Journal of Food Engineering 270 (2020) 109762

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: http://www.elsevier.com/locate/jfoodeng

A virtual prototyping approach for redesigning the vent-holes of packaging for handling pomegranate fruit – A short communication

Matia Mukama [a], Alemayehu Ambaw [b], Umezuruike Linus Opara [a,b,*]

[a] Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Food Science, Faculty of AgriSciences, Stellenbosch University, South Africa

[b] Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Horticultural Science, Faculty of AgriSciences, Stellenbosch University, South Africa

ARTICLE INFO

Keywords:
Punica granatum
Carton vent design
Virtual-prototype
Temperature reduction
Energy efficiency

ABSTRACT

In a previous study, experimental analysis and computational fluid dynamics (CFD) modelling were used to analyse the cooling performances of two corrugated fibreboard package designs (CT1 and CT2) for handling pomegranate fruit. In these analyses, the performance of the CT1 carton was shown to be low compared to the CT2 carton in terms of cooling rate, cooling uniformity and energy usage. The low performance of the CT1 carton was attributed to its improperly designed vent-holes. In the present communication, a virtual prototype approach, based on computational fluid dynamics (CFD), was used to redesign the CT1 carton for improved performance. This method enabled us to examine the thermal performance of new vent-hole configuration which was validated experimentally using the physical prototype of the new carton design. The new ventilation enabled 14.4% faster cooling and lowered pressure drop by 35.3 Pa m^{-1} (6.5%) in fruit loaded cartons.

1. Introduction

Fruit cold chain management is an interplay between the magnitude and uniformity of the cooling air, fruit-properties, package design, and stacking configurations (Berry et al., 2016). There has been renewed global interest in the development of cold-chain management systems, including ventilated packaging aimed at reducing postharvest losses, energy usage, and the carbon footprint (Opara, 2010).

The energy cost of refrigeration and to operate fans and blowers that drive cold air through stacked produce is profoundly affected by the packaging design. Attempts to enhance the energy performance of cold-chain processes through packaging design have shown significant potential (Defraeye et al., 2016; O'Sullivan et al., 2016; Ambaw et al., 2017; Mukama et al., 2017). Energy efficient ventilated packaging is the new focus of research through the use of vent-holes to achieve uniform and rapid cooling rates and yet without compromising the structural integrity of the packaging (Fadiji et al., 2016; Berry et al., 2017).

In corrugated fibreboard cartons, the vent-hole design affects the overall mechanical integrity of the cartons, unlike plastic crates. Fadiji et al. (2016) reported that the number, orientation, and shape of the vent-holes affected the buckling loads of cartons. The authors pointed out that rectangular vent-holes unlike circular ones better retain carton strength. Mitchell (1992) found that at carton vent-hole proportion ranging from 5-7%, the mechanical integrity of the carton becomes critically important. Additionally, Delele et al. (2013) observed reasonable increase in fruit cooling rates with ventilation area only up to 7% of the carton walls.

Recently, we examined the cooling performance of packaging (cartons) used for handling fruit in the pomegranate industry in South Africa (AmbawMukama and Opara, 2017; Mukama et al., 2017), and the result showed that the rate and uniformity of the precooling process and electricity costs were significantly affected by carton design. In these previous studies, we analysed the cooling performances of two corrugated fibreboard package designs (CT1 and CT2) (AmbawMukama and Opara, 2017; Mukama et al., 2017). The performance of the CT1 carton was lower than the CT2 carton in terms of cooling rate, cooling uniformity and energy usage, and the low performance of the CT1 carton was attributed to its improperly designed vent-holes. Particularly, it was demonstrated that due to the obstruction of the vent-holes during palletization of the cartons, there existed significant cooling heterogeneity with two distinctly different regions (high temperature and low temperature) inside the stack. We proposed to redesign the vent-hole

* Corresponding author. Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Food Science, Faculty of AgriSciences, Stellenbosch University, South Africa.

