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Assessing hygrothermal effects on the evaporative cooling of fruits with waste palm fruit fibre pads

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ABSTRACT

This study explores using recycled waste palm fruit fibres as wetting pads in evaporative cooling (EVC) systems. The goal is to analyze how this wetting pad, influences the drivers of the EVC process and the effects on the quality of pre-cooled orange and papaya. The collected data is a foundation for analyzing transient heat responses during the pre-cooling process. To achieve this, we conducted cooling experiments using direct evaporative cooling (EVC) systems at a constant air delivery velocity of 4 m/s. The air delivery temperature for cooled fruits ranged from 25.8 °C to 20.2 °C at an air relative humidity range of 85.6 – 96.8 %. We develop heat transfer models to understand the cooling mechanism using established methods. Our results revealed that our active EVC reduced inlet temperature by ~10 °C, with air delivery speed at 4 m s^{-1}. Our cooling efficiency ranged from 77% to 98.8%, and cooling capacity (CP) varied within $0.73 \leq CP \leq 2.52$ kW. For orange and papaya, core temperatures reached 21.38 °C and 21.14 °C, respectively, in 16 hours from a peak of about 25.81 °C. Papaya exhibited a higher moisture loss per unit area and moisture flux of (1.03×10^{-5} kg/m^2.s) compared to orange (1.501×10^{-7} kg/m^2.s),. Fruit quality index analysis indicated low-quality loss (< 1%) for both fruits. Thus, orange lost approximately 0.00257% of its quality, while papaya lost 0.63% during cooling. The evaporative flux increased with temperature with Papaya having a higher evaporative flux than orange with a maximum value of 8.75 W while orange exhibited a maximum value of 0.0424 W.

1. Introduction

Research by Lentzou et al. (2021) reveals that 45–55% of global fruits and vegetables are lost or rendered unsellable due to deterioration along the value chain. In post-harvest horticultural management, the impact of unfavourable temperatures extends beyond mere mass loss. Physical attributes like firmness and colour are profoundly affected (Nkolisa et al., 2019). When fruits are harvested, they retain field heat obtained from the farm. Subsequently, upon detachment from the parent stalk, the respiration rate of the fruits escalates due to the inability to replenish water. During respiration, the fruit's stored sugars oxidize through metabolic processes, producing not only heat but also water and CO_2. Additionally, transpiration contributes to post-harvest moisture loss as fruits release water vapour, influenced by factors such as relative

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humidity, air velocity, and ambient temperature (Bovi et al., 2018). This loss of moisture arises from both the water vapour deficit and respiratory activities (Caleb et al., 2013). Both respiration and transpiration processes are thermally driven; and susceptible to thermal fluxes surrounding the product. Uncontrolled thermal fluxes result in the loss of moisture and other components, leading to quality deterioration and rendering the product unsuitable for consumption. To counter increased respiration and transpiration rates, a well-established technique involves pre-cooling fruits to expel field heat, effectively elongating shelf life (Ndukwu, 2011; Nkolisa et al., 2018). Thus Kumer et al. (2023) and Ndukwu et al (2024) enumerated a range of pre-cooling methods, spanning hydro cooling, ice utilization, forced air cooling, vacuum cooling, and evaporative cooling. Among these, evaporative cooling emerges as an eco-friendly and cost-effective approach, relying solely on water, in contrast to vapour compression refrigeration systems that lean on energy-intensive greenhouse gases. In the evaporative cooling process for fruits, two standard methodologies are at play. The first is indirect evaporative cooling, which involves dehumidifying inlet air through a heat exchanger before its passage through a wetting or cooling pad. The second is direct evaporative cooling which takes a more direct route, guiding inlet air through water within the cooling pad before entering the cold space (Ndukwu et al., 2013; 2022; 2023). The efficiency of evaporative cooling hinges on the nature of the cooling pad, its geometric characteristics, and airflow rate. An array of synthetic and bio-based materials function as wetting media, including Eucalyptus fibre (Dogramaci et al., 2019), coconut coir (Rawangkul et al., 2008; Shrivastava et al., 2014), Luffa (Aziz et al., 2018), Khus (Shekhar et al., 2016), palm fibre, rice husk, and wood shavings (Tejero-Gonzalez and Franco-Salas, 2021; ;Ndukwu et al., 2023b). Ndukwu et al. (2014) stress the significance of using locally available materials to reduce costs in evaporative cooling systems, and the effectiveness varies based on the wetting media's characteristics and the stored product's attributes. Thus a host of researchers have harnessed local materials as cooling pads in evaporative cooling system to cool and conserve diverse fruits and vegetables, such as tomatoes (Islam and Morimoto, 2015), leafy amaranths (Ambuko et al., 2017), and even tomato, spinach, and green onions (Dalhich et al., 2008; Jain, 2007). This process has demonstrated notable improvements in fruit texture (Norton and Sun, 2006; Kumer et al., 2023). However, a substantial hurdle is faced in the development of evaporative cooling systems (Kasso and Bekele, 2015). This is because within the cooling unit, the fruit maintains its breathability resulting moisture loss, heat generation leading to increased heat load (Mahajan et al., 2016; Onwude et al., 2020.

Therefore, cooling process of fruits is associated with the generation of heat through three primary mechanisms: respiratory heat, evaporative heat, and condensation heat (Rauh et al., 2018; Kumar et al., 2023). These heat loads can be attributed to three main factors: the condensation of water vapour, the evaporation of moisture, and the convective cooling of surface air (Wang et al., 2019; Becker and Fricke, 2014). The rate at which these heat loads occur is influenced by various environmental factors, including ambient temperature, air velocity, and relative humidity (Ndukwu et al., 2023). Consequently, pre-cooling is a crucial step in mitigating these heat loads and maintaining the quality of the fruits. Kumar et al. (2023) therefore emphasized the need to consider the complete heat transfer dynamics within the product zone to achieve effective cooling during temperature reduction, entailing conduction and convection. Thus, to comprehend transient heat transfer during evaporative cooling of products for optimization of the cooling process, we must identify contributing heat loads in the governing equations. Although, Ndukwu et al. (2023) attempted to study the respiratory heat dynamics in oranges only under different biomasses and airflow considering evaporative and condensation heat dynamics they did not study its impact on mass loss.

