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Application of digital twin in evaluating quality changes in tomato value-chain in Nigeria

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ABSTRACT. Cooling tomatoes after harvesting and keeping them refrigerated during their transportation is a key step toward preserving the quality attributes of tomatoes. This is a challenging task to accomplish in Nigeria, mainly because shipments of tomatoes from the tomato-producing states in northern Nigeria to the non-producing states in southern Nigeria were predominately not transported in a refrigerated ambient condition. To minimize postharvest losses of tomatoes during transportation, quantification of changes in quality would be extremely valuable. For this purpose, a digital tomato twin was developed based on mechanistic physics-based modeling. This digital twin simulated the actual thermal profile of tomatoes during transportation, based on sensed ambient environmental conditions. The impacts of the adoption of a low-cost, simple plastic packaging container compared with the traditional container (raffia baskets) on tomato's quality evolution during transportation were analyzed in-silico using the developed digital twin. Generally, the values of colour parameter (a*), firmness (N), and lycopene content (LC, mg/100ml) predicted by the digital twin model for tomatoes transported in raffia baskets were all higher than prediction for plastic container. For example, in shipment #2 the predicted colour parameter (a*) was 46.9 % more than the value predicted for the tomatoes in the plastic container at the end of the transportation. Similarly, lycopene content (LC) increased from 1.14 mg/100ml to 2.58 mg/100ml and 1.80 mg/100ml for raffia baskets and plastic container and firmness (N) decreased by 89% and 58 % in the raffia basket and plastic container respectively.

Keywords. *Tomato value chain, fresh tomato. Transportation, Digital twin, Sensors, Simulations, Kinetic model.*

Introduction

Nigeria has the largest population in Africa, with 216.7 million people and an average annual population growth rate of 2.5% (UN. 2022). According to the Institute for Health Metrics and valuation (IHME) which came up with the World Population Peak report in 2020, Nigeria will overtake the United States to become the third-most populous country in the world before 2050. And by 2100, Nigeria is projected to overtake China as the second-most populous country in the world. However, more than 12% of Nigeria's population is undernourished. And the country loses up to 40% of its total food production on an annual basis (Balana et al., 2022; Olorunfemi & Kayode, 2021). The combination of population growth and food postharvest loss has continued to threaten food security in Nigeria. Currently, Nigeria is the second-largest producer of fresh tomatoes in Africa, producing 10.8% of fresh tomatoes in the region (Ugonna et al., 2015; Kok et al., 2019; Onu et al., 2021; Ayeni et al., 2021). Globally, the country is the 11th largest tomato producer with 4.1 million tons (FAO, 2019). Over the last decade, the production of fresh tomatoes in Nigeria has grown from 1.8 million tons to an estimated 4.1 million tons annually tons (Ugonna et al., 2015). However, tomato postharvest loss across the tomatoes value chain which has been estimated to be about 45-76% annually ($2.4 billion in value) continues to be a major challenge for the country (Ugonna et al., 2015). It has been particularly reported that most tomato losses occur during transportation (Aba et al., 2012; Kok et al., 2019).

Tomatoes are prone to a high incidence of post-harvest loss during transportation, largely in part due to their high moisture content (often exceeding 80%), high respiration rate, and high susceptibility to handling damage. One of the major processes and/or strategies to mitigate post-harvest loss during their transportation is to control the environmental ambient conditions, for example, cooling tomatoes after harvesting and keeping them refrigerated throughout the rest of the supply chain (Onu et al., 2021; Tapsoba et al., 2022). This is a challenging task to accomplish in Nigeria, mainly because transportation of tomatoes from the tomato-producing states in northern Nigeria (Kano, Kaduna, etc.) to the non-producing states in southern Nigeria (Lagos, Rivers, etc.) were predominately not transported in refrigerated trucks. Usually, for transportation, tomatoes would be loaded into raffia bamboo baskets, roughly stalked on top of each other, which has resulted in a huge amount of loss caused by mechanical bruises or exposure to adverse ambient conditions. In addition, poor road networks make it more difficult, expensive, and time-consuming to transport harvested tomatoes to southern Nigeria (Aba et al., 2012). To mitigate this hurdle, there is an ongoing early adoption of low-cost simple plastic containers and/or crates to cushion the effect of mechanical bruises as well as to mitigate the adverse effect of ambient conditions on the tomatoes (Kok et al., 2019; Onu et al., 2021).

Studies have been conducted to evaluate the effectiveness of these adopted plastic containers and/or crates compared with traditional raffia baskets. Although, many of these studies analyzed post-harvest loss in the tomato value chain by focusing on measuring quantitative losses (Aba et al., 2012; Ugonna et al., 2015; Kok et al., 2019 Onu et al., 2021). This is because measuring qualitative losses such as loss in nutritional quality, caloric value, or consumer acceptability of the products is much more difficult to assess along the post-harvest value chain (Kader, 2005). Measuring qualitative losses in fresh tomatoes during transportation and determining the impacts of plastic container adoption on the quality loss of tomatoes throughout the cross-country transportation can assist farmers or stakeholders (aggregator, wholesaler, retailer) to make profound decisions regarding price because the tomato grading classification in Nigeria is closely tied to the product's quality. Generally, tomatoes can be graded into three different grades with economic value (Grade A, Grade B, and Grade C) based on colour, firmness, and damage. Grade A's tomatoes are red, firm, and undamaged tomatoes. Apart from measuring both quantitative and qualitative losses in the tomato value chain, understanding the root causes, identifying the location within the value chain where a large amount of loss occur, and developing effective policies at this point for mitigation purpose is an essential first step toward addressing the problem.

Although, some experimental measurements have been conducted to evaluate the effectiveness and the impact of the newly adopted plastic containers on tomato loss in the laboratory (Onu et al., 2021) and along the value chain (Kok et al., 2019). However, using experiments can be expensive, difficult, and time-consuming. Mathematical modeling techniques are becoming increasingly popular as an alternative to expensive and difficult experiments in postharvest operations because of the sophistication and reliability of computers as well as the affordability and availability of modeling software. Several valuable kinetic mathematical modeling studies have been performed on various fruit including apples, bananas, grapes, and so on (Ambaw et al., 2021; Fadiji et al., 2021). However, in all these studies the interior fruit's temperature was not used in predicting the quality attributes, such as firmness or vitamin C content or remaining shelf-life, which are temperature driven biochemical reactions. To overcome this, Defraeye et al.(2019) developed a validated digital twin by demonstrating how temperature values computed by the simulation of heat transfer model for mango fruits serve as inputs for a kinetic rate model for predicting quality attributes of the mango fruit in real time. Similar studies have been completed. Pattanaik & Jenamani (2020) developed physics-based digital twins of three export variety of Indian mangoes to study their cooling characteristics (Melesse et al., 2022) employed the use of machine learning based digital twin to monitor banana fruit quality evolution using thermal camera.

