

Review

Evaluation and optimization of air-based precooling for higher postharvest quality: literature review and interdisciplinary perspective

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Abstract

Precooling is of significant importance for postharvest fruits and vegetables to control the quality degradation and prolong the shelf-life. Current precooling methods include room cooling, forced-air cooling, hydrocooling, vacuum cooling, contact or package icing, and cryogenic cooling, all of which have their advantages and disadvantages. The first two methods with the cooling medium of air are extensively used because of the wide applicable range of fruits and vegetables. Numerous studies have been devoted to cope with the drawbacks of these two air-based precooling methods with various evaluation criteria and optimization methods. A systematic literature review on these studies is firstly conducted with respect to experimental and numerical investigations respectively for the two methods. The main contributions from the previous studies are also summarized respectively with the research objectives and performance metrics. The literature review indicates that the current performance evaluation is limited to apparent parameters and the optimal design is only proposed based on the performance evaluation and comparison. Furthermore, with inspiration from the research in other domains, a scheme of advanced evaluation and optimization for air-based precooling methods is proposed with thermodynamic evaluation metrics and constructal optimization methods from the interdisciplinary perspective.

Key words: precooling; postharvest quality; evaluation; optimization; interdisciplinary.

Introduction

Shelf-life is the main concern to maintain high postharvest quality involved with attributes such as colour, flavour, moisture, hardness, visible decay, nutrient content, and microbiological enumeration. Temperature control is of great importance to achieve higher postharvest quality and longer shelf-life. The food supply chain for long-distance transport from farmers to consumers without temperature control usually results in much food wastage (FAO, 2013). Consequently, the cold chain logistics becomes more and more common for food security and quality preservation with the emphasis

on temperature management (Hsiao and Huang, 2016; Mercier et al., 2017). It was estimated that the cold chain market would be valued at USD 293.27 billion by 2023 driven by the growing international trade of perishable food products, while the segment of fruits and vegetables was predicted to be at the fastest growth rate from 2018 to 2023 (MarketsandMarkets, 2018). In particular, as firstly introduced in 1904, precooling is the first stage of cold chain logistics for postharvest fruits and vegetables (Ryall and Pentzer, 1982).

Precooling is defined as a postharvest procedure to rapidly remove the field heat and reduce the product temperature with the ultimate

motivation of prolonging the shelf-life (Brosnan and Sun, 2001). The postharvest horticultural products are still alive with diverse ongoing physiological activities and biochemical reactions leading to quality deterioration (Prasanna et al., 2007; Vandendriessche et al., 2013). Precooling will retard such biological processes by controlling the temperature at a lower level with the removal of field heat resulting in promoted postharvest quality and longer shelf-life (Manganaris et al., 2007; Pelletier et al., 2011; Souza et al., 2011; Rab et al., 2013; Han et al., 2017b). In the past years, different precooling methods were developed using various cooling mediums such as water, ice, dry ice, liquid nitrogen, and cold air.

Hydrocooling is a common precooling method to achieve heat exchange between the products and chilled water by flood, spray, or immersion operations. This method minimizes the moisture loss (Wills and Golding, 2016) while achieving a moderate cooling rate (Sargent et al., 1988), but decay and microbial contamination may affect the product quality under wet conditions (Vigneault et al., 2000; Macarasin et al., 2017). de Oliveira Alves Sena et al. (2019) investigated the effects of hydrocooling temperature on the quality of cashew apples, while Zainal et al. (2019) studied the effects of hydrocooling time on the physico-chemical attributes of the rockmelon. It was indicated that the products applicable to hydrocooling must be water tolerant.

Vacuum cooling is based on the removal of latent heat of water evaporation from the products under much lower pressure than the atmospheric pressure. Vacuum cooling becomes popular because of the rapid and uniform cooling (Sun and Zheng, 2006) as well as high energy efficiency (Thompson and Chen, 1988). Whereas, the removal of water during vacuum cooling leads to the restrictions of applicability to different kinds of postharvest products (Brosnan and Sun, 2001). On the one hand, vacuum cooling is more suitable for leafy vegetables with a much larger surface area for water evaporation when compared with non-leafy vegetables and fruits. On the other hand, vacuum cooling also results in certain weight loss which was undesirable for postharvest products. Zhu et al. (2019) reviewed the potential of process design and parameters to promote the vacuum cooling performances and found out the feasibility gap between the laboratory experiments and industrial applications.