Furthermore varying the operational factors such as, wetting pads and air temperature impact heat load and mass loss in evaporative-cooled products. Therefore various biomass pads are currently investigated to understand the impact on the hygrothermal effects on stored fruits in a cooling system (Ndukwu et al., 2023). Among these pads is palm fruit fibres which is a by-product of oil palm processing. Research have found that evaporative cooling of fruits using waste palm fruit fibre pads is a promising technique for reducing post-harvest losses and extending the shelf life of fruits (Ndukwu et al., 2013). However, the hygrothermal effects of this technique on the fruits and the fibre pads themselves are not well understood (Kumar et al., 2023). Investigating these effects is crucial for optimizing the design and operation of evaporative cooling systems (Tejero-Gonzalez and Franco-Salas, 2021). By assessing the hygrothermal effects of this technique, researchers can identify opportunities to improve the efficiency and effectiveness of evaporative cooling systems, ultimately leading to better preservation of fruits and reduced food waste.

Additionally, the use of waste palm fruit fibre pads in evaporative cooling systems also offers a unique opportunity to explore the potential of agricultural waste materials in sustainable cooling applications. Palm fruit fibre is a readily available and renewable resource that can be sourced from palm oil mills. Utilizing them in evaporative cooling systems can contribute to the development of more sustainable and environmentally friendly cooling technologies. This research can also help to promote the use of agricultural waste materials in innovative applications, reducing waste and supporting more circular economies. This research therefore aims to theoretically assess how palm fibre wetting media and delivery air temperature affect the cooling behaviour of orange and papaya cooled in a direct evaporative cooling. Widening the study to include papaya and deducing the empirical relationships will aid in the optimization of evaporative cooling of more fruits of similar characteristics. The acquired data will aid numerical simulations of transient heat response during pre-cooling or short-term storage of these fruits through evaporative cooling.

1.2. Potential of recycling palm fruit fibre

Recycling palm fruit mesocarp fibre waste as cooling pads holds significant global potential due to the abundance of raw materials. Major palm oil-producing countries like Malaysia, Nigeria and Indonesia generate millions of tons of mesocarp fibre waste annually (Ajayi et al., 2024). In some of these countries especially Nigeria, the waste is discarded in heaps constituting an eyesore within the palm fruit processing mills where it rots away or burns. Recycling and utilizing agricultural waste for cooling pads can mitigate environmental pollution and promote sustainable waste management practices (Abdullah and Sulaiman, 2013). The economic viability of palm mesocarp fibres is enhanced by their low cost and high availability (Singh et al., 2010). Studies have demonstrated that these fibres can achieve high cooling efficiencies, making them competitive with traditional materials like jute (Yusoff, 2006). Additionally, the use of palm mesocarp fibres aligns with global sustainability goals by promoting the use of renewable resources (Sulaiman et al., 2011). The performance of palm mesocarp fibres in evaporative cooling systems has been well-documented, showing significant benefits in terms of cooling efficiency and quality preservation (Ajayi et al., 2024). This performance is comparable to or better than other materials under similar conditions (Hassan et al., 2010). The integration of these fibres into cooling systems can also reduce reliance on synthetic materials (Ajayi et al., 2024). The economic and practical benefits of using locally available, cost-effective materials further support their adoption (Ajayi et al., 2024). The biodegradability, pest resistance, and compostability of palm mesocarp fibres make them suitable for various applications beyond cooling pads (Al-Sulaiman, 2001; Olagunju and Babatunde, 2011; Ajayi et al., 2024). This versatility enhances their appeal as a sustainable material for multiple industries (Hassan et al., 2010). Overall, the adoption of local fibre cooling pads can lead to significant environmental, economic, and performance benefits (Khalil et al., 2012).

In Nigeria and most other major palm oil-producing countries, the

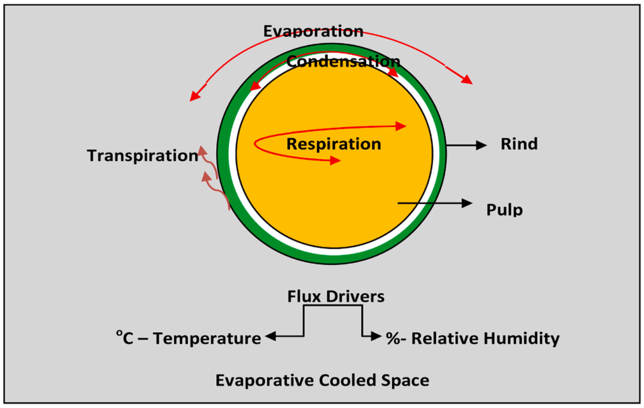

Fig. 1. Hygrothermal dynamics of stored fruit in an evaporative cooler.

potential for recycling palm fruit mesocarp fibre waste is particularly promising due to these countries's significant palm oil production (Ajayi et al., 2024). The local availability of mesocarp fibres can reduce costs associated with material procurement and transportation (Olagunju and Babatunde, 2011). Developing industries around the recycling of these fibres can create jobs and stimulate economic growth in rural areas (Oboh and Sani, 2009). This can be particularly impactful in regions where palm oil production is prevalent (Olagunju, 2008). Additionally, using palm mesocarp fibres supports Nigeria's sustainability goals by promoting the use of renewable resources and reducing waste (Oke and Awonorin, 2007). The high cooling efficiency of these fibres, as demonstrated in various studies, makes them a viable alternative to traditional cooling pad materials (Ajayi et al., 2024). By adopting palm mesocarp fibre cooling pads, Nigeria can improve its environmental footprint while supporting local economies (Oboh and Sani, 2009). This approach aligns with the country's broader goals of sustainable development and environmental conservation (Olagunju, 2008).

2. Material and methods

2.1. Theoretical analysis

The quality of cold stored products is driven by the hygrothermal condition, with temperature as the major driver. The hygrothermal behaviour of the stored product can be accounted for using respiratory heat, evaporation, and condensation heat flux. Descriptively, in Fig. 2, the respiratory heat flux is generated from the core made up of the pulp, while between the pulp and the rind occurs the condensation heat, while at the rind and ambient air interphase occurs the evaporative flux. These heat fluxes have been described in Onwude et al (2022) as illustrated in Fig. 1.