This study aims to use a similar digital-twin modeling framework to develop a tomato digital twin and evaluate in-silico using the developed digital tomato twin model the impacts of plastic packaging containers and traditional raffia baskets on tomato quality evolution during transportation in Nigeria – from farm to market – by using temperature and humidity sensor data. Also, open access weather and GPS geographical location data were incorporated to predict real-time quality attributes of tomatoes during transportation from the North-central (Kano) to South (Lagos). The targeted quality attributes in this study are colour (a*), firmness (N), and lycopene content (LC, mg/100ml) which were chosen to reflect tomato quality grading standard in Nigeria

Materials and Methods

Study Areas

This study was implemented to cover the LAKAJI (Lagos-Kano-Jibiya) agricultural trade corridor, one of the largest long-distance transportation routes that primarily connects tomato production zones located in the northern part of the country with the wholesale and consumer markets located in the south. The LAKAJI (Lagos-Kano-Jibiya) corridor is approximately 1,225 kilometers long and runs through eight major states. In this study, the LAKAJI corridor was chosen to represent a worst-case scenario since the route is characterized by poor road conditions, severe congestion due to traffic accidents or disabled trucks, security checkpoints, and flooding from heavy rain, which can stall trucks for extended periods. And of recent, header-farmers clashes, banditry, and Boko haram insurgency, mainly in the northern areas of the corridor have further caused the delay in transportation for much longer than ideal and without cooling systems in the loaded trucks.

Tomato loading and transportation

One tomato transporter and different farmers were selected for this study in the northern part of the country (Kano). Individual farmers harvested their produce as usual and packed them in the traditional raffia baskets (scenario A) and into the provided plastic container (scenario B) ready for shipment to the southern part of the country (Lagos) by the selected transporter or (aggregator). One sample of each of the containers (plastic container and raffia basket) was selected from the entire batch per shipment in order not to hinder the normal loading and transportation business procedures. The selected samples were labeled for sensor tracking and to differentiate them from other batches. Just before transportation, all samples were weighed and recorded. Also, temperature sensors were calibrated and then fixed on the samples (raffia basket and plastic container). The sensor was designed on Arduino, and it was capable of monitoring temperature inside the containers and ambient with high sensitivity.

Figure 1. Raffia baskets and plastic containers loaded into a truck for transportation

Sensor and data collection

This study measured the air temperature inside the loaded truck and surrounding temperature of the tomatoes in both the selected raffia baskets and plastic containers using the developed sensor. Currently, there are no available temperature datasets for tomato shipment in Nigeria. For this study, we captured the air temperature surrounding tomatoes during transportation along the LAKAJI transport corridor. The temperature sensor data were recorded every 15 minutes starting from when the truck was loaded at the aggregator center in Kano to the wholesale market in Lagos passing through Kaduna and other major cities. Additional to the air temperature data, geolocation data were recorded for each shipment using GPS (Garmin eTrex 78s Handheld). The trucks were loaded in three rows, and four columns, each row comprised of two layers of tomato container (raffia basket and/or plastic container) stacked on top of each other. This resulted in a total of 24 tomato crates in each truck. A total of five (5) shipments were completed for this preliminary study. The temperature sensors were placed inside the raffia baskets and plastic containers at the bottom level of the last row of the stacked shipments inside the truck

Physics-based digital twin concept

A continuum 2D axisymmetric multiphysics model was developed to simulate tomato conditions and its boundary convective exchange with the ambient environment during transportation through the LAKAJI transport corridor. The heat transfer equation was solved for the dependent temperature variable to calculate temperature distribution within the interior of the tomato fruit. These computed temperature values were coupled with the boundary sensed real-time ambient air temperature to form the so-called digital twin. The developed digital twin of the tomato fruit was then applied to provide insights into the intrinsic tomato quality by incorporating a kinetic rate model to predict the quality attributes of tomatoes during transportation. From the schematic diagram shown in Figure 2, the digital twin would simulate the temperature within the tomato fruit based on the real-time temperature sensor data and then incorporate kinetic models to predict changes in quality attributes.

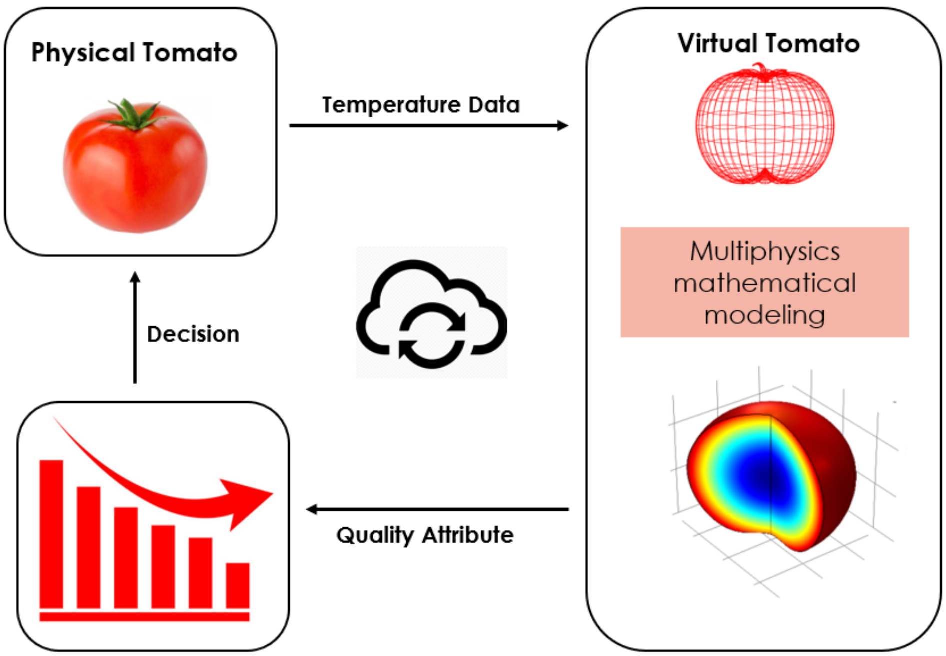

Figure 2. Schematic representation of tomato digital twin

Heat transfer modeling of tomato

The model was developed for one single tomato geometry with similar dimensions and properties as shown in Table 1 measured from actual tomato samples. The heterogeneous variability in both physical and thermal properties among tomato samples was not considered in developing the model for simplification purposes.