Contact or package icing is conducted with crushed ice or ice slurry inside or on top of the containers or packages. The melting of ice into water results in steady transport conditions with low temperature and high relative humidity which reduce the weight loss (Gillies and Toivonen, 1995), but the problems with wet conditions still exist (Wills and Golding, 2016). Moreover, additional weight to the products as well as the expensive water-proof packages leads to inefficiency in terms of energy and cost (Thompson et al., 2008). Alternatively, in spite of high operation cost, dry ice or liquid nitrogen can be used for cryogenic cooling by conveying the products through the cooling tunnel (Senthilkumar et al., 2015). Due to the possible chilling damage and high operational cost, such precooling methods are mainly employed for the fish industry (Zhao et al., 2019).

Air-based methods are old and traditional for the precooling of fruits and vegetables in comparison with the aforementioned precooling methods. The products within packages and containers for room cooling are simply placed inside a cold room where the circulated air from the fan coils cools down the products by flowing around them. Room cooling enables consequent *in-situ* storage and thus lower loss and cost caused by less handling, but the cooling time tends to be longer in comparison with other precooling methods (Kader and Rolle, 2004). In order to improve the cooling rate,

forced-air cooling is developed to force air to flow through the containers and packages with a higher velocity at the product surface by differential pressure. However, the high-power fans used to generate desirable pressure difference lead to high energy consumption in particular for the extremely rapid cooling (Baird et al., 1988; Thompson and Chen, 1988).

Numerous studies have been devoted to cope with the drawbacks of the air-based precooling methods with various evaluation criteria and optimization methods. Therefore, a review on these studies is necessary to give insights into the optimal design of air-based precooling processes with enhanced performances. Furthermore, novel methods for evaluation and optimization of air-based precooling processes are also proposed from the interdisciplinary perspective with inspiration from the research in other domains. The new evaluation parameters in terms of thermodynamics give insight into the mechanisms behind the evolution of postharvest quality. The new constructal optimization method will result in higher postharvest quality.

Current Evaluation and Optimization Methods of Air-Based Precooling

The research on air-based precooling methods including room cooling and forced-air cooling extends from the last century to recent years with experimental and numerical studies.

Room cooling

Early experimental observations for room cooling indicated a lower cooling rate than 0.5°C/h (Gibbon, 1972), which hardly met the IIR recommendations for the precooling operation within 24 h (IIR, 1967). Nonetheless, the higher cooling rate can be obtained with well-ventilated packages or containers. For example, 8 h of room cooling for carnations was performed with open boxes (Reid et al., 1983). Furthermore, proper packaging was also investigated for table grapes that were only suitable for air-based precooling (Nelson, 1978).

In addition to the above experimental studies on optimal packaging design, Geyer et al. (2018) developed a new sensor for omnidirectional measurement of air velocity in the space between postharvest products and further measured the air velocity inside the bins and gaps between bins for room cooling of apples (Praeger et al., 2020). Duret et al. (2014) conducted a more comprehensive experimental research on the characteristics of airflow and heat and mass transfer during room cooling by measuring the temperature, velocity, humidity, and heat transfer coefficient. Based on such experimental measurements, Laguerre et al. (2015) subsequently proposed a simplified model to quickly predict the heat and mass transfer involved with the room cooling process by solving the linear system of equations. Thanh et al. (2008) also developed a mechanistic model based on the experimental data to achieve the real-time monitoring and control of the temperature distribution inside a cold room contained with boxes of potatoes.

In recent years, the numerical modelling approach was also used to evaluate and optimize the room cooling process. Chourasia and Goswami (2007) numerically analysed the effects of the product and operating parameters on the cooling time and moisture loss during the cooling of stacks of bagged potatoes in the cold store. They concluded that the product temperature and moisture loss decreased with higher bulk medium porosity and product diameter while increased with the respiration heat and higher air temperature. The humidification system with high pressure fogging of the cold room

