An overview of recent advances in cooling techniques for fresh fruits and vegetables

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Abstract: Postharvest cooling techniques applied for fresh fruits and vegetables (FFVs) have received considerable research efforts in the recent years. The research efforts have been geared towards reducing respiration rate, weight loss, and water loss during cooling whilst reducing field heat and microbial activity in FFVs. Some recent advances including the application of disinfectants such as chlorine dioxide (ClO_2), 1-methylcyclopropene (1-MCP) and calcium chloride ($CaCl_2$) in hydrocooling, modification of air flow pattern and vent design during forced air cooling, and integration of vacuum cooling with modified atmosphere system have been applied as effective methods in reducing respiration rate and weight loss, producing enhanced quality of cooled fruits and vegetables. However, information on the recent advances in cooling techniques of FFVs would be of great benefits to the food engineers and food industries.

Keywords: postharvest, fruits and vegetables, cooling techniques, advances, respiration rate, weight loss

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1 Introduction

Cooling is one of the methods of ensuring freshness and high quality of fresh fruits and vegetables (FFVs), and is the modest method of preservation for many years (Alabi et al., 2020, 2021, 2022; Carlos et al., 2018; Ferreira et al., 2018; Zhu et al., 2019). Cooling of FFVs has been accomplished by traditional room cooling (TRC). Several studies have discussed the problems associated with TRC method. The method can change important physical (i.e. size and color), nutritional (i.e. vitamins and minerals), and sensory (appearance, odor, taste, texture, and overall acceptance) properties (Kochhar and Kumar, 2015). Besides, TRC gives little scope to further processing or storage after cooling for minimal quality degradation (De et al., 2020; Kochhar and Kumar, 2015). The uncontrolled-slow cooling process is a main cause for quality degradation. Increasing the cooling process has great potential for improving the quality of cooled products. In the recent years, the production of cooled FFVs by the use of innovative cooling techniques has received much attention among consumers due to minimal quality and weight loss (Garrido et al., 2015; Gleice et al., 2019; Lomeiko et al., 2019; Ribeiro et al., 2018; Zainal andPhebe, 2018).The innovative cooling techniques, which base on the phenomenon of heat transfer from cellular materials by partial contact, or by immersion in water (hydro), are applied to: (i) lowering temperature of harvested products, or removal of field heat, (ii) reducing senescence, and (iii) lowering microbial activities, producing better quality final product when compared with TRC method. The techniques hydrocooling, forced air cooling, and vacuum cooling (VC) have been

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reported to positively impact cooling processes of cellular foods (Alabi et al., 2021). Kochhar and Kumar (2015) reported that hydrocooling offered low physiological loss in weight and reduction in shivering of cooled stored broccoli. In the same way, forced air cooling have been reported as having a great potential in lowering the temperature of polylined kiwifruit faster than TRC (Sullivan et al., 2017), and significantly enhanced the color and firmness of cooled broccoli after 15 days of storage (Kochhar and Kumar, 2015). Furthermore, VC technique has been applied to preserved quality of porous food materials such as Broccoli (Carlos et al., 2018), Pakchoi (Zhu et al., 2020) and cherry fruits (Lomeiko et al., 2019). With all the above benefits, there are some recent improvements on the techniques that enhance their applications. Therefore, the current study presents an overview of the recent advances in cooling techniques for FFVs.

2 Significance of cooling FFVs

FFVs deteriorate immediately after harvesting due to active respiration and transpiration metabolisms, and consequently lead to loss of water, weight, and turbidity (Devani etal., 2011; Rab et al., 2013).Living plant cells consume sugars, starches and moisture and give out carbon dioxide and heat as by-products. If the heat is not removed, it can be re-absorbed, causing molds growth on the produce. On the other hand, mechanical damages like cut or crack can promote these processes, leading to loss of sensory and nutritional quality (Garrido et al., 2015; Song et al., 2016; Zainal et al., 2019). However, these losses affect the freshness and market value.

As mentioned earlier, cooling can be described as an act of lowering temperature and respiration process of FFVs in order to preserve their quality. In most cases, cooling enhances optimal storage life. Regardless of optimal storage conditions, delaying at reducing field temperature of about 35^{o}C, normally lead to a loss of shelf-life of about one day for most fresh cellular foods (Garrido et al., 2015). Importantly, the cooling technique varies among biological products because of their characteristics. According to the FAO (2015) bulletin, particularly Horticulture section, berries, grapes, mango, lettuce, cabbage, pepper, peas, spinach etc., require prompt cooling to maintain high quality during further processing(FAO, 2015). Some important fruits like banana require special ripening treatment and thus not cooled.