The evaporation heat (W) and condensation heat load (W) of different fruits can be related to the latent heat of vaporization using Eqs. 1 and 2, respectively, as follows (Kumar et al., 2023):

$$E_{ev} = m_o A_p L_p \tag{1}$$

$$E_{con} = m_{con} A_p L_p \tag{2}$$

Where:
A_p = mean surface area of orange (0.01622 m^2), papaya (0.048m^2)
m_o = moisture loss rate (kg/m^2s)
m_{con} = condensation heat coefficient
L_p = latent heat of vaporization per unit mass (J/kg) of product based on the mixture of gases given by Kumar et al. (2023) as follows:

$$L_p = 9.1T_p^2 - 7.5129 \times 10^3 T_p + 3875.1 \times 10^3 \tag{3}$$

Where $T_{p,}$ is the time-dependent product temperature determined at the core for a fruit under air cooling as follows (Laguerre et al., 2022):

$$mC_p \frac{dT_p(t)}{dt} = n\varphi \left(\frac{T_{p(t)} - T_{c(t)}}{\frac{R/4}{k} + \frac{1}{h_c}} \right) \tag{4}$$

Where:
m = mass of product
$C_{p,\,air}$ = specific heat capacity of air taken at room condition as 1012 J/kg.K
R = radius of the fruits determined as 0.025m for orange and 0.0425m for papaya
φ = air exchange area of the fruit covered by pores taken as 0.1% of fruit area (Banks et al., 1993), n, is the number of fruits in the cooler (approximately 10 for orange and 2 for papaya)
$T_{p(t)}$ and $T_{c(t)}$ = time-dependent inlet and outlet air temperature (^oK) of the cooling pad which is a function of ambient and pad condition
k = thermal conductivity of fruit taken as 0.58 W/m.K for orange (Onwude et al., 2022) and 0.60 W/m.K for papaya (Kurozawa et al., 2005)

Assuming a laminar flow regime ($0 < Re < 5\times10^5$), h_c can be deduced using the Nusselt number as follows (Santos da Silva et al., 2014):

$$Nu = \frac{h_c d_f}{k_f} = 0.664 Re^{1/2} Pr^{1/3} \tag{5}$$

Where:
h_c = convective heat transfer coefficient
d_f = geometric diameter of the fruit
k_f = thermal conductivity of air
Pr = Prandt number
Re = Reynolds number determined as a function of airflow speed as follows (Onwude et al., 2022):

$$Re = d_f \times u_{air} \times \frac{1}{\upsilon_{air}} \tag{6}$$

Where:
υ_{air} = kinematic viscosity of air at the cooler temperature taken as (1.5×10^{-5} $m^2/_s$)
u_{air} = air speed (m/s) around the fruit ($u_{supeficial}/\varphi$), (Dehghannya et al., 2010), where $_{superficial}$ is the delivery air speed (4 m/s) and φ, is the porosity of orange (42%)

The rate of moisture loss (m_o) per unit surface (kg/m^2s) per moisture flux at the surface of the fruit is given as follows (Kumar et al., 2023, Mukama et al., 2020)

$$m_o = \begin{cases} k_t(p_s - p_h) \; when \; p_s > p_h \\ 0 \; otherwise \; 0 \end{cases} \tag{7}$$

Where:
p_s and p_h = partial pressure of water vapour in the air and evaporating surface given in Eqs. 13 and 15, respectively
k_t = transpiration coefficient (m/s) provided as follows:

$$k_t = \frac{1}{\frac{1}{k_a} + \frac{1}{k_s}} \tag{8}$$

Where:
k_s = skin mass transfer coefficient (m/s) of the fruits determined to be constant for each fruit (Becker et al., 1996). For orange, Onwude et al (2022) gave the value as 1.72×10^{-9} m/s
k_a = air film mass transfer coefficient (m/s) deduced from the Sherwood correlation according to Onwude et al (2022) as follows:

$$Sh = \frac{k_a \times d_f}{D_w} = 2 + \left(0.552 \times Re^{0.53} \times Sc^{0.33}\right) \tag{9}$$

Where:
d_f is the geometric diameter of the fruits determined by direct

measurement as 0.05m for orange and 0.085m for papaya

D_w is the air-water vapour diffusion coefficient (m^2/s) defined as a function of cooler temperature as follows (Kumar et al., 2023):

$$D_w = \frac{9.1 \times 10^{-9} T_c^{2.5}}{T_c + 245.18} \tag{10}$$

Where T_c is the cooler temperature (^oK)

$$Sc = \frac{\upsilon_{air}}{D_w} \tag{11}$$

The experimental value of k_s is not available in the literature to deduce the k_t value for papaya. The method used by Santos da Silva et al (2014), was applied. The value of k_t for papaya was estimated from the convective heat transfer coefficient (h_c) using Eq. 12 so far as the Chilton-Colburn analogy is valid by satisfying the range $0.6 < Sc < 3000$ and $0.6 < Pr < 60$ (Santos da Silva et al., 2014). Thus

$$k_t = \frac{h_c}{\rho C_p}\left(\frac{Pr}{Sc}\right)^{2/3} \tag{12}$$

Where ρ and C_p are the density and specific heat capacity of papaya taken as 1371 kg/m^3 and 3934J/(kg.K) (Santos da Silva et al., 2014).

The partial pressure (p_a) of water vapour at the evaporating surface (p_s) is given as follows:

$$p_s = VPL \times p_w(T_s) \tag{13}$$

Where VPL is the water vapour lowering effect of fruits taken from Becker et al (1996) as 0.98, p_w is the partial vapour pressure (p_a) of water at saturation deduced with Antoine equation as follows (Becker et al., 1996):

$$p_w = Exp\left(23.48 - \frac{3990.5}{T - 39.317}\right) \tag{14}$$

Where T is the temperature (^oK) of the fruit surface or air. Due to temperature fluctuation resulting from the variation in ambient conditions, which drives the cooler conditions, this value is not constant but varies with time.