Table 1
Thermal and physical properties of fresh tomato fruit.

Properties	Symbol	Value	Unit	Reference
Diameter	D_L	0.051	m	Onifade & Aregbesola (2013)
Height	D_T	0.045	m	Onifade & Aregbesola (2013)
Surface area	A_t	0.002	m^2	(Onifade & Aregbesola, 2013)
Mass	m_t	0.050	kg	Onifade & Aregbesola (2013)
Density	ρ_t	710	$kg.m^{-3}$	(Onifade & Aregbesola, 2013)
Specific heat capacity	c_p	4.02	$kJ.kg^{-1}K^{-1}$	ASHRAE (2006)
Thermal conductivity	k_t	0.59	$W.m^{-1}K^{-1}$	Greidanus & Verhoeven (1986)

Temperature distribution within the tomato fruit was computed using the heat transfer model as shown in equation (1).

$$\rho_t c_p \frac{\partial T_t}{\partial t} + \nabla.(k_t \nabla T_t) = Q_R \tag{1}$$

ρ_t is the density of tomato fruit ($kg.m^{-3}$), c_p is the specific heat capacity of tomato fruit ($kJ.kg^{-1}K^{-1}$), k_t is the thermal conductivity of tomato fruit ($W.m^{-1}K^{-1}$), Q_R is volumetric heat source (Wm^{-3}).

The internal heat generated within the tomato fruit because of physiological respiration was incorporated into the model through the source term, Q_R and it is defined as follows in equation (2).

$$Q_R = W_t \cdot \rho_t \tag{2}$$

where W_t is a respiratory heat generation rate ($W.kg^{-1}$) determined by linear interpolation of experimental values of W_t that ranges from 60.6 to 126.6 $mW.kg^{-1}$ obtained by Scholz et al. (1963) for mature green tomatoes from 15 to 27°C. Therefore, in this model a linear interpolation function was used to recalculate W_t for each T, the average of tomato fruit temperature.

The heat exchange between the tomato and the ambient air during transportation was accounted for through a thermal boundary at the surface of the tomato where conductive heat flux from the fruit was set to be equal to the convective heat exchange with the ambient environment as shown in the equation (3)

$$n.(-k_t \nabla T_t) = q_s = CHTC(T_s - T_{ref}) \tag{3}$$

n is the unit vector normal to the interface, q_s is the heat flux at the interface ($J.m^{-2}s^{-1}$), $CHTC$ is a convective heat transfer coefficient ($W.m^{-2}K^{-1}$), T_s is the derived temperature at the interface (K) and T_{ref} is the measured air temperature (K). $CHTC$ was calculated using its relationship with the Nusselt number (Nu) as illustrated in equation (4).

$$Nu = CHTC\frac{D_L}{k_a} \tag{4}$$

k_a is the thermal conductivity of air ($W.m^{-1}K^{-1}$) and D_L is the diameter of the tomato fruit (m).

Nu was derived from the correlation corresponding to the spherical shape of the tomato fruit. It should be noted that this correlation considers an average CHTC, neglecting the circumferential variation. This simplification was sufficient for this study as the circumferential variation has a limited impact on the fruit warming or cooling at lower air velocities.

$$Nu = 2 + (0.4Re^{0.5} + 0.06Re^{0.667})Pr^{0.4}\left(\frac{\mu_a}{\mu_{awall}}\right)^{0.25} \tag{5}$$

In the equation (5), μ_a and μ_{awall} are the dynamic viscosity of air and at the container wall [$kg.m^{-1}s^{-1}$] and it was assumed that there is no difference between the two for this study. Re is the

Reynolds number and Pr is the Prandtl number which were both calculated using equation (6) and equation (7) respectively.

$$Re = \frac{U_{ref} D_L}{v_a} \tag{6}$$

$$Pr = \frac{v_a}{\alpha_a} \tag{7}$$

v_a is the kinematic viscosity of air ($m^2 s^{-1}$) calculated as ${}^{\mu_a}/{\rho_a}$ and α_a is the thermal diffusivity of air ($m^2 s^{-1}$). U_{ref} ($m\ s^{-1}$) airflow around the tomato fruit inside the container calculated as shown in equation (8).

$$U_{ref} = \frac{v}{\varepsilon_p} \tag{8}$$

Where v ($m\ s^{-1}$) is the speed of air blowing over the tomato container and/or basket through the truck's trailer roughly estimated as 0.01 ms^{-1} depending on the average wind speed that ranges between 4.56 – 0.87 ms^{-1} based on the measurements from Venus et al. (2013) during tomatoes transport in West Africa from Burkina Faso to Ghana. In this study, ε_p corresponds to the fraction of the void space within the raffia basket or the plastic container. This was estimated as 30 % (0.3) based on the number of the tomato fruits occupying the containers. The air properties used for the simulation were stated in Table 2. All calculated values were obtained as follows: $Re = 118$, $Pr = 0.74$, $Nu = 7.13$ and $CHTC = 3.41\ W.m^{-2}K^{-1}$

Table 2
Air properties used in simulation.

Properties	Symbol	Unit	Value
Density of air	ρ_a	$kg.m^{-3}$	1.25
Thermal conductivity of air	k_a	$W.m^{-1}K^{-1}$	2.44×10^{-2}
Thermal diffusivity of air	α_a	$m^2 s^{-1}$	1.94×10^{-5}
Specific heat capacity of air	c_{pa}	$kJ.kg^{-1}K^{-1}$	1.005
Dynamic viscosity of air	μ_a	$kg.m^{-1}s^{-1}$	1.78×10^{-5}
Kinetic viscosity of air	v_a	$m^2 s^{-1}$	1.43×10^{-5}

For calibration purposes, core temperature of an actual tomato fruit measured by using thermometer as a function of time for the two scenario A (Raffia Baskets) and Scenario B (Plastic Container) were recorded and then compared with the center temperature obtained from the simulation results.