was numerically studied by the modelling approach of combined discrete element and computational fluid dynamics (CFD) and the effects of operating parameters were analysed to optimize the performances of the humidification system (Delele et al., 2009). Ambaw et al. (2013) provided a comprehensive review on the CFD models used to investigate the postharvest handling of horticultural products including room cooling processes. They suggested new strategies using multiscale models to cope with complicated physical phenomena involved in product geometry, turbulence, and porous media. In another review of modelling of postharvest storage, Grubben and Keesman (2015) divided the modelling structures into data-based models, lumped parameter models, and distributed parameter models for postharvest storage of potatoes and respectively reviewed the specific models in the scope of different modelling structures. In order to achieve more accurate simulation with less computation time, different turbulence and product models were compared for the numerical study on the airflow and heat transfer involved with room cooling of apples (Hoang et al., 2015). It was indicated from the comparison that shear stress transport (SST) $k-\omega$ turbulence model and solid bulk model of the products were respectively more appropriate considering the accuracy of Nusselt number and cooling time. For the room cooling and forced-air cooling of fresh cauliflowers, Le Bideau et al. (2018) combined the one-dimensional numerical model with the *in-situ* experiments to predict the temperature history and mass loss. The heat transfer mechanisms combined with convection, evaporation, and radiation were investigated.

Numerical methods were also used to evaluate potential optimization strategies. The novel staggered placement of the product boxes for room cooling of oranges was compared with the traditional arrangement of in-line arrays in terms of different cooling performances through numerical simulation (Sajadiye and Zolfaghari, 2017). The reduction of cooling time and the promotion of the surface heat transfer coefficient were obtained with the staggered arrangement. Ghiloufi and Khir (2019) also proposed new air deflectors to optimize the distribution of airflow from the fan outlets of the cooling unit. The use of these air deflectors resulted in enhanced heat transfer between the cold air and products and consequently reduced cooling time during room cooling of dates. In fact, air distribution systems such as supply/return diffusers and fabric ducts in the chilled food processing facilities were numerically and experimentally proved to be able to achieve more uniform distributions of air velocity and temperature, which consequently could be the optimization strategies of airflow organization for room cooling (Parpas et al., 2017, 2018).

In general, as given in Table 1, the research on room cooling was initially focussed on experiments and turned to numerical simulation in recent years. Most of these studies are mainly for evaluation of apparent performances, while optimizations from experience are achieved in some of them.

Forced-air cooling

In spite of 4–10 times higher cooling rate compared with room cooling (Ryall and Pentzer, 1982), the effectiveness of forced-air cooling is also affected by a series of factors related to the products, packaging design, and operating conditions (Hass et al., 1976). The effect of the ventilation rate was firstly investigated by experiments. It was reported that 30%–40% reduction of seven-eighths cooling time was achieved with double airflow rate (Emond et al., 1996), while three to six times decrease of cooling time could be obtained with the increase of air velocity from 0.2 to 3.65 m/s (Lambrinos et al., 1997). Albayati et al. (2007) further pointed out that higher air

velocity resulted in reduced energy consumption because of shorter cooling time.

Optimal process design for forced-air cooling was still required due to higher energy consumption in comparison with other precooling methods (Thompson et al., 2010). Mukama et al. (2017) studied the energy consumption of forced-air cooling by experiments with pomegranate fruit and found out the significant effects of airflow resistance inside the packages. In fact, the airflow characteristics in terms of the pressure drop within the packaging system for forced-air cooling of table grapes were investigated in earlier research (Ngcobo et al., 2012). The cooling rate and weight loss in addition to the airflow with different packaging designs for table grapes were further studied and the trade-off between the cooling rate and weight loss had to be reached when choosing the packages (Ngcobo et al., 2013). Ferrua and Singh (2011) proposed a new multi-scale packaging system ranging from clamshells and trays to overall airflow pattern across the pallets for forced-air cooling of strawberries with higher uniformity and energy efficiency. Additionally, more performance parameters were evaluated on the scale of the entire forced-air cooler. Olatunji et al. (2017) proposed the overall heterogeneity index to quantify and visualize the non-uniform distribution of temperature during forced-air cooling of kiwifruit. Mukama et al. (2019) investigated the dynamics of quality loss for forced-air cooling of pomegranate fruit. They obtained the spatiotemporal profile of quality loss and analysed the effects of relative humidity, packages, and stack orientation. In addition to lab-scale research, experiments in commercial forced-air coolers were recently conducted. Defraeye et al. (2016) conducted ambient loading experiments with citrus using three airflow strategies within refrigerated containers. The integral performance evaluation involved with the quantification and spatial distribution of cooling rate, shelf-life, and other quality attributes. Wu et al. (2018b) investigated the influences of packages for three kinds of citrus fruits on the cooling rate and heterogeneity and identified the decreasing cooling rate and increasing cooling heterogeneity caused by fruit wrapping. Mercier et al. (2019) studied the non-uniform distribution of temperature and cooling time for strawberries and achieved temperature prediction using limited sensors by the correlation between the cooling times on the outside and inside of the tunnel. Moreover, in the case of the difficulties for practical forced-air cooling experiments, produce simulators could be used to replace the real products with design guidelines in accordance with the geometry parameters, thermophysical properties, and other constraints (Redding et al., 2016).