The partial pressure (p_w) of water vapour in the air (p_h) is as follows:

$$p_h = RH \times p_{w\ (T_{air})} \tag{15}$$

Where RH is the relative humidity of cold air, which varied with the storage period as determined from the experiment

The condensation coefficient (m_{con}) in Eq. 2 is given as follows:

$$m_{con} = \begin{cases} k_a(p_h - p_s)\ \textit{when}\ p_h < p_w \\ 0\ \textit{otherwise}\ 0 \end{cases} \tag{16}$$

According to Onwude et al (2022), a decrease in fruit weight is a significant market evaluation metric for cold chains due to price dependency on the weight of a particular product. Loss in weight implies a loss in profit. Thus, the transpiration-driven weight loss ($m_i - m_t$) during cooling is determined using Eq. 17 presented in Xanthopoulos et al. (2014) and Lentzou et al (2021) for cooled product that accounted for the effect of temperature and time presented.

$$\begin{aligned} m_l &= m_i - m_t \\ &= \left\{k_0 \exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_p}\right)\right] \times \left(a_w - \frac{RH}{100}\right) \times t \times \left(\frac{m_i}{1000}\right)\right\} \end{aligned} \tag{17}$$

Where:

m_i = initial mass of fruit (2 kg)

m_t = mass (kg) of fruit at time t (s)

a_w = water activity taken as 0.987 for orange and 0.990 for papaya (Barbosa-Cánovas et al., 2008)

RH = average relative humidity (%) of storage space which varied with the ambient condition

R = gas constant (8.314J/mol.K)

E_a = activation energy for citrus taken as 4.59×10^4J/mol (Berry et al., 2021; Wu et al., 2018) while that of papaya is taken as 3.774×10^4J/mol (Umayal and Veeramanipriya, 2022)

T = absolute temperature (^oK)

T_p = product core temperature

k_0 = rate exchange (s^{-1}) or characteristic diffusion per skin thickness determined from the inverse of characteristic time of diffusion for fruits as presented in Pereira et al (2009).

$$k_0 = \frac{1}{\tau} = \frac{2D_w}{s^2} \tag{18}$$

Where s is the skin thickness of the fruit determined as 0.003m for orange and 0.001m for papaya.

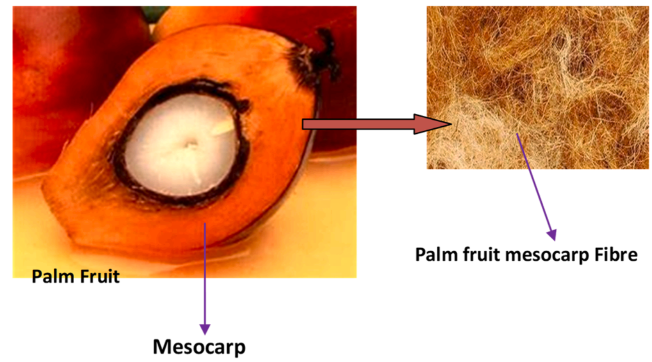

Fig. 2. Palm fruit mesocarp.

2.2. Quality evaluation

During cooling, fruit still respires, affecting the product's overall quality. The rate of this quality degradation can be presented in kinetic rate form as follows (Berry et al., 2021)

$$A = A_o - kt \tag{19}$$

Where:

A_o = initial quality of the orange before storage taken as 1 (100%)

k = temperature-dependent parameter which can be presented in Arrhenius form.

$$k(T) = k_0 e^{-\frac{E_a}{RT_p}} \tag{20}$$

3. Wetting pad material

Wetting pads were made using palm fruit fibre mesocarp from processed palm fruit oil as shown in Fig. 2. Palm fruit mesocarp fibre is characterized by its high tensile strength (51.73–600 MPa), durability, and low density (0.3–0.5 g/cm^3), with a chemical composition of 21.0–42.8% cellulose, 27.2–36.0% hemicellulose, and 20.5–30.0% lignin (Ajayi et al., 2024). It exhibits thermal stability and a caloric value of 18.067–21 MJ/kg1. Mechanically, it has a Young's modulus of 0.95–35 GPa. Additionally, palm fruit mesocarp fibre is renewable, biodegradable, pest- and disease-resistant, and compostable, making it suitable for various applications, including biocomposites, insulation materials, paper and pulp production, textiles, and evaporative cooling pads (Ajayi et al., 2024). Its unique properties make it an attractive sustainable material for industries seeking eco-friendly alternatives (Ajayi et al., 2024). The palm fruit mesocarp fibre was obtained from a palm oil mill's waste dump. It accounts for 10 to 15 % of the fresh palm fruits before processing. After processing, the fibre contains some oil residue, which, in most cases, is combusted as a heat source for other heating. However, before being stretched into sets of strings, the fibres were cleansed of the oil by thoroughly washing with water and detergent and dried. They were assembled into a dimension of 1m x 0.3m x 0.03m.