Kinetic rate modeling of tomato

A first-order kinetic rate model stated in equation (9) was coupled with the average temperature values computed by the simulation of the heat transfer model from equation (1) to study the effect of temperature on quality attributes of tomatoes.

$$-\frac{dA_i}{dt} = k_i[A_i]^{n_i} \tag{9}$$

where the subscript i indicates the specific quality attribute (e.g., colour (a*), firmness (N)), k_i is the corresponding rate constant(s^{-1}), n_i and is the order of the reaction. If the order of reaction, $n = 0$, then equation (9) can be solved to form equation (10)

$$A_i = A_{0,i} - k_i t \tag{10}$$

And if the order of reaction, $n = 1$, then equation (9) can be solved to form equation (11)

$$A_i = A_{0,i}e^{-k_i t} \tag{11}$$

where $A_{0,i}$ is the value of the quality attribute at the start of transportation at $t = 0$ and A_i is the value of the quality attribute at the end of transportation at $t = t$

The temperature dependency was incorporated into the rate constant through an Arrhenius relationship shown in equation (12).

$$k_i(T) = k_{o,i}e^{-\left(\frac{E_{a,i}}{RT}\right)} \tag{12}$$

where $k_{o,i}$ is a constant (s^{-1}), $E_{a,i}$ is the activation energy ($J.mol^{-1}$), R is the ideal gas constant ($8.314\,J\,mol^{-1}K^{-1}$), and T is the absolute temperature (K).

In this study, the target quality attributes are colour (a*), firmness (N), and lycopene content (LC, mg/100ml), which are used as economic grading characteristics for fresh tomatoes in Nigeria. (i.e., color, firmness, and damage for classification into grade A, grade B, and/or grade C). The values of the model parameters were obtained from literature and were presented in Table 3.

Table 3

Kinetic rate model parameter for quality attribute prediction.

Parameter	Symbol	Unit	[1]Firm (N)	[1]Colour, (a^*)	[2]Lycopene(mg/100ml)
Initial value	A_o	-	12.4	-14.4	1.14
Order of reaction	n	-	1	1	1
Activation energy	E_a	$kJ.mol^{-1}$	64.8	84.4	45.96
Reaction constant	k_o	s^{-1}	2073	5097.6	864

[1](Pinheiro et al., 2013)

[2]Badin et al. (2021)

Numerical configurations and implementations in COMSOL multiphysics

The tomato digital twin model was developed in COMSOL Multiphysics (version 5.5), a finite-element-based commercial software. The time-dependent heat conduction equation was solved in COMSOL's Heat Transfer in Solids interface for a dependent temperature variable within the tomato geometrical model as a domain with convective heat flux boundary condition. The kinetic rate model was implemented in the COMSOL's Domain ODEs and DAEs interface and was solved to obtain quality attributes colour (a*), firmness (N), and lycopene content (LC, mg/100ml) based on the fruit temperature. Quadratic Lagrange elements were used together with a fully coupled direct solver, relying on the MUMPS (Multifrontal Massively Parallel sparse direct Solver) solver scheme.

Meshing was developed using the COMSOL's built-in meshing tool. Three different computational grid styles (coarse, base, and fine) were tested during the grid sensitivity analysis. Result of predicted core temperature and surface temperature as function of time for the tomato geometrical model revealed that the percentage difference between coarse and fine grid as well as the percentage difference between the base and the fine grid were not significant. Therefore, the base grid which consists of 6721 tetrahedral finite elements was chosen in this study to minimize computation time and ensured convergence. All simulations were run on 12 core dual processors, Intel Xeon E7-4830 v3 (30 M cache, 2.1 GHz processor base frequency), 144 GB memory with QPI 8 GT/s system bus

Statistical analysis

We used Pearson's correlation coefficients (Pearson's r) to determine the correlation between quality data from the raffia basket and plastic containers. Data processing and analyses were conducted in R (version 4.0.2) (R Core Team 2018) and Microsoft Excel (2016).

Results and Discussion

Time-Temperature Tracking

Using the installed sensors, we monitored the ambient air temperature of inside the truck without any cooling capacities during tomatoes transportation to the southern state – Lagos, through the LAKAJI transport route. Preliminary results that covered transport from Kano (Jibiya) to Kaduna enroute to Lagos were completed. Results revealed higher deviation of air temperature inside the truck trailers among shipments. These huge temperature fluctuations of the microclimate observed inside the truck trailer (Venus et al., 2013) suggested higher impacts of the prevailing outside weather conditions on the transport process (Figure 3).

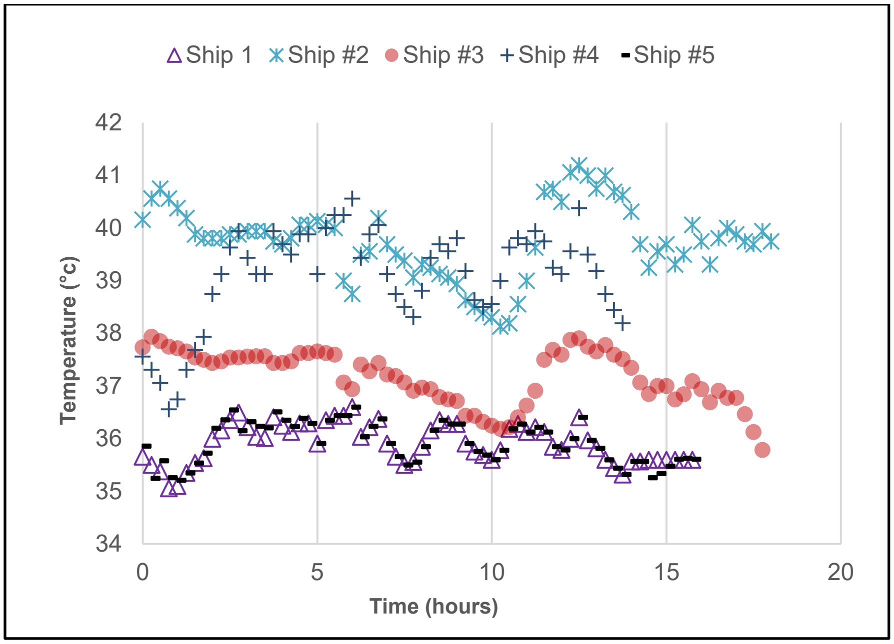

Figure 3. Air temperature distribution inside the truck during shipments

Also, it was observed that the ambient air temperature inside the raffia basket and plastic container for the all the shipments completed in these preliminary studies had their average temperature greater than the optimum temperature range (17- 21℃) for tomatoes throughout the duration of the transportation as shown in figure 4. This might have contributed to the visible quality degradation of the tomatoes fruit during transportation and further suggests the need for cold-chain transport system in Nigeria.