E-mail addresses: umunam@yahoo.co.uk, opara@sun.ac.za (U.L. Opara).

https://doi.org/10.1016/j.jfoodeng.2019.109762
Received 30 May 2019; Received in revised form 23 July 2019; Accepted 11 October 2019
Available online 12 October 2019

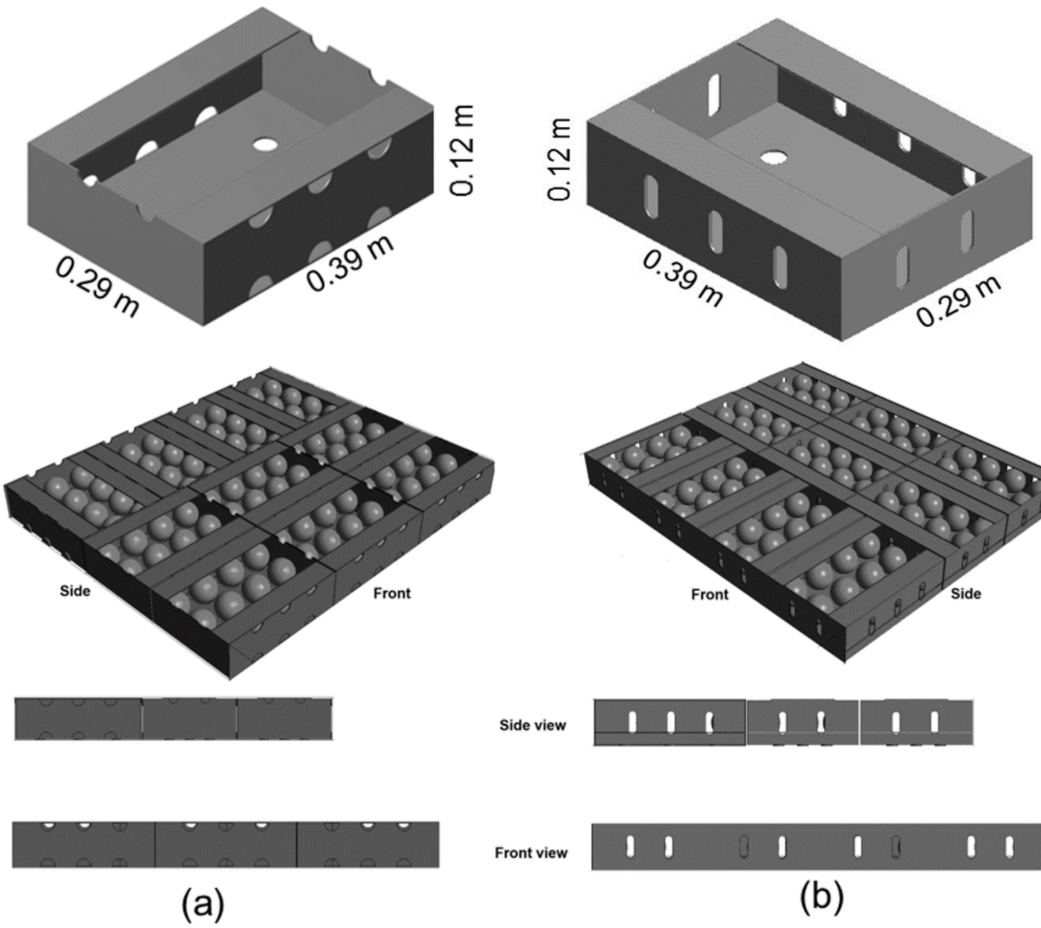

Fig. 1. Schematic diagram showing the dimensions (top row), stacking patterns (second row), vent-hole obstructions along the sides (third row), and vent-hole obstructions along the front (bottom row) of the current commercial design (CD) (a) and the new design (ND) (b) cartons.

location of this carton to alleviate the problem. Herein, we present results from the cooling performance of the new vent-hole design. The airflow, cooling rate, and cooling uniformity performances of the new design were compared to the existing counterpart.

2. Materials and methods

2.1. Fruit

Pomegranate fruit (*Punica granatum* L., cv. Wonderful) was procured from Sonlia Pack-house (33°34851″ S, 19°00′360″E), Western Cape, South Africa. The pomegranates were 8.0 ± 0.2 cm in diameter and