Mathematical and CFD models for forced-air cooling processes were also developed for performance evaluation and optimization (Dehghannya et al., 2010; Zhao et al., 2016). The forced-air cooling of kiwifruit with palletized packages was numerically simulated with explicit geometry models of the packaging system in order to achieve an accurate prediction of the temperature history (O'Sullivan et al., 2016). Han et al. (2018) conducted similar numerical simulations for apple pallets and integrally evaluated the cooling rate and uniformity, moisture loss, and energy consumption. Wu and Defraeye (2018) numerically investigated the heterogeneities of airflow and cooling rate within an entire pallet of citrus fruit during forced-air cooling as one of the scenarios in the whole cold chain and further predicted the quality evolution by combining with kinetic rate law models. In addition, Wu et al. (2019) further studied the influences of the design and placement of the package on these heterogeneous performances. The packaging design was also the main concern for other numerical research. Delele et al. (2013a) developed a three-dimensional CFD model with explicit geometry of oranges within

Table 1. Overview of research related to room cooling.

Produce	Reference	Research method	Research objectives	Performance metrics
Vegetables Grape	(Gibbon, 1972)	Experiment	Data collection	Temperature history, cooling rate
	(Nelson, 1978)	Experiment	Process optimization	Temperature history, cooling time, quality loss
Carnation Potato	(Reid et al., 1983)	Experiment	Process optimization	Cooling time, vase-life
	(Chourasia and Goswami, 2007)	CFD model	Effects of product and operating parameters	Airflow pattern, temperature history, moisture loss, cooling time
Apple	(Thanh et al., 2008)	Experiment-based theoretical model	Monitoring and control of temperature distribution	Temperature history, temperature field
	(Duret et al., 2014)	Experiment	Experimental characterization	Air velocity, convective heat transfer coefficient, temperature history, cooling time, weight loss
	(Laguerre et al., 2015)	Experiment-based theoretical model	Fast performance prediction	Temperature history, weight loss
	(Hoang et al., 2015)	CFD model	Comparison of numerical models	Temperature history, cooling time, fields of air velocity, pressure, and temperature
	(Geyer et al., 2018; Praeger et al., 2020)	Experiment	Experimental characterization	Air velocity
Orange	(Wang and Zhang, 2020)	Experiment	Process evaluation and optimization	Temperature history, cooling time, energy flow, entropy generation, exergy destruction, entransy dissipation
	(Sajadiye and Zolfaghari, 2017)	CFD model	Optimization of placement pattern for pallets	Air velocity, surface heat transfer coefficient, temperature history, cooling time, temperature heterogeneity
Cauliflower	(Le Bideau et al., 2018)	One-dimensional numerical model and experiment	Process evaluation and mechanism clarification	Temperature history, mass loss, air velocity
Dates	(Ghiloufi and Khir, 2019)	CFD model	Optimization of airflow distribution	Fields of air velocity and temperature
Spherical produce	(Delele et al., 2009)	CFD model	Effects and optimization of operating parameters for the humidification system	Histories of temperature and humidity, fields of air velocity, temperature, and humidity, tracks of droplets