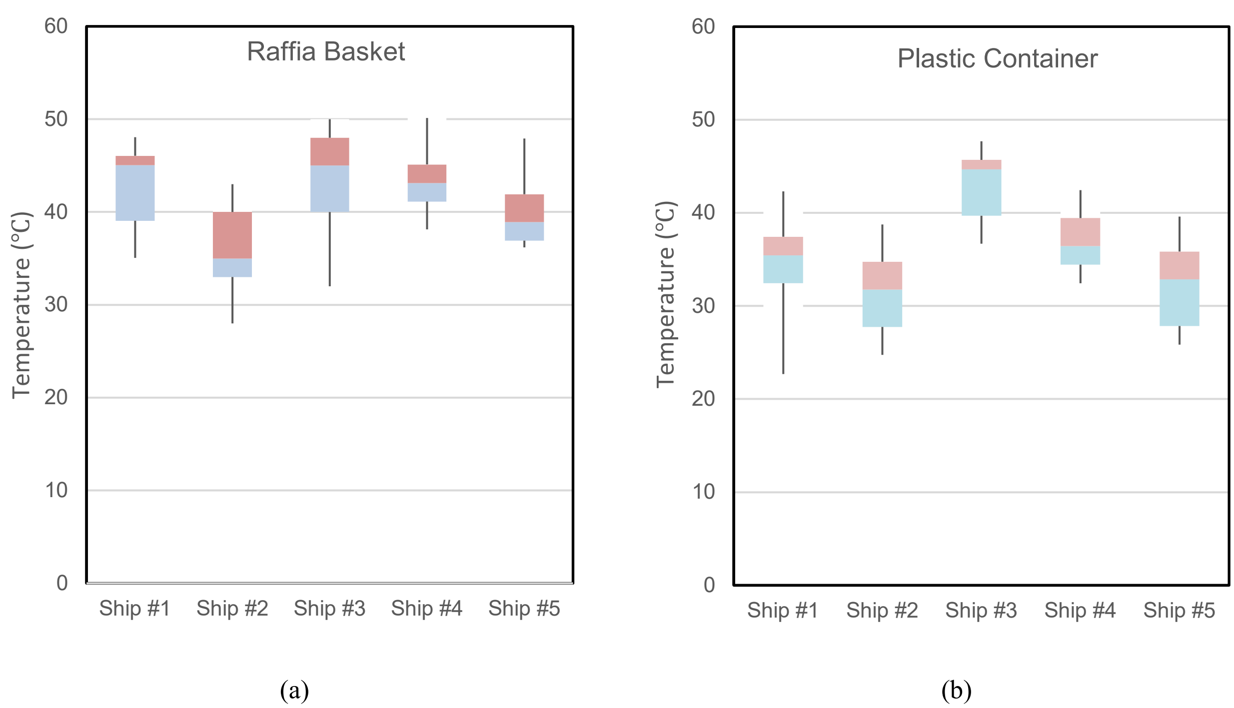

Figure 4. Air temperature distribution inside the (1) Raffia basket and (b) Plastic container during transportation

To further investigate the temperature variability, we analyzed the temperature fluctuation inside the raffia and the plastic container for a single shipment #2. The results revealed higher fluctuation in the raffia basket when compared to the plastic containers as shown in figure 5. The temperature variations within the raffia basket are larger than plastic container. Similar results were obtained for all other shipments. This might be associated to the novel design of the plastic container that promotes uniform ventilation across the container (Onu et al., 2021).

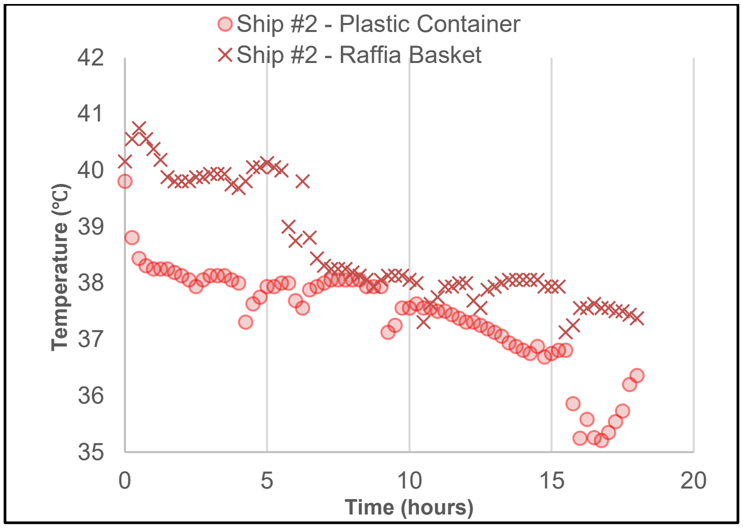

Figure 5. Comparison between air temperature distribution raffia basket and plastic container during shipment #2

The predicted temperature profile of the center of the digital tomato twin for both the raffia baskets and the plastic container were approximately close to measured temperature of actual tomato fruit in each of the containers respectively (Figures 6 and 7). This finding is somewhat anticipated, as the digital fruit was designed as its real-life equivalent (or vice versa) and so they share a similar thermal response. Similar results have been reported by (Defraeye et al., 2019; Shoji et al., 2022).

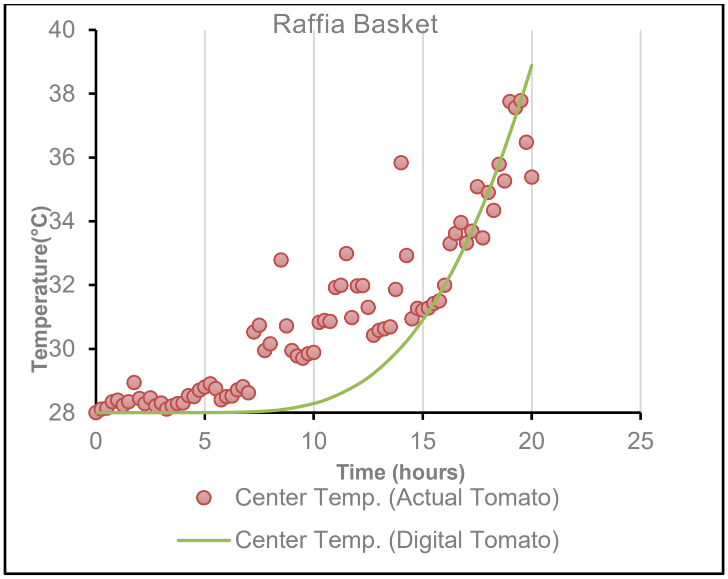

Figure 6. Center temperature distribution of digital tomato twin model and actual tomatoes transported in raffia basket

A good agreement with the real mango fruit was also obtained over the entire transport duration. Generally, higher center temperatures were observed and predicted in case of the raffia basket compared to the plastic container as transportation proceed (figure 9). Heat generated because of increase in internal respiration caused due to bruises or mechanical loading on tomatoes reported in the case of raffia baskets might have contributed to the over-all increase in the internal center temperature for the raffia baskets when compared to the predicted internal center temperature of the tomatoes for the plastic container. A study completed by Aba et al. (2012) observed increased in mechanical damage for tomatoes that were transported in the local raffia baskets when compared to transport using plastic container and/or crates.

