilated plastic crate is most preferred. Hence, an alternative tomato packaging container expected to reduce postharvest losses was developed using Acrylonitrile-Butadiene-Styrene (ABS) plastic sheet.

2 MATERIALS AND METHODS
2.1 MATERIALS AND METHODS SELECTION
Several materials like glass, metals, paperboards, woods, and plastics were found to be suitable for developing packaging containers. Acrylonitrile-Butadiene-Styrene (ABS) plastic was chosen based on some of its properties found suitable for tomato packaging container. Few among these properties are high impact strength at low temperature, tough and strong over the recommended temperature range of -30 °C to +60 °C, abrasion resistant, chemical resistance, ultraviolet resistance, good machineability, recyclable and low cost (Mantax et al., 2004; Crawford, 1985 and Olanrewaju et al., 2017).

2.2 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. Simulation results showed that ABS has linear elastic isotropic, tensile strength of 4 X 105 N/m2; elastic and shear modulus of 2.41 X 109 N/m2 and 8.62 X 109 N/m2 respectively with a mass density of 1070 kg/m3. Assuming a normal force of 200N exerted on the weight of the tomatoes, and a corresponding reactive force considered, stresses on the container base and handles, ability to stack, drop and buckling tests when simulated revealed that the conceived container when developed can withstand the transportation rigor with insignificant damages to the packaged tomato (Olanrewaju et al., 2018). The design calculations were then done accordingly.

2.3 DESIGN CALCULATIONS
2.3.1 Aerodynamic Considerations
Forces acting on an object moving through a fluid (air) are mostly characterized by drag and lift forces. Lift and drag forces are usually quantified by defining a coefficient of lift CL and a coefficient of drag CD for the object, and then using the formulae (Khumri & Gupta, 2004).

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

(1)

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 (Khumri & Gupta, 2004) 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.

$bV$ 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,

$$F_D = \frac{1}{2} \rho A C_D V^2$$

(3)

where $\rho$ = density of fluid (air) = 0.9 kg/m³

$A$ = maximum cross-sectional area presented by moving objects.

The container shape assumes a frustum. Hence, the area of the frustum is

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

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

(4)

$r_1 = 0.22$ m, $r_2 = 0.175$ m, $h = 0.25$ m and $A = 0.566 m^2$

$C_D$ = drag coefficient – dimensionless number depending on shape of objects; 0.3 – 1.2

$V$ = Speed of truck = speed of fluid (air) = 56 km/hr.

$$F_D = \frac{1}{2} \times 0.9 \times 0.566 \times 1.2 \times 56 = 17.12N$$

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

2.3.2 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 literature is 37 °C, found to be the same as the environmental temperature of Nigeria (Naajib et al., 2017).
and Adakayi, 2012). The O₂ level is at 3%, and tomato respiration rate will be at
20°C → 30 mg/kg · hCO₂
(5)
It is therefore expected that a normal tomato fruit at
20°C → 30 mg/kg · hCO₂
(6)
37°C → x, and \( x = \frac{37 \times 30}{20} = 55.5 \text{ mg/kg} \cdot \text{hCO}_2 \)
(7)
will respire at 55.5 mg/kg · h CO₂

Transportation of tomato from the north to the western part of Nigeria usually takes a day, 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 (Abubakar, 2009). Heat produced in 36 hours at 55.5 mg/kg·h respiration will be as shown below through the entire journey.

\[
\frac{55.5 \times 10.7 \times 24 = 14,252.4 \text{ J/kg} = 14.25 \text{ kJ/kg}}
\]
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 (Onifade et al., 2013).

\[
Q = mc_p \Delta t
\]
(8)

\( Q \) = total heat produced by the tomato (sensible), J
Cₚ = Specific heat of tomato - J/kg · °C
\( \Delta t \) = Temperature rise - °C

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

\[
\Delta t = \frac{Q}{mc_p} = \frac{327000}{23 \times 3.978 \times 10^3} = 3.5^\circ \text{C}
\]
(9)

### 2.3.3 Ventilation of the Package

The anaerobic compensation point (ACP) of tomato as reported by Studman (1999) and Ruiz-Alsinsent and Ortiz-Canavate (1999) ranges between 1 and 3% O₂. The highest value is chosen to maintain the organoleptic properties of tomato. Also, the Oxygen (O₂) in air = 21 %. If 100 % air passes through the packaging container, it is expected to have 21% O₂. At ACP, X % pass of air through the container will give 3% O₂. This is mathematically expressed as,

\[
X = \frac{3 \times 100}{21} = 14 \%
\]
(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 (Abubakar, 2009).