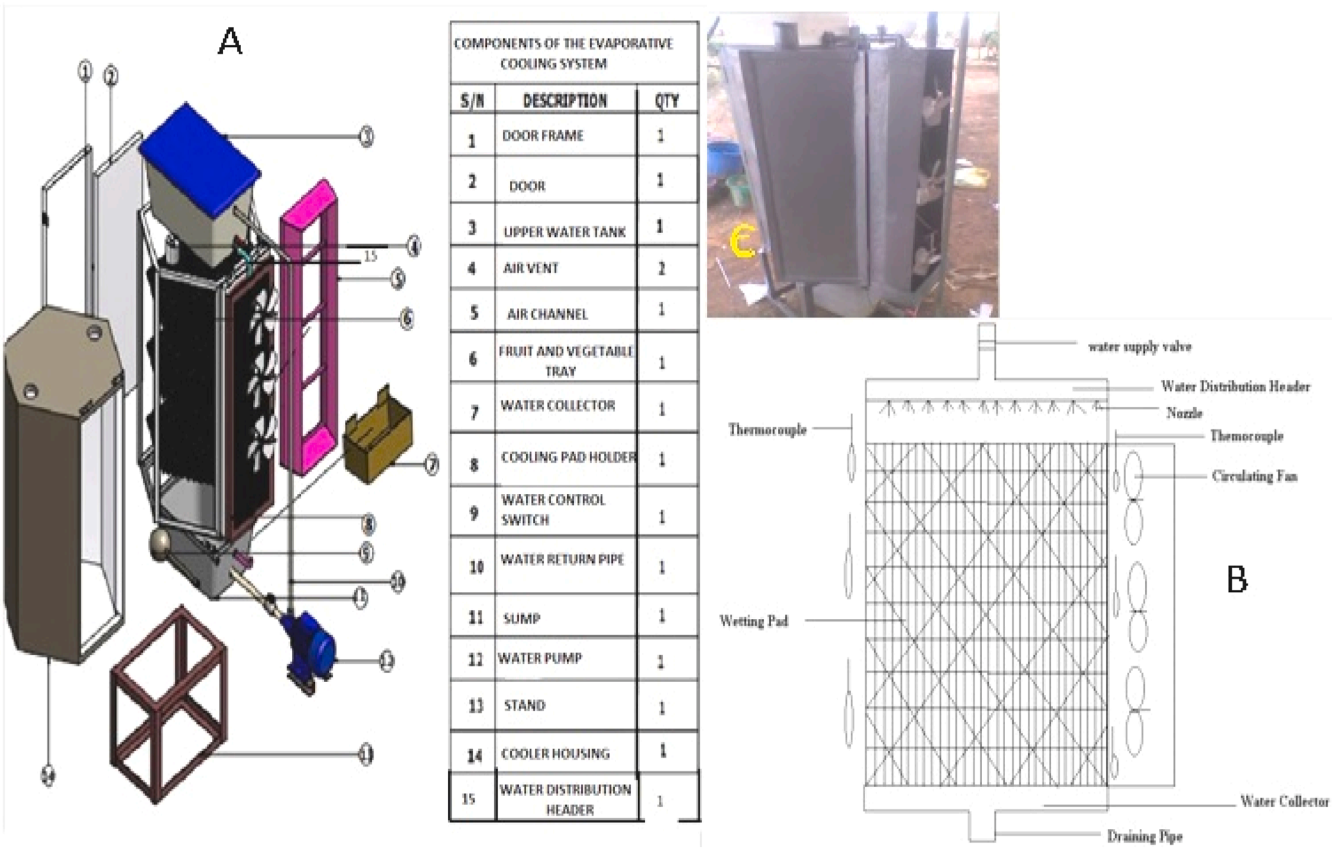

Fig. 3. Exploded view of the DEC (A), Schematics of the DEC (B), Picture of the DEC (C).

The study was carried out for cooling sweet orange (C.sinensis) and paw-paw (C.papaya) in Southwestern Nigeria. The fruits were directly harvested from the stalk, and cooling and storage were done with the evaporative cooler. A total of 2kg of orange and 2kg of papaya fruit were used for the experiment.

2.3. Description and operation of the direct evaporative cooling (EVC) systems

Unlike the window type prevalent in commercial levels, the evaporative cooler used for the analysis is standalone. The evaporative cooler (Fig. 3A) comprises a 0.24 m^3 removable storage chamber (1) with six double walls arranged in a hexagon, and each wall joined at an obtuse angle. Obtuse angled joints are used to lessen turbulence brought on by sharp edges. However, fibreglass was fitted between the double walls to stop heat loss. The exterior wall is constructed of galvanized steel plate, while the inside wall is built of aluminium. A 0.3m^3 cuboid-shaped pad holding compartment (8) for loading the wetting materials is mounted on one of the walls. A perforated water distribution header (15) connected to the water supply tank with a valve is horizontally positioned at the top edges of the pad holder. A horizontal water collector (7) is located beneath the pad holder, into which the saturated water from the pad drains before entering a sump tank (11) situated beneath the storage chamber. The storage chamber was held in position with an angular frame (13), which also serves as the stand. The sump tank is equipped with a sump water pump (12) to circulate the water back to the supply tank (3) through a PVC pipe linkage (10) to continue the water circulation. The water pump frequency is controlled by an automated water control switch (9) fitted inside the sump tank. The supply and sump tanks are 20l plastic material that can be covered or left open for wind cooling. The cooling pad is attached to three axial fans linked to a rheostat to drive and control the airflow. Inside the storage room is equipped with vegetable trays (6) for keeping the fruits and vegetables. Behind the storage room is a door (2) held by a door frame (1) for adding or removing stored products. The door is sealed with a gasket to prevent air leakage. On both sides of the supply tank installed at the top of the storage room are two air vents (4) with air channels (5) to evacuate warm air from the storage room. The picture and schematics views of the evaporative cooler are shown in Fig. 3 B and C, respectively. The operation scheme involves delivering water from the upper water tank on the water header, which sprays the water on the top edges of the cooling pads. The water is spread by gravity throughout the pads as it absorbs the water by capillary action. When saturated, the water from the cooling pad drains into the water collector linked to the water sump. A floating switch fitted into the water sump activates the pump when the sump's water level reaches more than 15l The pump pumps the water back to the upper tank, and the circle continues.

Table 1
Specifications and sensitivities of data acquisition instruments.

Instruments	Specifications	Sensitivity	Manufacturer
Data logger	HH1147	±0.1 °C and ±1 %	Omega Stanford USA
Thermocouple	K-type, USB linked	±0. 1 °C	Omega Stanford USA
Pyranometer	Apogee MP-200, serial 1250,	±1 W/m^2	APOGEE USA
Digital balance	KERRO model	±0.01 g	KERRO, China
Temperature and humidity clock	DTH-82	±0.1 °C, ±1.0 %	TLX, Guandong China
Vane anemometer	AM-4826	±2% of the velocity	Landesk, Guangzhou, China

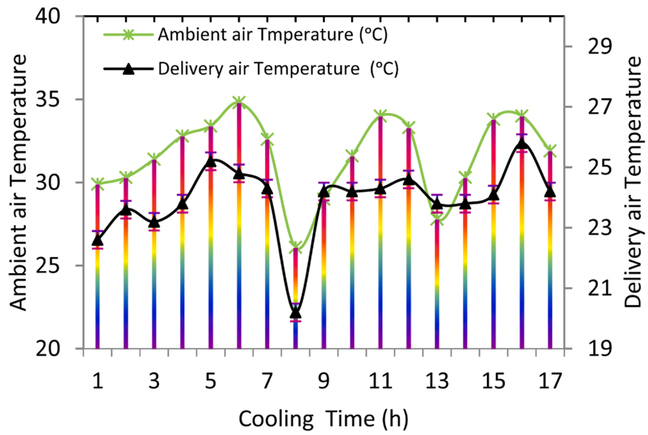

Fig. 4. Delivery and ambient air Temperature variation with cooling time.