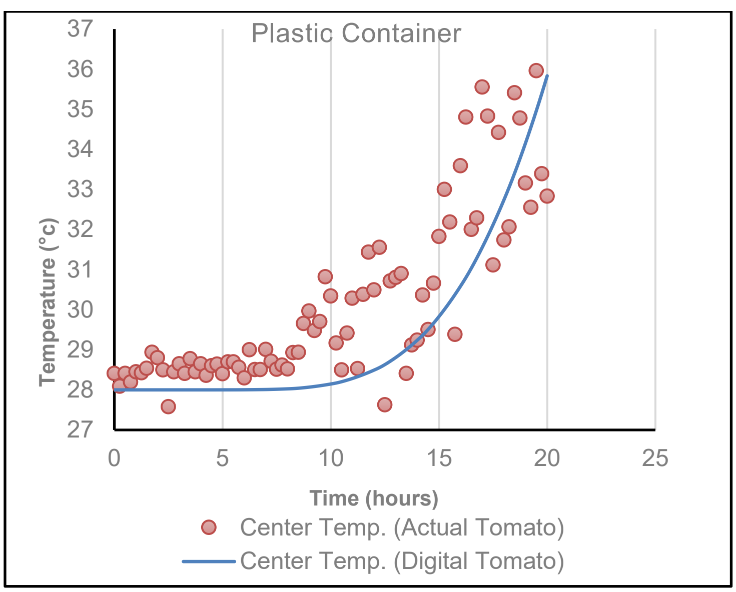

Figure 7. Center temperature distribution of digital tomato twin model and actual tomatoes transported in plastic container

Tomato quality evolution

The impact of the temperature variation on quality attributes was examine along the transportation route using the developed tomato digital twin. The colour parameter (a*) that usually varies from -60 to +60 to indicate variation of greenness to redness were predicted to increase across all the shipments completed for both scenario (Scenario A – transport in raffia basket and Scenario B – transport in plastic container). For shipment #2, the colour parameter increase (a*) from -14.40 to + 5.00 and + 3.10 for the raffia basket and plastic container respectively as shown in figure 6a. This increase means emerging evolution of redness of the tomatoes from the matured green colour. The main reason for the increase in the value of the colour parameter from green (-a*) to red (+a*) might be as result of the degradation in chlorophyl during repining which permit red colour development because of formation of ethylene (figure 6a). Al-Dairi & Pathare (2021) confirmed that lycopene accumulation and chlorophyll degradation were the main reasons for the rapid increase in a* value of tomato during transportation and storage. Similar results have also been reported by Pinheiro et al. (2013) which concluded that tomatoes stored at ambient temperature leads to ripening which consequently caused increase of the red values (a*) compared to low storage condition. Al-Dairi et al. (2021) concluded that colour parameters including (a*) increased significantly for tomatoes in long distance transportation. And the higher increment predicted on (a*) value for tomatoes in the raffia baskets compared to tomatoes in the plastic container was 46.9 % more than the value predicted for the tomatoes in the plastic container at the end of the transportation might be due to the increase in the respiration rate of tomatoes contain in the raffia baskets which caused increase in respiration and consequently leads to increase in temperature. And as temperature increases, most biochemical reaction within the transported tomatoes would increase including repining (Abdul-Hammed et al., 2022).