To determine the number of holes required for adequate ventilation of the packaging container, the expression; 14% ventilation X Area of circular hole (Campos, 2006). But,

\[
\text{Area of circular hole} = \frac{\pi d^2}{4} = 9 \pi \text{ mm}^2
\]
(11)

Number of holes on bottom surface = Area of bottom = 5,655 mm²

No. of hole at bottom side = \( \frac{0.14 \times 6500}{9 \pi} = 280 \)
(12)

### 2.3.4 Design of Container Thinness

Wall thickness is typically determined when structural strength requirements, aesthetics, and economics (including material and production costs) are considered. INEOS (2007) advised that wall thickness should be kept uniform and avoid abrupt thickness changes. Allowable working stress/hoop’s stress is \( \sigma_1 \) (Babalis et al., 2013) and Yield stress of materials i.e. plastic is \( \sigma_y \), while n is the factor of safety, that includes impact and vibration within the range of 1.5 – 5.

\[
\sigma_1 = \frac{2\sigma_y}{n}
\]
(13)

For ABS material:

Yield stress \( \sigma_y = 29 \text{ N/mm}^2 \), density of 1040 kg/m³

\[
\sigma_1 = \frac{29}{5} = 5.8 \text{ N/mm}
\]

Material thickness is expressed with the equation (Clément & Stefanie, 2009)

\[
t = \frac{P_r \times 0.35}{2\pi d} = \frac{196.2 \times 0.35}{2 \times 5.8} = 0.59 \text{ mm}
\]
(14)

The thickness of ABS plastic sheets is available in 0.3 mm, 0.5 mm, and 2 mm. The material selected for this study was 2 mm since it is the range adequate for the container development based on the design calculation.

### 2.3.5 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.

### 2.3.6 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) (Nouriéddine, 2018). The RWL for a task represents a load value that almost all healthy workers could perform over substantial time, mostly, up to 8 hours without an increased risk of developing lifting-related aches.

**Recommended Weight Limit (RWL)**

\[
\text{LC x HM x VM x DM x AM x FM x CM} \quad \text{(15)}
\]
where \( \text{LC} = \text{Load Constant}, \text{HM} = \text{Horizontal Multiplier}, \text{VM} = \text{Vertical Multiplier}, \text{DM} = \text{Distance Multiplier}, \text{AM} = \text{Asymmetry Multiplier}, \text{FM} = \text{Frequency Multiplier}, \text{CM} = \text{Coupling Multiplier} \) (Thomas et al., 1993).

These parameters used for computing the recommended weight limit was selected from a tabulated figure provided by the National Institute of Safety Health; 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:
Load Index is 5.03, which is within the recommended safe load by NIOSH.

### 2.4 Plastic Packaging Container Production

The ABS plastic sheet was cut to size, fixed to the plastic holder, placed on top of the oven, and heated till it softens up. The softened plastic was then gently removed, placed on the mould and the vacuum pump switched on till the plastic takes the shape of the mould. These steps are shown in Figures 1 to 4. This procedure is repeated to form the container cover.

The developed containers were neatly trimmed out, then the sides and bottom were drilled with a 2 mm handheld drill bit to allow free airflow as presented in Figure 5.

![Fig. 1: Heating of ABS sheet](image1)

![Fig. 2: Mould of the container](image2)

![Fig. 3: Mould of the cover](image3)

![Fig. 4: (a) Vacuum formed plastic container and (b) cover](image4)

![Fig. 5: Finished Packaging container with different views](image5)
2.5 PERFORMANCE EVALUATION

The developed packaging containers were subjected to a compression test at the strength of materials laboratory of the Mechanical Engineering Department at Ahmadu Bello University, Zaria. Load (kN) and drop height (cm) were applied and recorded using a Dennison Universal Testing Machine (UTM) (Model 50 ST). The containers were taken to Kadawa market (Figure 6) along Kano to purchase fresh tomato fruits, harvested and sorted fresh tomato fruits were arranged inside a vehicle (Figure 7) and transported back to Zaria. The farm gate weight, market weight, damaged weight was measured using weighing scale (Figures 8 to 9). The transit weight loss was computed from the difference in farmgate weight and market weight; damaged weight was the difference between market weight and undamaged weight after sorting. Bruise damage was also measured by randomly selecting some battered samples subjectively, and bruise areas were calculated using simple mathematical expressions (Figure 11).
3 RESULTS AND DISCUSSION

The varying loads and the corresponding drop height as applied to the containers is presented in Figure 12.