ventilated cartons to simulate the airflow and heat transfer characteristics on the scale of the overall forced-air cooler. Getahun et al. (2017a) developed a CFD model for cooling of palletized apple inside a fully loaded refrigerated shipping container with the simplification by porous medium approach and validated the numerical model by experimental measurements. The same authors further compared the airflow and heat transfer characteristics affected by different packages and airflow resistance (Getahun et al., 2017b). The cooling rate and uniformity of stacked pomegranates with two different package designs were compared by numerical and experimental studies and the increase of cooling time could be caused by the plastic liner (Ambaw et al., 2017). The cooling conditions and packaging design were optimized to achieve reduced cooling time and improved cooling uniformity by rearrangement of airflow according to the numerical simulation with a three-dimensional CFD model of palletized kiwifruit (O'Sullivan et al., 2017). Similarly, the CFD models of stacked citrus fruit were developed to compare the effects of different containers (Defraeye et al., 2013) and cooling conditions (Defraeye et al., 2014) on the cooling performances in terms of the cooling rate, convective heat transfer coefficient, and energy consumption. Gruyters et al. (2019) numerically compared the cooling rate, temperature uniformity, energy consumption, and quality loss for forced-air cooling of apples contained in corrugated boxes and reusable plastic crates and suggested the use of reusable plastic crates for energy-efficient processes.

There was also other research focussed on the numerical simulation on the individual package scale. A two-dimensional

mathematical model of the cross-section of a single package with spherical produce inside was solved by direct numerical simulation for forced-air cooling operation and the effects of vent configurations on the cooling rate and uniformity were analysed (Dehghannya et al., 2011, 2012). Delele et al. (2013b) numerically studied the effects of packaging design in terms of vent area, shape, number, and position on the individual carton scale for forced-air cooling of oranges using an explicit geometry model. Han et al. (2015) developed a CFD model of an individual slotted box with explicit geometry of apples inside to study the airflow and heat transfer therein. A similar modelling approach was also used to evaluate the new packaging design for strawberries with improved airflow pattern (Nalbandi et al., 2016). Defraeye et al. (2015) conducted a comprehensive review on different evaluation metrics of packaging performances and further proposed the trend of integral evaluation for future optimization. Han et al. (2017a) integrally evaluated the packaging design for forced-air cooling of apples in terms of energy consumption, chilling injury, and mass loss based on the simulation results obtained from their previous numerical model. Berry et al. (2016, 2017) also conducted a multi-parameter evaluation of carton design for apples considering both the cooling and mechanical performances. Wu et al. (2018a) evaluated the spatial distribution of cooling time and estimated the quality loss for forced-air cooling of a single package of orange fruit using the CFD model combined with the kinetic quality model. Wang et al. (2019) established a numerical model of forced-air cooling for strawberries in the packaging system of the clamshell and box to study the effects of the vent design on the

cooling time and cooling uniformity and further propose the optimal design guidelines. Similarly, Wang et al. (2020) recently numerically investigated the effects of opening ratio of the packaging system on the cooling time, cooling uniformity, and energy consumption during forced-air cooling of apples and further established a fitting function of energy consumption in terms of opening ratio and air velocity for fruits with different diameters.

Forced-air cooling seemed a more popular topic especially in these years when compared with room cooling indicated by numerous studies shown in Table 2. Both experimental and numerical investigations were extensively conducted with regard to different kinds of products. Moreover, the packaging design was the main research focus because of the significant effects on the apparent performances. In addition, most of the optimization was mainly performed with regard to the packaging design, which was also a posteriori based on performance evaluation and comparison.

Advanced Evaluation and Optimization With Interdisciplinary Methods

Air-based precooling involves complex mechanisms of airflow and heat transfer with respect to the products and facilities. The performances of such airflow and heat transfer directly affect the postharvest quality. As given in the previous section, current evaluation and optimization methods for air-based precooling are based on simple flow and heat transfer characteristics such as velocity, temperature, heat transfer coefficient, and so on. However, recent development regarding evaluation and optimization of flow and heat transfer indeed provides more advanced methods which are promising for future applications for air-based precooling.

Some of the thermodynamic parameters as the evaluation metrics have been already used in the food industry. The system performance of vacuum cooling for mushroom was evaluated by exergy analysis of experimental results and the system efficiency was respectively assessed in terms of energy and exergy (Ozturk and Hepbasli, 2017). Zisopoulos et al. (2017) conducted a review to investigate the use of exergy indicators in the food industry. The statistical results from their review indicated that exergy indicators were more popular for analyses of the energy-intensive drying technologies and processes. Özilgen (2018) summarized the values of the specific cumulative energy and exergy for various kinds of foods in order to facilitate such thermodynamic analysis of food processing processes. Wang and Zhang (2020) recently conducted a comprehensive thermodynamic analysis in terms of energy, entropy, exergy, and entransy for multi-scale precooling processes for apples and proposed a new air-based precooling method based on the trade-off between room cooling and forced-air cooling.