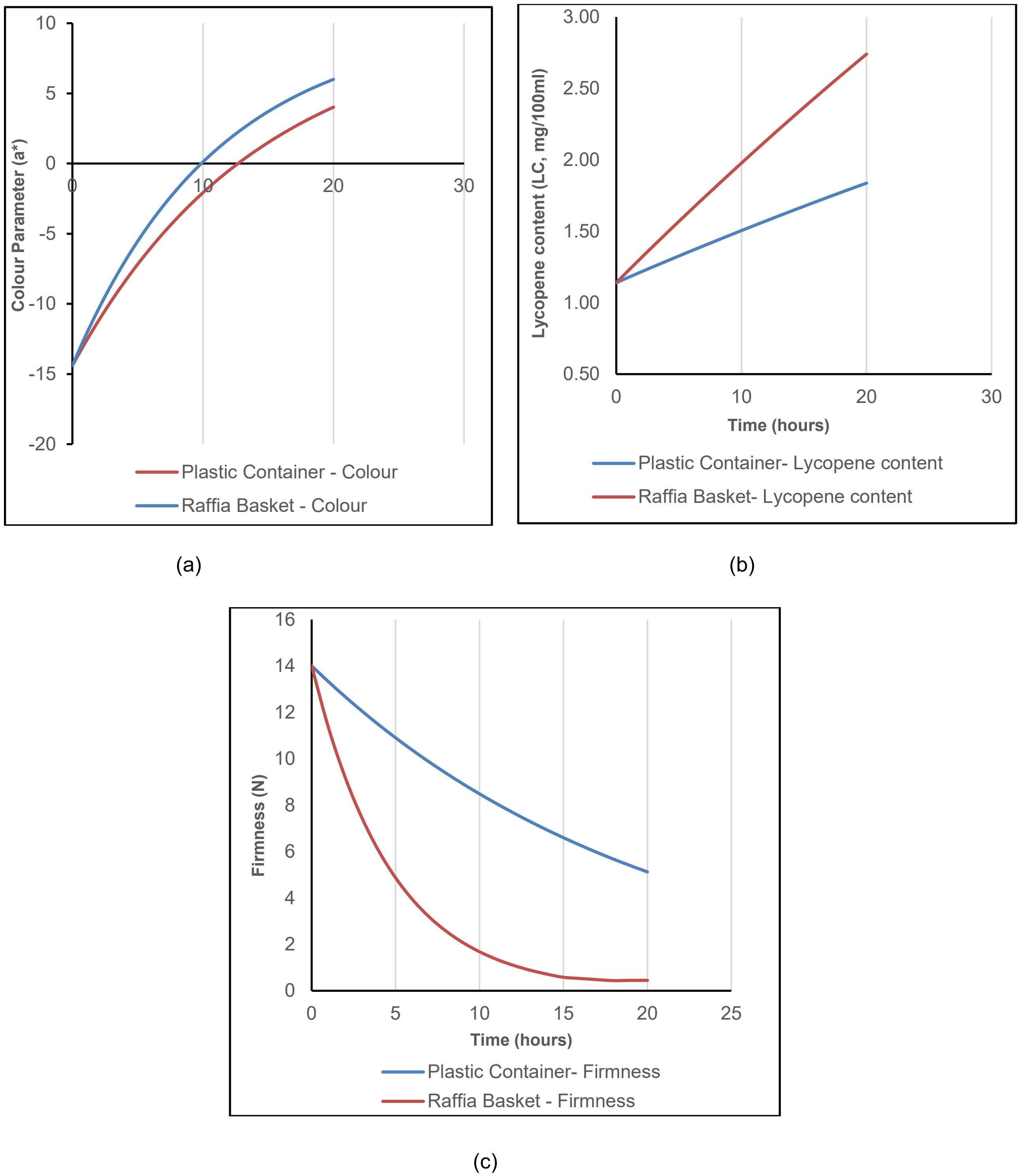

Figure 8. Change in tomato quality attributes (a) colour (a*) (b) firmness (N), and (c) lycopene content (LC, mg/100ml) for transport inside raffia baskets and plastic container along the Lakaji transport route.

For both scenario (raffia baskets and plastic container) in all shipments, the firmness of the tomatoes was predicted to drop over the transport duration. For example, in shipment #2 shown in figure 8c, firmness (N) decreased by 89% and 58 % in the raffia basket and plastic container respectively. Considerable firmness quality loss was predicted in the case of transportation of tomatoes in raffia baskets. One major reason for this drastic decrease in firmness for tomatoes in the raffia basket may be as result of damage cause by the overlying baskets which consequently caused increase in temperature and consequently increase in respiration and the breakdown that occurs during the process of respiration may lead to the drastic reduction in firmness for the tomatoes. Also, this may be as the low over-bearing strength of the baskets, which can caused collapse when stacked in two or three levels. Onu et al. (2021) compared the effectiveness of other tomato containers including plastic container with the traditional raffia basket and concluded that the raffia baskets have the least resistance to overbearing pressure during transportation and this could greatly impact firmness of tomatoes stored in the raffia baskets. Also, for all shipments completed, increase in lycopene content were predicted. Lycopene content (LC) continue to increase noticeably inside the tomato fruit transported both in the raffia baskets and the plastic containers respectively. There was a visible linear increase in lycopene content from the start to the end of transportation. For shipment #2, LC increased from 1.14 mg/100ml to 2.58 mg/100ml and 1.80 mg/100ml for raffia baskets and plastic container within the 20 hours transportation period. In a recent study completed by Abdul-Hammed et al. (2022), they concluded that lycopene and beta-carotene in three different cultivars of tomatoes increased in ambient temperature. Al-Dairi et al. (2021) concluded in their study the accumulation of lycopene and carotenoids in tomato transported from all distances and stored at temperature of 10℃ and 22 ℃ for 12 days respectively. Similar results about the accumulation of lycopene and carotenoids in tomato during storage period have also been severally reported in literatures (Shi & Maguer, 2000; Pinheiro et al., 2013; Badin et al., 2021). This increase in lycopene contents of fresh tomatoes after postharvest have been attributed to the biochemical ripening process (Abdul-Hammed et al., 2022).

Impacts of the plastic container and traditional container on tomato quality

Further analysis of obtained predicted results are still required to effectively study significant impacts on quality of tomatoes transported in raffia baskets compared with the plastic container. However, preliminary results analyzed above suggested that quality loss of tomatoes in raffia baskets might represents a considerable component of the total quality losses occurring in the transportation chain in Nigeria. This was attributable to certain defects of the raffia baskets such as presence of sharp edges which can greatly cause mechanical bruises on the tomatoes because of vibration during transportation and consequently increase in the temperature of the fruits (Kok et al., 2019). However, plastic containers have better smoothness with adequate ventilation designs which may be responsible for the considerably minimize impacts on quality of tomatoes during transportation. Also, the over-bearing strength of the plastic container could stabilize stacks effectively during transportation and consequently reduced mechanical damages. The use of plastic container for packaging tomatoes for interstate road transportation along the Lakaji transport corridor may considerably reduce quality loss incurred in the tomato haulage in Nigeria.

Conclusion

This study developed a physics-based model that was coupled with tomato quality decay models and temperature sensor data to create a digital twin of tomato fruit during un-cold chain transportation in Nigeria. The developed digital twin model predicted temperature and quality attributes of tomatoes transport in both raffia baskets and plastic container. Generally, the values of colour parameter (a*), firmness (N), and lycopene content (LC, mg/100ml) predicted by the digital twin model for tomatoes transported in raffia baskets were all higher than they were predicted for plastic container. For example, in shipment #2 the predicted colour parameter (a*) was 46.9 % more than the value predicted for the tomatoes in the plastic container at the end of the transportation. Similarly, lycopene content (LC) increased from 1.14 mg/100ml to 2.58 mg/100ml and 1.80 mg/100ml for raffia baskets and plastic container and firmness (N) decreased by 89% and 58 % in the raffia basket and plastic container respectively. These are preliminary analysis of the results obtained, we aim to further analyze obtained data using the developed digital twin and then compare the impacts of tomatoes transported in raffia basket and plastic container on over-all quality of transported tomatoes. Furthermore, we aim to develop a data-based mobile application that can leverage machine learning coupled with the developed physics-based digital twin model to provide smallholder farmers and/or stakeholders with real-time quality metrics and market price analytics. With this information, farmers and/or stakeholders (aggregators, wholesalers, or retailers) can make informed decisions on when and how to sell their products based on real-time information on changes in tomato quality.

References

Aba, I. P., Gana, Y. M., & Ogbonnaya, C. (2012). *Simulated transport damage study on fresh tomato (Lycopersicon esculentum) fruits*. *14*(2), 8.