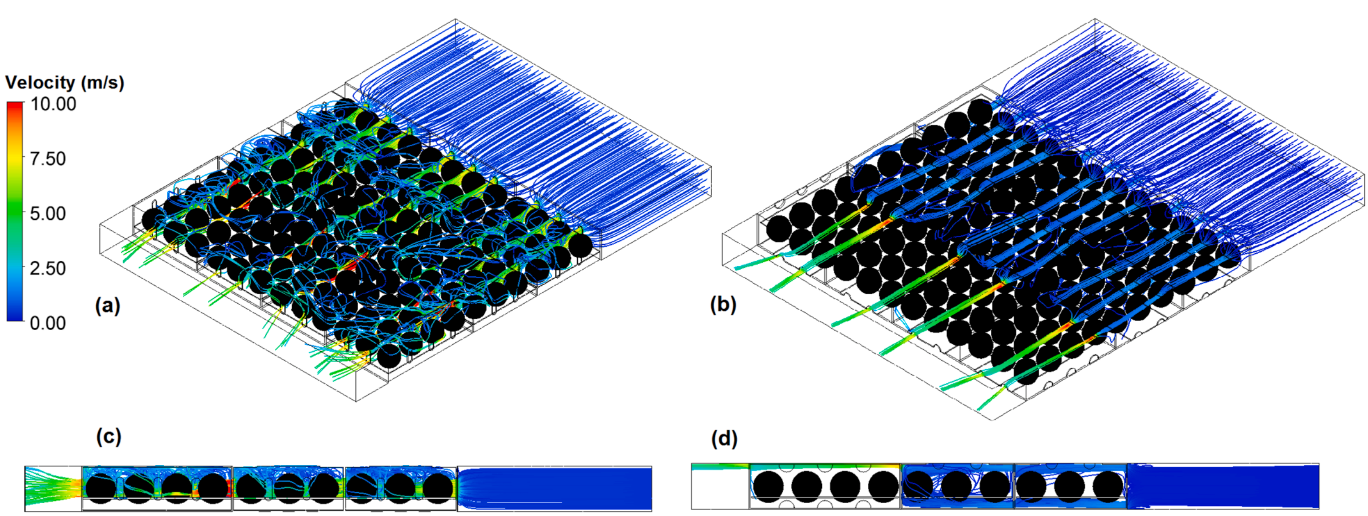

Fig. 2. Schematic showing simulated airflow distribution in stack of new design cartons (ND) (a) and current commercial design (CD) (b). Side view of ND (c) and side view of CD (d).

Table 1
Package dimensions, vent-hole ratios, and loading of the current commercial design (CD) and new design (ND) cartons.

Design	Dimensions [m]	Vent-hole ratio [%]			Loading	
		Short side	Long side	Bottom side	Number of fruit	Total weight [kg]
CD	0.39 × 0.29 × 0.12	2.0	8.0	3.0	12	4.3
ND	0.39 × 0.29 × 0.12	7.3	7.9	3.0	12	4.3

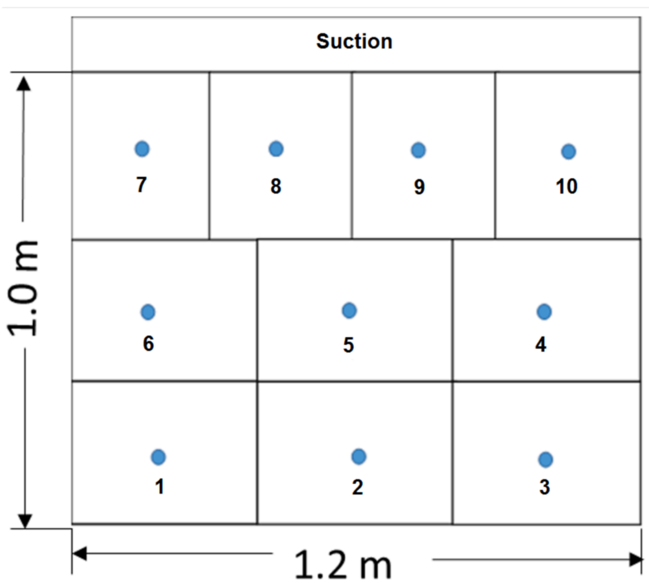

Fig. 3. Schematic showing layout of cartons and location of data logged sample fruit.

358 ± 10 g in mass. Before the start of the cooling experiment, fruit were equilibrated to ambient air temperature (20 ± 3.0 °C).