2.1 Some benefits of cooling

Cooling reduces workload of a refrigeration and frozen storage.

Cooling decreases rate of respiration, and the enzymatic activity, thereby, prevents softening, water loss, and wilting.

Cooling prevents microbial growth, such as bacteria and fungi, thus prevents decay at storage.

Cooling delays chilling injuries.

Cooling inhibits ethylene production and the impact on ethylene sensitive produce.

3 Recent advances in cooling techniques

3.1 Hydrocooling

Hydrocooling method has great benefits for the preservation of FFVs, especially in hot climate regions. Hydrocooling method is considered extremely important and efficient for reducing the temperature, maintaining the quality, and increasing the shelf life of FFVs (Manganaris et al., 2007; Shen et al., 2012). It consists of ice or cold water. Hydrocooling technique is simple, and easy to apply. The technique removes field heat, slows down respiration and transpiration metabolisms and reduces postharvest deterioration of FFVs (Ribeiro et al., 2018).Besides cooling, hydrocooling cleanses product from dirt and chemical contaminants (Elansari, 2009).Studies that evaluated the efficiency of hydrocooling on some FFVs showed satisfactory results that delayed wilting, increased turbidity and reduced water loss in lettuce leaves (Ribeiro et al., 2018), litchi (Shen et al., 2012), and rockmelon fruit (Zainal et al., 2019). In general, hydrocooling is beneficial to high surface to volume ratio (i.e. amaranths) and low surface to volume ratio commodities (i.e. cucumber), making the technique explicitly dynamic (Chepngeno et al., 2015). Cucumber hydrocooling with water temperature above 10°C improves surface color when compared to non-hydrocooled samples after 10-12 days of storage (Elsisi et al., 2020). Evaluation of the effect of water temperature on quality of hydrocooled products have showed that water temperature is directly related to the appearance of surface chilling injury, and vary in plant-based food materials (Ribeiro et al., 2018).

Water temperatures below 6°Care known to be the threshold temperature for chilling (Cantre et al., 2017). Amaranths quality and postharvest shelf life can also be improved with hydrocooling. Hydrocooling leafy vegetables delayed pericarp browning and improved the overall quality of the leaves after storage (Gleice et al., 2019). Many hydrocooling systems are commercially available for large scare farming operations. They are typically expensive and have short life span. Moreover, hydrocooling with contaminated water can add microorganisms (i.e. bacteria and fungi) to products being cooled thereby pose serious danger to consumers. In developing countries where there exist many small scales horticultural farmers cannot avoid the technique and depend on unsafe running water, which is mostly seasonal. The unsafe water applied by small scale farmers has limited the application of hydrocooling technique by the small scale farmers. However, research efforts have been geared towards the discoveries and use of disinfectants in hydrocooling. Among numerous disinfectants discovered, 1-methylcyclopropene (1-MCP), Chlorine dioxide (ClO_2), Calcium chloride ($CaCl_2$), and Sodium hypochlorite (NaOCl) have been proved to be infective in antimicrobial, antioxidant, and inhibition of ethylene production (Zhao et al., 2018). The benefits and limitations of the available disinfectants used during hydrocooling of FFVs are presented in Table 1.

Table1Some disinfectant(s) used during hydrocooling of FFVs

Disinfectant	Advantages	Limitations
1-MCP	Fast surface cooling, inhibit ethylene production	Unstable in liquid phase
ClO_2	Antimicrobial, antioxidant, keeping quality, prevent decay during further storage	Induce pigment changes
$CaCl_2$	Anti-browning	
NaOCl	Rapid cooling, reduce loads of yeast and molds	

Note: Where ClO_2 = Chlorine dioxide; 1-MCP = 1-methylcyclopropene; $CaCl_2$ = Calcium chloride; NaOCl= Sodium hypochlorite

However, the limitation in the use of 1-MCP during hydrocooling is that, it is unstable in liquid phase and induces pigment changes during the cooling process (Ghan et al., 2021). Meanwhile, 1-MCP can be integrated with α-cyclodextrin to maintain its stability, as demonstrated in the cooling of ‘Bartlett’ fruit (Ghan et al., 2021; Zhao et al., 2018). This development served as a main step towards commercialization of 1-MCP hydrocooling of FFVs. Therefore, food regulatory bodies have given approval on the use of 1-MCP technology worldwide. Similarly, application of ClO_2 remarkably alleviates certain physiological disorders, like chilling injury of avocado (Ghan et al., 2021), inhibits growth of postharvest pathogens (bacteria and fungi).