In addition to the overall evaluation of the processes and systems, the thermodynamic parameters can also be used as the objective functions for the optimization of flow and heat transfer. The minimization of entropy generation was first proposed as the optimization criterion for performance enhancement of heat transfer processes and thermodynamic systems (Bejan, 2013). As derived from the entropy generation, minimal exergy destruction was also used for the enhancement of convective heat transfer (Wang et al., 2015; Liu et al., 2018). The extremum principle of entransy dissipation was another widely used optimization method for conductive, convective, and radiative heat transfer processes (Chen et al., 2013) and was further found out to be more appropriate for convective heat transfer optimization (Chen et al., 2019). Therefore, thermodynamic parameters are suitable for evaluation and further optimization of flow and heat transfer characteristics

for air-based precooling processes, which will have a great influence on the postharvest quality. Such interaction among different evaluation parameters is shown in Figure 1.

With inspiration from the natural evolution laws, the constructal theory is widely used to predict the optimal design of various processes and systems, a majority of which is involved with flow and heat and mass transfer (Bejan and Lorente, 2008). The applicability of the constructal design to the problems of forced convective flow within channels for cooling of volumes with heat generation results in the possible use for optimization of airflow strategy for air-based precooling (Feijó et al., 2018). The objectives of constructal optimization can be case-sensitive, e.g. including minimization of the temperature difference (Bejan, 1997), flow resistance (Bejan and Errera, 2000), and entropy generation (Ghodoossi, 2004). Chen et al. (2018) recently combined the entransy dissipation extreme principle with the constructal theory to deal with a series of optimization problems and they achieved the improvement of global transfer performance with the optimized devices.

A similar problem of airflow maldistribution to the air-based precooling method also exists for thermal management in data centre and different strategies have been proposed to promote the uniformity of airflow and cooling (Chu and Wang, 2019). The aforementioned advanced evaluation and optimization methods have been already used for the design of data centre cooling strategies. Qian et al. (2015) conducted a thermodynamic analysis of airflow in data centre in terms of exergy and entransy based on the heat transfer network model and concluded that entransy analysis was more applicable for such research. Xie et al. (2019) also proposed new exergetic evaluation parameters on different levels to identify the inefficient parts of the cooling system based on the experiment and simulation. Tian et al. (2019) developed a new mathematical model to implement the entransy theory to the multi-scale thermal management in data centre and provide optimization measures for practical operations. Zhang et al. (2019) further employed the constructal design of the airflow strategies to improve the cooling uniformity and extended the modular design to the whole large-scale data centre.

As indicated from the above research, the scheme of advanced evaluation and optimization for air-based precooling methods is shown in Figure 2. The original design can be evaluated by thermodynamic metrics according to experimentally measured data or numerical simulation results. The constructal design is conducted based on the simplified geometry of the original design. Afterwards, the reconstruction of the geometry in consideration of the operating conditions results in the modified design. The thermodynamic performance of the modified design is then assessed by CFD simulation and compared with that of the original design. Further adjustments in consideration of the performance comparison and practical operation are then performed and result in the optimal design. Such an optimal design can be in different configurations that have to be compared in terms of thermodynamic performance by CFD simulation. Finally, the most appropriate optimization strategy is selected based on the performance comparison and experimental verification.

Conclusions

A systematic literature review on the studies related to air-based precooling methods, i.e. room cooling and forced-air cooling, is firstly conducted with respect to experimental and numerical investigations, respectively. The performance evaluation parameters and optimization methods to promote postharvest quality are specifically pointed out. Afterwards, from the interdisciplinary perspective, thermodynamic

Table 2. Overview of research related to forced-air cooling.