2.2. Cartons

The dimensions and vent-hole locations of the currently used commercial design (CD) and the newly designed (ND) cartons are presented in Fig. 1 (a) and Fig. 1 (b), respectively. The CD has 6 semi-circular vent-holes along its long side located at the top and bottom rim of the sides and two vent-holes widthwise located at the top rim of the side. The ND carton was proposed based on virtually experimenting on vent-hole locations in such a way that vent-hole obstruction is avoided or minimized during stacking on the standard ISO pallet (1.2 × 1.0 m) (compare the free air path achievable along the front and sides of the ND, Fig. 1). The new vent-hole design aimed to provide more direct air stream into the stack during forced air cooling and thereby reduce cooling non-uniformity (Fig. 2). The ND has 3 and 2 vent-holes along the long and short sides, respectively.

Table 1 summarizes the fruit loading capacities and vent area characteristics of the cartons. Plastic wrapping was done by placing pomegranates in a single non-perforated 10 μm thick high-density polyethylene (HDPE) plastic film.

2.3. Measurements

2.3.1. Resistance to airflow

The resistance to airflow (RTA) was measured based on the method described by Mukama et al. (2017). RTA measurements were made for the empty carton, cartons loaded with fruit with no liner, and cartons loaded with fruit wrapped with polyliner. Measurement was made on one layer of carton and cooling air was drawn through the 1.2 m side of the setup.

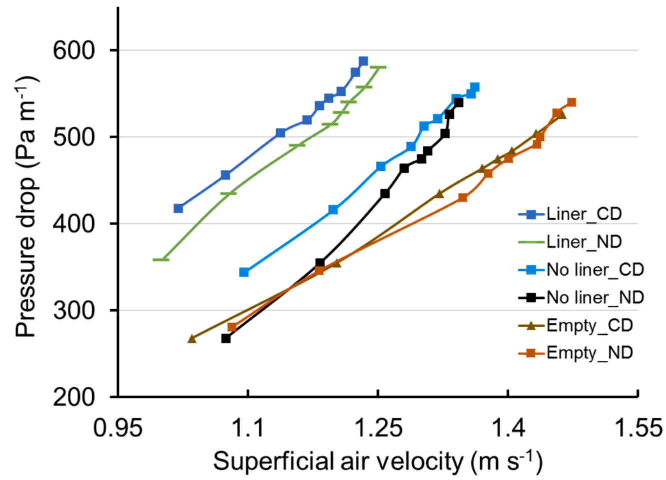

Fig. 4. Pressure drop vs. flow rate data of forced airflow through stack of pomegranate fruit in the new design (ND) and the current commercial carton design (CD).

2.3.2. Measuring the cooling characteristics

The cooling characteristics were measured by monitoring fruit core temperatures of sample fruit in each carton (Fig. 3). Cooling air at 7 °C was drawn through the 1.2 m side of the stack. The forced air cooling set up was as in (Mukama et al., 2017) but for one layer of cartons.

2.3.3. Numerical modelling

Computational fluid dynamics (CFD) modelling of the temperature distribution for the CD and ND was done as described by AmbawMukama and Opara, 2017. The analysis was done on pomegranate fruit packed with no liners inside the carton.

2.4. Statistical analysis

Analysis of variance (ANOVA) was carried out using STATISTICA 13 (StatSoft, Inc. Oklahoma, USA). Means were separated using Duncan's multiple range tests (Factors: carton design and lining).

3. Results and discussion

3.1. Effect of carton design and polyliner on pressure drop

The pressure drop pattern of the ND in comparison to the CD is shown in Fig. (4). Generally, the ND had relatively lower pressure drop compared to the CD, which implies that the vent-hole modification on the ND enabled easier airflow channelling in the carton layer compared to the CD. For example, taking superficial air velocity 1.25 m s^{-1}, the measured pressure drop (Pa m^{-1}) was 380 and 385 for empty ND and CD, respectively, 435 and 466 for no liner packaging in ND and CD, respectively, and 580 and 620 for fruit in polyliner in ND and CD, respectively (Fig. 4). The order of pressure drop was liner > no liner > empty, which corroborated the observations by Mukama et al. (2017) and AmbawMukama and Opara (2017).

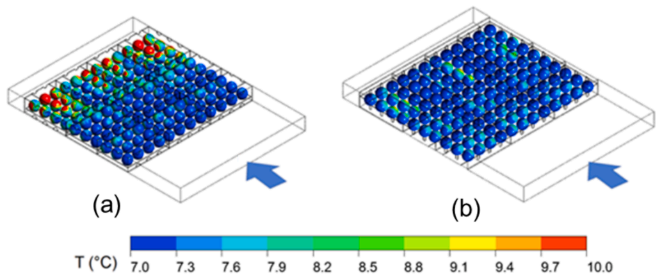

Fig. 5. Simulated temperature distribution in a layer of (a) current commercial design (CD) and (b) new design (ND) cartons stacks with no lining. Cooling was done at constant airflow rate of 0.5 L kg^{-1} s^{-1}, air temperature 7 °C.