Abdul-Hammed, M., Olajide, M., Adepoju, A., Adegboyega, S., & Adedotun, I. (2022). Quality Parameters, Empirical and Kinetic Models of Lycopene and Beta-carotene Bioformation in Tomatoes (Solanum lycopersicum). *Physical Chemistry Research*, *10*(1). https://doi.org/10.22036/pcr.2021.283758.1916

Al-Dairi, M., & Pathare, P. B. (2021). *Kinetic modeling of quality changes of tomato during storage*. *23*(1), 11.

Al-Dairi, M., Pathare, P. B., & Al-Yahyai, R. (2021). Quality changes kinetic of tomato during transportation and storage. *Journal of Food Process Engineering*, *44*(10). https://doi.org/10.1111/jfpe.13808

Ambaw, A., Fadiji, T., & Opara, U. L. (2021). Thermo-Mechanical Analysis in the Fresh Fruit Cold Chain: A Review on Recent Advances. *Foods*, *10*(6), 1357. https://doi.org/10.3390/foods10061357

ASHRAE, 2006. Refrigeration. American Society of Heating, Refrigerating an Air Conditioning Engineers (ASHARAE).

Ayeni, K. I., Atanda, O. O., Krska, R., & Ezekiel, C. N. (2021). Present status and future perspectives of grain drying and storage practices as a means to reduce mycotoxin exposure in Nigeria. *Food Control*, *126*, 108074. https://doi.org/10.1016/j.foodcont.2021.108074

Badin, E. E., Quevedo-Leon, R., Ibarz, A., Ribotta, P. D., & Lespinard, A. R. (2021). Kinetic Modeling of Thermal Degradation of Color, Lycopene, and Ascorbic Acid in Crushed Tomato. *Food and Bioprocess Technology*, *14*(2), 324–333. https://doi.org/10.1007/s11947-021-02579-1

Balana, B. B., Aghadi, C. N., & Ogunniyi, A. I. (2022). Improving livelihoods through postharvest loss management: Evidence from Nigeria. *Food Security*, *14*(1), 249–265. https://doi.org/10.1007/s12571-021-01196-2

Defraeye, T., Tagliavini, G., Wu, W., Prawiranto, K., Schudel, S., Assefa Kerisima, M., Verboven, P., & Bühlmann, A. (2019). Digital twins probe into food cooling and biochemical quality changes for reducing losses in refrigerated supply chains. *Resources, Conservation and Recycling*, *149*, 778–794. https://doi.org/10.1016/j.resconrec.2019.06.002

Fadiji, T., Ashtiani, S.-H. M., Onwude, D. I., Li, Z., & Opara, U. L. (2021). Finite Element Method for Freezing and Thawing Industrial Food Processes. *Foods*, *10*(4), 869. https://doi.org/10.3390/foods10040869

Kok, M. G., Groot, J. J., Dastoum, S., Plaisier, C., Dijkxhoorn, Y., & Wagenberg, C. P. A. (2019). *A measurement tool on food losses and waste: Applied in a tomato value chain in Nigeria*. Wageningen Food & Biobased Research. https://doi.org/10.18174/470201

Melesse, T. Y., Bollo, M., Pasquale, V. D., Centro, F., & Riemma, S. (2022). Machine Learning-Based Digital Twin for Monitoring Fruit Quality Evolution. *Procedia Computer Science*, *200*, 13–20. https://doi.org/10.1016/j.procs.2022.01.200

Olorunfemi, B. J., & Kayode, S. E. (2021). Post-Harvest Loss and Grain Storage Technology- A Review. *Turkish Journal of Agriculture - Food Science and Technology*, *9*(1), 75–83. https://doi.org/10.24925/turjaf.v9i1.75-83.3714

Onifade, T., & Aregbesola, O. (2013). Some physical properties and thin layer drying characteristics of local varieties of tomatoes (Lycopersicon lycopersicum). *Agriculture and Biology Journal of North America*, *4*(3), 275–279. https://doi.org/10.5251/abjna.2013.4.3.275.279

Onu, O. B., Ani, O. A., Asoiro, F. U., Uzoejinwa, B. B., Ugwu, S. N., Abu, N., & Uguru, I. (2021). *Evaluation of different packaging types for adoption in safe handling and transportation of fresh tomato fruits in nigeria*. *23*(4), 10.

Pattanaik, S., & Jenamani, M. (2020). Numerical Analysis of Cooling Characteristics of Indian mangoes using Digital Twin. *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, 3095–3101. https://doi.org/10.1109/IECON43393.2020.9254303

Pinheiro, J., Alegria, C., Abreu, M., Gonçalves, E. M., & Silva, C. L. M. (2013). Kinetics of changes in the physical quality parameters of fresh tomato fruits (Solanum lycopersicum, cv. 'Zinac') during storage. *Journal of Food Engineering*, *114*(3), 338–345. https://doi.org/10.1016/j.jfoodeng.2012.08.024

Shi, J., & Maguer, M. L. (2000). Lycopene in Tomatoes: Chemical and Physical Properties Affected by Food Processing. *Critical Reviews in Food Science and Nutrition*, *40*(1), 1–42. https://doi.org/10.1080/10408690091189275

Shoji, K., Schudel, S., Daniel Onwude, Shrivastava, C., & Defraeye, T. (2022). Mapping the postharvest life of imported fruits from packhouse to retail stores using physics-based digital twins. *Resources, Conservation and Recycling*, *176*, 105914. https://doi.org/10.1016/j.resconrec.2021.105914

Tapsoba, L. D. S., Kiemde, S. M. A., Lamond, B. F., & Lépine, J. (2022). On the Potential of Packaging for Reducing Fruit and Vegetable Losses in Sub-Saharan Africa. *Foods*, *11*(7), 952. https://doi.org/10.3390/foods11070952

Ugonna, C., Jolaoso, M., & Onwualu, A. (2015). Tomato Value Chain in Nigeria: Issues, Challenges and Strategies. *Journal of Scientific Research and Reports*, *7*(7), 501–515. https://doi.org/10.9734/JSRR/2015/16921

United Nations Population Fund. (2022). Word Population Dashboard, Nigeria. Assessed, Jan 14, 2022.

https://www.unfpa.org/data/world-population/NG

Venus, V., Asare-Kyei, D. K., Tijskens, L. M. M., Weir, M. J. C., de Bie, C. A. J. M., Ouedraogo, S., Nieuwenhuis, W., Wesselman, S. L. M., Cappelli, G. A., & Smaling, E. M. A. (2013). Development and validation of a model to estimate postharvest losses during transport of tomatoes in West Africa. *Computers and Electronics in Agriculture*, *92*, 32–47. https://doi.org/10.1016/j.compag.2012.11.011