Fig. 12: Baskets compression test

The compression of the developed basket using UTM is presented in figure 12. As force is applied to the basket, the openings began to close until all strands were on top of one another. This is explained between points A to B. At point B to C, the basket behaves like an elastic material, absorbing the forces applied and retaining its original shape when the applied force is removed and continued up to point D. Between point D and E, the basket was observed to begin to lose shape, forces applied between these points has no effects on the basket anymore. The developed packaging container absorbs gradual increase in the applied force until it reaches its threshold of 0.903 kN (92 kg) where the packaging container burst and the applied load became uniform despite further increase in the distance. This phenomenon was found to align with Hook’s law as explained in Muhammad et al. (2015) 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 of baskets on top beyond what the simulation result presented.

Table 1. Results of weight tomato loss

<table>
<thead>
<tr>
<th>Basket type</th>
<th>Position</th>
<th>Replicate 1</th>
<th>Replicate 2</th>
<th>Replicate 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% transit weight loss</td>
<td>% damaged weight</td>
<td>% transit weight loss</td>
</tr>
<tr>
<td>Plastic Basket</td>
<td>FT</td>
<td>0.6</td>
<td>4.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>FB</td>
<td>0.3</td>
<td>3.9</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>0.4</td>
<td>5.9</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>MB</td>
<td>0.8</td>
<td>6.1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>1.3</td>
<td>8.1</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>RB</td>
<td>1.3</td>
<td>8.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.8</td>
<td>5.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.83</td>
<td>5.73</td>
<td>1.15</td>
</tr>
</tbody>
</table>

FT – Front top, FB – Front Back, MT – Middle Top, MB – Middle Back, RT – Right Top, RB – Right Bottom

Table 1 presented the percentage weight loss in terms of transit and damaged loss of fresh transported tomato fruits. The mean transit weight loss for the three replicates considered were 0.83, 1.15 and 1.32 while for damaged weight loss are 5.73, 4.83 and 5.17. The overall mean for the transit weight loss and damaged weight loss are 1.1 and 5.24 respectively. It was observed from the table that baskets placed at the bottom have higher percentages of transit and damaged loss. This implied that the arrangement of basket inside the vehicle resulted in the loss of fresh tomato fruits during transportation (Fernando et al., 2018). Overfilling and inappropriate arrangements of baskets inside the vehicle may have caused transit loss (Sibomana et al., 2016).

3.1 BRUISE DAMAGE

Bruise damage are injuries inflicted on the tomato fruits mainly by the packaging container after transportation. It was revealed in this study that associated tomato injuries were observed to be abrasion due to the smooth inner walls of the developed packaging container. Bruise areas were observed to be between 6.5 and 33.1 cm² for the fruits randomly sampled from the containers. These damages were a result of basket positions inside the vehicle, vibration during transit, rubbering actions of the tomato fruits against the walls of the packaging containers, resulting in abrasion of the fruits rather than puncture or cut experienced in other types of tomato packaging containers. These findings are in agreement with the studies of Vursavuş and Ozguven, 2004; Çakmak et al., 2010 and Idah et al., 2007a, who reported that bruise was resultant effects of fruits rotation onto sharp edges inside packaging containers.

4 CONCLUSION

The packaging container developed using ABS plastic sheets was designed to specificity. Results revealed that the developed baskets could withstand a maximum load of 0.903 kN, a maximum compression force of 904 N, which implies that five baskets of fresh tomato fruits can be stacked on top of one another with minimal bruise damage and damaged weight of 20 cm² and 5%, respectively. The developed tomato packaging container allows air to circulate in it when loaded in the truck, collapsible, allowing space in the truck when not filled with tomato fruits and easy to maintain by cleaning with water. The tendency of the plastic packaging container to be stacked on top of one another with minimal postharvest losses makes it better than the conventional baskets currently used for packaging and transporting fresh tomato fruits.

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