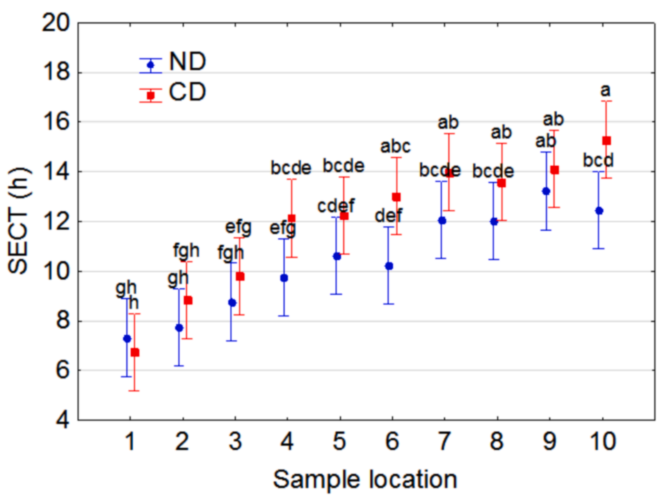

Fig. 6. Seven eighth cooling time (SECT) of pomegranate fruit in polyliner per sample location in the current commercial carton design (CD) and new carton designs (ND). Verticle bars denote 0.95 confidence intervals of 3 replicates. Different letters indicate significance difference. Cooling was done at constant airflow rate of 0.5 L kg^{-1} s^{-1}, air temperature 7 °C.

Table 2
Seven eighth cooling time (SECT) of pomegranate fruit cooled with no liner in the current commercial carton design (CD) and new carton design (ND).

Fruit sample location	SECT (h)	
	CD	ND
1	1.7 ± 0.1^{i}	1.3 ± 0.1^{j}
2	2.5 ± 0.2^{g}	2.0 ± 0.2^{hi}
3	2.6 ± 0.1^{fg}	2.4 ± 0.1^{gh}
4	3.4 ± 0.2^{e}	2.6 ± 0.3^{fg}
5	3.6 ± 0.1^{bcde}	2.9 ± 0.2^{f}
6	3.8 ± 0.2^{abcd}	2.9 ± 0.4^{f}
7	3.9 ± 0.1^{abc}	3.4 ± 0.1^{de}
8	4.0 ± 0.1^{ab}	3.8 ± 0.5^{abcde}
9	3.9 ± 0.3^{abc}	3.5 ± 0.2^{cde}
10	4.1 ± 0.2^{a}	3.8 ± 0.3^{abcd}

Values mean ± standard deviation of 3 replicates. Different letters indicate significance difference. Cooling was done at constant airflow rate of 0.5 L kg^{-1} s^{-1}, air temperature 7 °C.

3.2. Cooling characteristics

3.2.1. Temperature distribution

Modification of vent-holes in the new design resulted in improvement in the uniformity of temperature distribution (Fig. 5). The variation in cooling rate of fruit in the 3rd row (high temperature region) from the air inlet side observed in the CD (Fig. 5 (a)) is solved in the ND (Fig. 5 (b)). This is because of better alignment of the vent-holes in the new design on stacking the cartons enabling easier airflow channelling across the stack effecting faster and more uniform cooling of pomegranate fruit. However, the experimental results showed slight and generally insignificant cooling time differences across the layer, in liner (Fig. 6) and no liner (Table 2) packaged fruit.

Generally, fruit in ND with no liner cooled significantly faster (in 2.85 h) than fruit in the CD (3.33 h). The seven eighths cooling time variability among the temperature logged fruit with no liner in the ND was also lower than for fruit in the CD (Table 2). Fruit cooling rates followed a similar trend as observed by Mukama et al. (2017) and AmbawMukama and Opara (2017), with fruit upwind cooling relatively faster than those at the back of stack from the air inlet side (Table 2).