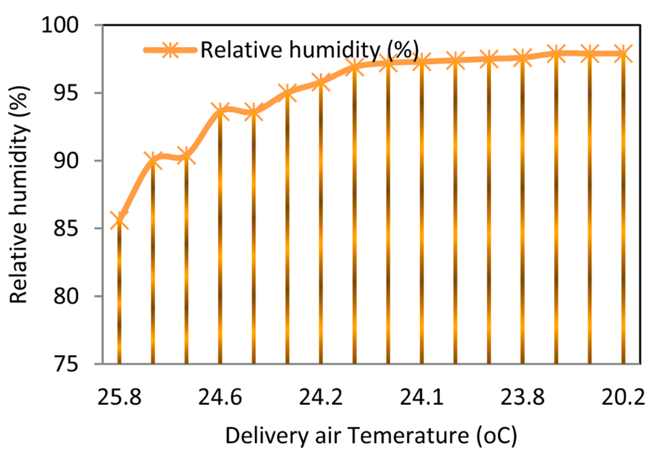

Fig. 5. Delivery air temperature variation with the relative humidity.

2.4. Data acquisitions

Before loading the fruits into the DEC storage room, the fan is switched on, and the desired speed is set through the rheostat. The fan is allowed to run for 0.5h before loading the orange on the vegetable trays installed inside the storage room. The fan is switched on after the pad is saturated with water. Measurement of storage temperature and relative humidity of the exhaust air were made at three points inside the storage room with the aid of a thermocouple linked to a data logger. In contrast, the inlet air temperature and humidity were made with a temperature-humidity clock. The airspeed was measured with a vane anemometer, while the solar intensity was measured with a pyranometer. Each data point was acquired in triplicate, and the average was used for the analysis. The specifications and the sensitivities of the data acquisition instruments are presented in Table 1.

3. Result and discussion

3.1. Cooling performance of the EVC

Direct evaporative cooling of fruits and vegetables is environmentally dependent. Most of the time, the temperature flux between the inlet air and the delivery air to the cooled product is a function of the solar radiation flux and the atmospheric relative humidity. Thus, due to the intermittent nature of the weather conditions, these temperature fluxes do not produce a smooth curve but vary periodically as the weather changes. This has also been observed by Chopra et al. (2023) in the design of evaporative coolers for perishable products. These

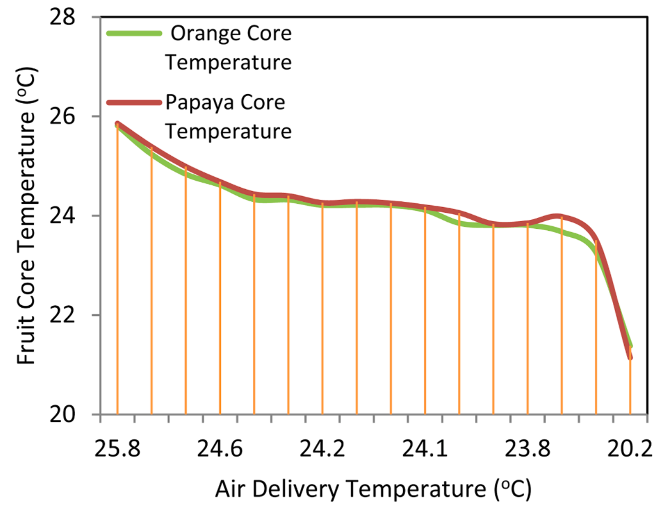

Fig. 6. Variation of delivery temperature with calculated fruit core temperature.

temperature fluctuations are shown in Fig. 4 as the cooling time of the fruits progresses. The delivery air temperature to the cooled fruit varied from 25.8 to 20.2 °C as shown in Fig. 3. Notably, the minimum temperature a direct EVC can lower the air delivery temperature is its wet bulb temperature. Therefore, with the initial core temperature of the fruits around the room temperature of about 26–28 °C, the targeted temperature range for the fruits in EVC lies around the wet bulb temperature of the ambient air dry bulb temperature presented in Fig. 4. Thus, from Fig. 4, the direct active evaporative cooler lowered the inlet air temperature by 4.8 – 13 °C with an average value of 7.69 °C at a 4m/s air flow rate. Within this value, the calculated percentage cooling efficiency $\left(\frac{T_a - T_c}{T_a - T_w}\right)$ ranged from 77 to 98.8 %, with a cooling capacity $\left[\dot{m}_a C_{p,a}(T_a - T_c)\right]$ ranged between 0.73 and 2.53kW. The relative humidity of the cooler ranged from 85.6 – 96.8 % as observed during the experiment, shown in Fig. 5. This shows the level of air saturation due to moisture humidification. Xuan et al. (2012) have stated that 100 % relative humidity might be impossible in direct evaporative cooling systems because 100 % air saturation is difficult. This is because the process air might escape humidification due to a loosely packed pad, causing poor pad water saturation. In addition, if their–water contact duration is insufficient, the heat transfer will not be adequate (Ditchfield et. al., 2006).

3.2. Fruit pulp/core temperature evolution

The evolution of the core/pulp temperatures of orange fruits and papaya, as determined theoretically, is presented in Fig. 6. This method has been used by Berry et al (2021) to determine the temperature of oranges stored in a pallet that is in transit from Africa to Europe. The obtained values decreased with decreasing cooler delivery air temperature. Yet, at any instant, it is slightly above the delivery air temperature, with the lowest core temperature reaching 21.38 and 21.14 °C in 16 h for orange and papaya, respectively, from a peak temperature of about 25.81 °C. The slightly higher temperature of the fruit pulp compared to the delivery air can be attributed to some factors. Pereira

Table 2
Constants for Eq. 22.

Fruit	Equation	Constants			
		β	ϵ	ϑ x 10^3	R^2
Orange	22	-27.5	1.743	5.568	0.9993
Papaya		-13.9	1.364	3.063	0.9920

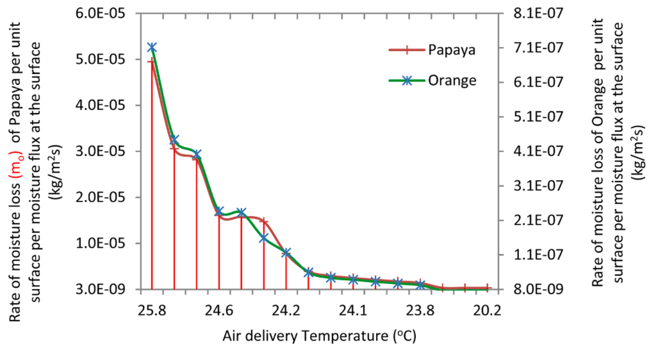

Fig. 7. Determined rate of moisture loss per unit surface of fruits as a function of delivery air temperature.