Produce	Reference	Research method	Research objectives	Performance metrics
Straw- berry	(Emond et al., 1996)	Experiment	Effects of airflow rate and packages	Cooling time
	(Thompson et al., 2010)	Experiment	Data collection	Energy consumption, energy coefficient
	(Ferrua and Singh, 2011)	Experiment	Package optimization	Temperature history, cooling time, energy consumption
	(Nalbandi et al., 2016)	CFD model	Optimization of airflow system	Fields of air velocity and temperature, temperature history
Kiwifruit	(Mercier et al., 2019)	Experiment	Correlation for temperature prediction	Temperature history, cooling time
	(Wang et al., 2019)	CFD model	Effects and optimization of packages	Fields of air velocity and temperature, temperature history, cooling time, cooling uniformity coefficient
	(Lambrinos et al., 1997)	Experiment	Effects of air velocity and packages	Temperature history, cooling time
	(O'Sullivan et al., 2016)	CFD model	Process evaluation	Temperature history, cooling time, fields of air velocity and temperature
Apple	(O'Sullivan et al., 2017)	CFD model	Optimization of cooling conditions and packages	Temperature history, cooling time, fields of air velocity and temperature, energy consumption
	(Olatunji et al., 2017)	Experiment	New heterogeneity index	Overall heterogeneity index
	(Albayati et al., 2007)	Experiment	Effects of air velocity	Temperature history, convective heat transfer coefficient, Nusselt number
	(Han et al., 2015)	CFD model	Package optimization	Fields of air velocity and temperature, temperature history, cooling time, cooling heterogeneity
	(Berry et al., 2016)	CFD model	Effects of packages	Cooling time, convective heat transfer coefficient, energy consumption
	(Han et al., 2017a)	CFD model	Process evaluation	Temperature history, cooling time, convective heat transfer coefficient, fields of air velocity and temperature, energy consumption, mass loss, quality loss
	(Berry et al., 2017)	CFD model	Effects of packages	Compression strength, cooling time, convective heat transfer coefficient, energy consumption,
	(Getahun et al., 2017a)	CFD model	Process evaluation	Temperature history, cooling time, fields of air velocity and temperature
	(Getahun et al., 2017b)	CFD model	Effects of packages	Airflow resistance, air velocity, temperature history, temperature field
	(Han et al., 2018)	CFD model	Process evaluation	Temperature history, cooling time, fields of air velocity and temperature, mass loss, quality loss, energy consumption
Papaya	(Gruyters et al., 2019)	CFD model	Effects of packages	Cooling time, fields of air velocity and temperature, energy consumption, quality loss
	(Wang et al., 2020)	CFD model	Effects of air velocity and packages	Cooling time, air velocity field, cooling inhomogeneity, energy consumption
	(Wang and Zhang, 2020)	Experiment	Process evaluation and optimization	Temperature history, cooling time, energy flow, entropy generation, exergy destruction, entransy dissipation
	(Albayati et al., 2007)	Experiment	Effects of air velocity	Temperature history, convective heat transfer coefficient, Nusselt number
Grape	(Albayati et al., 2007)	Experiment	Effects of air velocity	Temperature history, convective heat transfer coefficient, Nusselt number
	(Thompson et al., 2010)	Experiment	Data collection	Energy consumption, energy coefficient
	(Ngcobo et al., 2012)	Experiment	Effects of packages	Airflow resistance
Citrus	(Ngcobo et al., 2013)	Experiment	Effects of packages	Airflow resistance, temperature history, cooling time, quality loss
	(Delele et al., 2013a)	CFD model	Process evaluation	Fields of air velocity, pressure, and temperature, temperature history
	(Delele et al., 2013b)	CFD model	Effects of packages	Fields of air velocity, pressure, and temperature, temperature history
	(Defraeye et al., 2013)	CFD model	Effects of packages	Temperature history, cooling time, convective heat transfer coefficient
	(Defraeye et al., 2014)	CFD model	Effects of packages and cooling conditions	Temperature history, cooling time, convective heat transfer coefficient, energy consumption