Fruit cooled in liners took significantly longer to cool down (Fig. 6). Taking on average 8.1 h longer compared to fruit in no liner in both the ND and CD. Cooling rates of polylined fruit are influenced primarily by the temperature of the cooling air and to a lesser extent the airflow distribution (O'Sullivan et al., 2016). A similar trend of improved cooling performance was observed in fruit in polyliner where fruit in the ND cooled on average in 10.4 h while fruit in CD cooled in 12.0 h. Additionally, fruit upwind cooled relatively faster than fruit at the back of the stack from the air inlet side (Fig. 6). However, the difference in cooling time was larger in fruit in polyliner (7.3 h) compared to fruit in no liner (2.4 h).

4. Conclusion

The application of computational fluid dynamics for conducting experiments on the virtual prototype combined with experimental testing helped to perform important parametric studies. This is based on the exponential growth of computer power in recent years that has eased the tedious nature and cut costs and time required to perform experiments. Therefore, different and complex scenarios are quickly and cheaply virtually tested before a validation experiment is later conducted. Fruit cooled in the new carton design (ND) had more uniform temperature distribution and significantly cooled faster compared to fruit in the commercial design (CD). The ND carton also recorded lower pressure drop in the forced air cooling operation (over 35.3 Pa m^{-1} less, in cartons with fruit). Fruit wrapped in a polyliner took 8.1 h longer to cool than fruit with no liner. The results from this study demonstrate the influence of vent-hole design on the cooling characteristics of fruit. By ensuring unobstructed airflow in the stack of fruit during precooling, the performance of the fruit cooling process is significantly improved.

Declaration of competing interest

None.

Acknowledgements

This work is based on the research supported wholly/in part by the National Research Foundation of South Africa (Grant Numbers: 64813). The opinions, findings and conclusions or recommendations expressed are those of the author(s) alone, and the NRF accepts no liability whatsoever in this regard. We acknowledge the DAAD (German Academic Exchange), the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM), THRIP and Agri-Edge for support.

References

Ambaw, A., Mukama, M., Opara, U.L., 2017. Analysis of the effects of package design on the rate and uniformity of cooling of stacked pomegranates: numerical and experimental studies. Comput. Electron. Agric. 136, 3–24.
Berry, T., Defraeye, T., Nicolai, B.M., Opara, U.L., 2016. Multiparameter analysis of cooling efficiency of ventilated fruit cartons using CFD: impact of vent hole design and internal packaging. Food Bioprocess Technol. 9 (9), 1481–1493.
Berry, T.M., Fadiji, T.S., Defraeye, T., Opara, U.L., 2017. The role of horticultural carton vent hole design on cooling efficiency and compression strength: a multiparameter approach. Postharvest Biol. Technol. 124, 62–74.

Defraeye, T., Nicolai, B., Kirkman, W., Moore, S., van Niekerk, S., Verboven, P., Cronjé, P., 2016. Integral performance evaluation of the fresh-produce cold chain: a case study for ambient loading of citrus in refrigerated containers. Postharvest Biol. Technol. 112, 1–13.

Delele, M.A., Ngcobo, M.E.K., Getahun, S.T., Chen, L., Mellmann, J., Opara, U.L., 2013. Studying airflow and heat transfer characteristics of a horticultural produce packaging system using a 3-D CFD model. Part II: effect of package design. Postharvest Biol. Technol. 86, 546–555.

Fadiji, T., Coetzee, C., Opara, U.L., 2016. Compression strength of ventilated corrugated paperboard packages: numerical modelling, experimental validation, and effects of vent geometric design. Biosyst. Eng. 151, 231–247.

Mitchell, F.G., 1992. Cooling methods. In: Kader, A.A. (Ed.), Postharvest Technology of Horticultural Crops, second ed. University of California, Davis, California, USA, p. 35.

Mukama, M., Ambaw, A., Berry, T.M., Opara, U.L., 2017. Energy usage of forced air precooling of pomegranate fruit inside ventilated cartons. J. Food Eng. 215, 126–133.

O`Sullivan, J., Ferrua, M.J., Love, R., Verboven, P., Bart Nicolaï, B., East, A., 2016. Modelling the forced-air cooling mechanisms and performance of polylined horticultural produce. Postharvest Biol. Technol. 120, 23–35.

Opara, U.L., 2010. High incidence of postharvest food losses is worsening global food and nutrition security. Int. J. Postharvest Technol. Innovation 2 (1), 1–3.