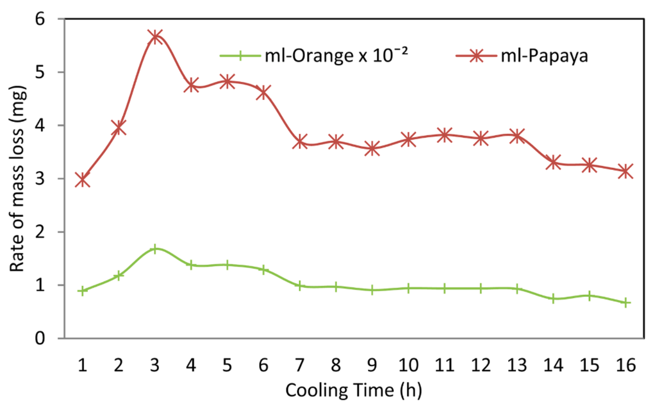

Fig. 8. Variation of mass loss with cooling time.

et al. (2009) have stated that ripe fruits experience poor intercellular aeration due to discontinuity of intercellular space and cell membrane breakdown, leading to reduced gas exchange rate and accumulation of liquid that can increase the temperature build-up within the pulp. Thus, the fruits' minimum pulp/core temperature relationship with delivery air temperature (°C) can be represented with a non–linear heat capacity model best described with Eq. 22 with the parameters presented in Table 2.

$$T_p = \beta + \epsilon T_{air} + \frac{\vartheta}{T_{air}^2} \tag{22}$$

However, the lowest pulp/core temperature (21.38 and 21.14 °C) obtained in this research falls within the room pre-loading temperature (20± 2 °C) of orange (Berry et al., 2021) obtained in South Africa before loading in a refrigerated container which is the target of initial cooling in the developed evaporative cooler. In Nigeria, the determined room temperature falls within 26 -28 °C. Therefore, the product must be pre-cooled to achieve a pre-loading temperature of 20± 2 °C. This is because the ambient temperature can reach 40 °C in a tropical environment like Nigeria. Thus, many regulations advocate on-farm cold handling before refrigerated shipment (< 2 °C) to stem the effect of phytosanitary pest attacks (Moore et al., 2016). Initial Pre-cooling using a low-energy evaporative cooler will reduce the cooling load in the refrigerated shipment and conserve energy.

3.3. Mass loss evolutions and quality evaluation

The impact of delivery air on moisture loss per surface area was assessed, as shown in Fig. 7, for the two fruits during the 16 h of cooling. Transpiration-driven moisture loss per surface area was higher at high temperatures but decreased as the delivery temperature decreased. Fig. 5 shows that higher humidity was associated with lower temperature. Thus, increased humidity might have reduced the rate of moisture loss as shown in Fig. 7. This corroborates with the study conducted by Onwude et al (2022) and Defraeye et al. (2019), which linked high moisture loss with increased storage temperature and lower humidity, increasing the transpiration rate of fruits. However, the moisture loss per surface area per moisture flux was higher in papaya (average value 1.03×10^{-5} kg/m^2.s) than in orange (1.501×10^{-7} kg/m^2.s) though both were stored in the cooler. This might be linked to the papaya's larger surface area and weight.

Additionally, the calculated average skin mass transpiration and air film mass transfer coefficient shown in Table 1 was higher than orange due to the smaller skin thickness of papaya, resulting in a higher transpiration rate. However, this moisture loss resulted in an increased amount of weight decrease with time at the first 3 hours of cooling, as shown in Fig. 8. Still, the trend was reversed from four hours of cooling as the amount of weight loss decreased. However, the average mass loss per hour for orange was 0.0104 mg, while papaya lost 3.96 mg per hour. On the whole orange fruit lost 0.167 mg of its total weight in 16 h of cooling while papaya lost 63.3 mg of its total weight.

The moisture loss per surface area per moisture flux (kg/m^2.s) was non-linearly fitted with delivery air temperature with the best equation presented in Eq. 23 while the constants for the equation are presented in Table 3.

Table 3
Constants for Eq. 23.

Fruit	Equation	Constants				
		$\alpha\times10^{-8}$	$\gamma\times10^{-10}$	ω x 10^{-2}	$\sigma\times10^{-3}$	R^2
Orange	23	-1.644	6.988	7.835	1.534	0.9515
Papaya		-113.78	483.53	7.821	1.533	0.9526

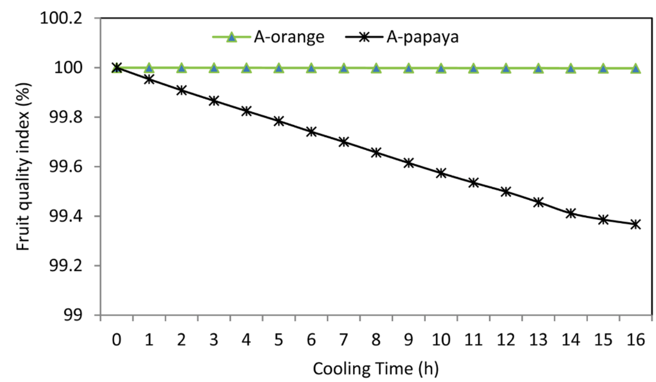

Fig. 9. Fruit quality index at the end of the cooling period.

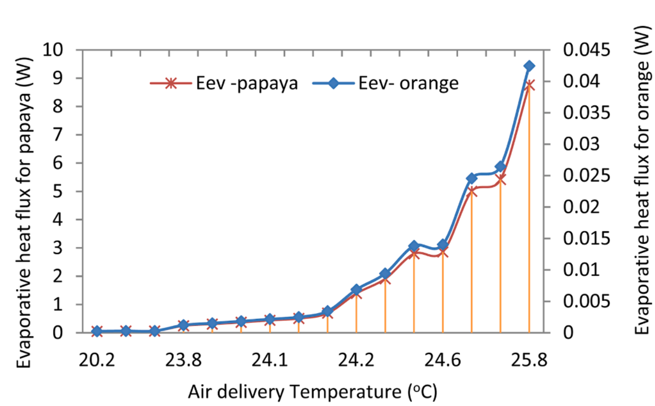

Fig. 10. Variation of evaporative heat flux with delivery air temperature.