Table 2. Continued

Produce	Reference	Research method	Research objectives	Performance metrics
Pom- granate	(Defraeye et al., 2016)	Experiment	Effects of airflow strategies	Temperature history, cooling time, mass loss, quality loss
	(Wu et al., 2018a)	CFD model	Process evaluation	Temperature history, cooling time, convective heat transfer coefficient, quality loss
	(Wu et al., 2018b)	Experiment	Effects of packages and fruit sizes	Temperature history, cooling time
	(Wu et al., 2019; Wu and Defraeye, 2018)	CFD model	Process evaluation and effects of packages	Air velocity, temperature history, cooling time, quality loss
	(Mukama et al., 2017)	Experiment	Effects of packages	Airflow resistance, cooling time, energy consumption, energy coefficient
	(Ambaw et al., 2017)	CFD model	Effects of packages	Temperature history, cooling time, heat transfer coefficient, fields of air velocity, pressure, and temperature
Cauli- flower	(Mukama et al., 2019)	Experiment	Dynamics of quality loss	Weight loss, cooling time, quality loss
	(Le Bideau et al., 2018)	One-dimensional numerical model and experiment	Process evaluation and mechanism clarification	Temperature history, mass loss, air velocity
Spherical produce	(Dehghannya et al., 2011)	CFD model	Effects of packages	Temperature field, cooling heterogeneity, temperature history
	(Dehghannya et al., 2012)	CFD model	Effects of packages	Temperature field, cooling heterogeneity, temperature history, cooling time

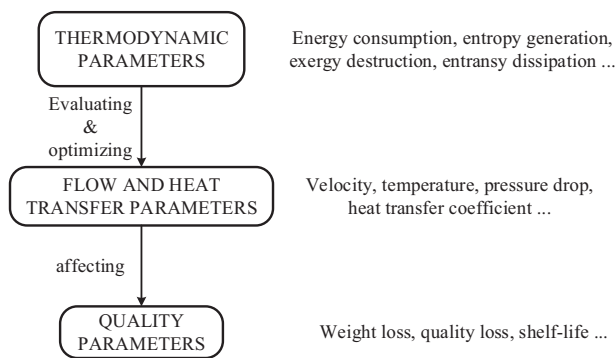


Figure 1. Interaction among different evaluation parameters.

metrics and constructal theory are respectively introduced for advanced evaluation and optimization of air-based precooling methods for higher postharvest quality. The main concluding remarks are as follows:

- (1) The research on room cooling was initially focussed on experiments and turned to numerical simulation in recent years. In comparison with room cooling, there was more research by either experimental or numerical methods on forced-air cooling with a wider range of products, and the packaging design was the main research focus.
- (2) Current performance evaluation of air-based precooling methods is limited to apparent parameters such as air velocity, temperature, cooling time, quality attributes, and their statistical characteristics and derivations. The optimization method is a posteriori based on performance evaluation and comparison.
- (3) Advanced evaluation and optimization methods should be considered from the interdisciplinary perspective. The thermodynamic evaluation metrics and constructal optimization method are widely used in various domains including data centre cooling. This results in a possible application to solve the similar problem of airflow maldistribution for air-based precooling methods.

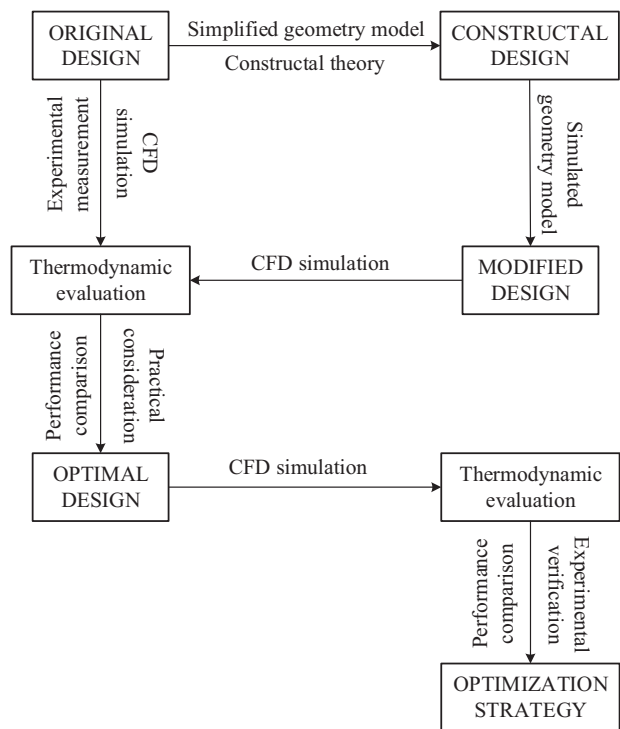


Figure 2. Scheme of advanced evaluation and optimization for air-based precooling methods.

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