Table 4
Average values of thermal parameters.

Fruit	T_a	T_c	T_p	Lp x 10^6	Dw x 10^{-5}	Re	Sc	k_a x 10^{-4}	k_t x 10^{-9}	k_s x 10^{-7}	p_w	p_s	RH	pH	m_o x 10^{-7}	k_o
Orange	31.7	24	24.22	3.7	2.55	317.46	0.6	6.04	1.72	1.72	2996.34	2936.42	95.24	2849.1	1.5	5.677
Papaya	31.7	24	24.33	3.7	2.55	317.46	0.6	60.27	117.1	117.2	2996.34	2936.42	95.24	2849.1	103.62	51.03

Note: T_a- ambient temperature (°C), T_c – EVC exhaust temperature (°C), T_p- is fruit pulp/core temperature (°C), L_p- latent heat of vaporization of product moisture-air mixture (J/kg), D_w is the air-water vapour diffusion coefficient (m^2/s), Re=Reynolds number, Sc – Schmidt number, k_a – is air film mass transfer coefficient (m/s), k_t – the transpiration coefficient (m/s), k_s-is the skin mass transfer coefficient (m/s), P_s-The partial pressure (Pa) of water vapour at the evaporating surface, pH- the partial pressure (Pa) of water vapour in the air, p_w - is the partial vapour pressure (Pa) of water at saturation, m_o -The rate of moisture loss per unit surface (kg/m^2s) per moisture flux at the surface, k_o is the rate exchange (s^{-1})

$$m_o = \frac{\alpha + \gamma T_{air}}{1 + \omega T_{air} + \sigma T_{air}^2} \tag{23}$$

Furthermore, the mass loss during 16 h of cooling was analysed using the fruit quality index, with an initial value of 100%, as shown in Fig. 9. A decrease in mass and moisture loss is associated with a loss in quality. For the studied period, the loss in quality of both fruits was not statistically significant (< 5%). However, orange fruit lost about 0.00257% of its quality, while papaya lost 0.63% during the cooling periods.

3.4. Evaporation heat flux

The impact of delivery air on the evaporation heat flux is shown in Fig. 10. The figure showed that the evaporative flux increased with temperature. This is because the cooling rate increases at high temperatures and low humidity, resulting in higher evaporative flux. However, papaya had a higher evaporative flux than orange due to its thin skin. It is worth mentioning that the condensation heat flux was zero because the calculated partial pressure of water vapour in the air is lower than the partial pressure of water vapour on the evaporating surface, according to Eq. (16). However, the average input parameters used to determine the evaporation heat flux are presented in Table 4. The evaporative flux is a function of the moisture loss per unit surface, the air-film mass transfer coefficient and the resistance to moisture transfer through the fruit's skin.

4. Conclusion

The study on quantifying the effect of delivery air on the hygrothermal impact on orange and papaya fruits during evaporative cooling using palm fruit mesocarp as a cooling pad is presented. This research used an evaporative cooler with palm fruit mesocarp fibre waste as cooling material to pre-cool down the pulp temperature of orange and papaya for about 16h The study addressed some critical issues as follows:

- Palm fruit mesocarp fibre waste can be recycled by deploying them as cooling pads for inlet air in evaporative cooling systems with high cooling efficiency for cooling oranges and papaya.
- Using the Palm fruit mesocarp fibre waste cooling pads in EVC, the pulp temperature of both fruits can be lowered by at least 17.7 to 27.2 % below the initial pulp temperature.
- Using the heat transfer models to generate data for various processes, empirical regression models were developed that can respectively predict the moisture flux and pulp temperature with the cold delivery air temperature at high R^2 values.
- However, the moisture loss per surface area per moisture flux was calculated at 1.03×10^{-5} $kg/m^2.s$ for papaya and 1.501×10^{-7} $kg/m^2.s$ for orange. The higher value obtained in papaya was linked to its larger surface area and weight. Conversely, orange's average mass loss per hour within the cooling period was 0.0104 mg/hr, while papaya was 3.96 mg/hr. Generally, orange fruit lost 0.167 mg of its total weight in 16 h of cooling, while papaya lost 63.3 mg of its total weight.
- The impact of delivery air on the evaporation heat flux showed that the evaporative flux increased with temperature, and papaya showed higher evaporative flux than orange due to its thin skin.
- The fruit quality index analysis shows that both fruits' quality loss was not statistically significant (< 5%). Nonetheless, orange fruit lost about 0.00257% of its quality, whereas papaya lost 0.63% during cooling.
- The study concluded that the air delivery temperature and velocity influence the heat flux, mass losses and product quality during the cooling process. The knowledge of these parameters is necessary for enhanced optimization.

With the high cost of energy and very high sensitivities of fruits (chilling injury) to very low temperatures over a long haul, this research presents cooling alternatives to high-energy compression refrigeration systems in cooling fruits before shipment or during shipment. The data generated provides a parametric pool that might be needed to optimise the entire system and probably needed for scaling up the EVC design for industrial applications, which should form the basis for further studies in this aspect.

CRediT authorship contribution statement

Macmanus Chinenye Ndukwu: Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Cyprian N. Tom:** Writing – review & editing. **Godwin Akpan:** Data curation, Writing – review & editing. **Godwin A. Usoh:** Writing – review & editing. **Samuel Nditoi Akpanmkpuk:** Writing – review & editing. **Djoukeng Henri Grisseur:** Investigation, Writing – original draft. **Leonard Akuwueke:** Writing – review & editing. **Augustine Edet Ben:** Data curation, Writing – original draft. **Fidelis I. Abam:** Methodology, Writing – original draft. **Merlin Simo-Tagne:** Methodology, Writing – review & editing. **Lyes Bennamoun:** Visualization. **Hongwei Wu:** Visualization. **Joseph Edeth:** Writing – review & editing. **Daniel I. Onwude:** Writing – review & editing.

Declaration of competing interest

The content of the manuscript has no potential conflict of interest to the best of our knowledge

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Data availability

Data will be made available on request.

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