Moreover, the use of $CaCl_2$ in hydrocooling remarkably reduces weight loss and increase volume, and gave best storage characteristic of tomato, when compared with samples cooled under hydrocooling and force air cooling, resulting in increase in shelf life up to 13 days (Chandra et al., 2012).

De et al.(2020) evaluated and compared room cooling (RC), forced air cooling (FAC) and hydrocooling with sanitizer (sodium hypochlorite; NaOCl) HS treatment of peaches to reduce their surface microbial population and to determine the effect of the cooling methods on shelf life and microbial quality. The findings revealed that average aerobic plate count 5.29 log cfu/peach, and average yeast and mold counts 6.21 log cfu/peach for fresh samples remain unchanged after RC or FAC but reduced significantly (p<0.05) to 4.63 log cfu/peach and 4.05 log cfu/peach, respectively after HS treatment.

3.2 Forced air cooling

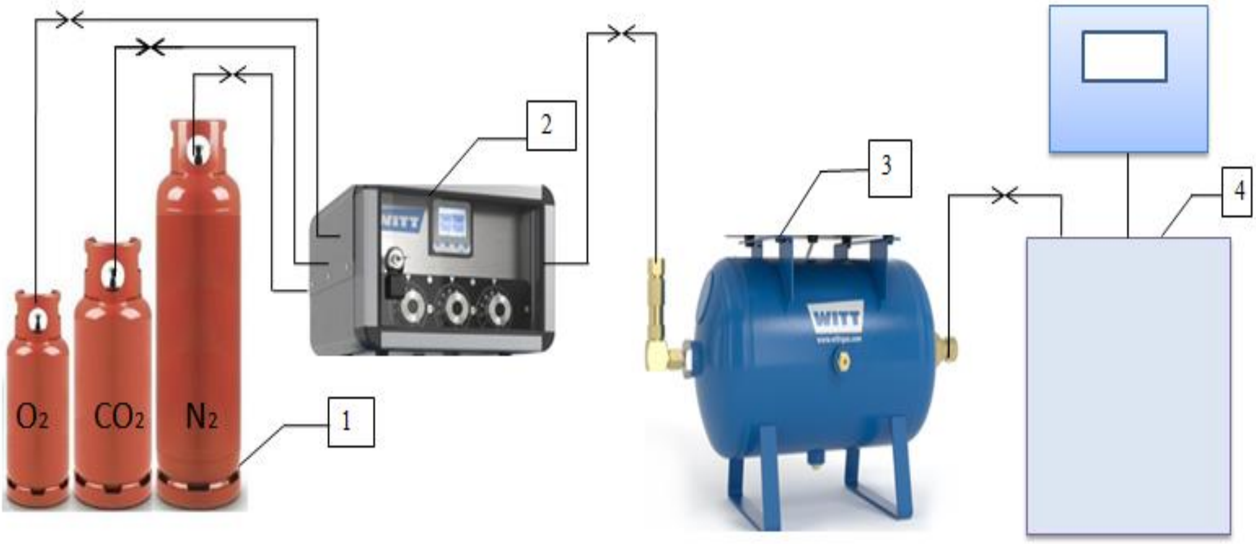
Forced-air cooling technique is another cooling method applied to all kinds of horticultural products (Aswaney, 2007; Garrido et al., 2015; Gong et al., 2021; Kochhar and Kumar, 2015; Sullivan et al., 2017). However, performance of forced-air cooling, in terms of cooling rate, quality preservation and energy consumption, is affected by several parameters. For instance, cooling rate depends on the geometry (size and shape), composition, and cell arrangement. This is because heat is transfer across food products mass as it varies with main fruits and vegetables(Kumar et al., 2008).In general, big size products cause slow cooling, due to a long distance required for heat transfer through the sample mass. On the other hand, small size products promote fast cooling (Alabi et al., 2020; Kumar et al., 2008).Typically, the cooling rate is influence by air characteristics (i.e. temperature, velocity and relative humidity) inside a cooling chamber (Han et al., 2017). Studies on airflow characteristics and temperature distribution inside a cooling chamber revealed the mechanisms occurring during forced-air cooling (Salamat et al., 2020). The complexity cellular food materials make the analysis of heat and mass transport during cooling a difficult task. Nowadays, advances in computational fluids dynamics (CFD) simulation tool has been applied to depict a realistic results of air flow pattern and temperature drop during the cooling process of apple (Han et al., 2017), mushroom (Salamat et al., 2020) and main fresh produce (Zhao et al., 2016). Although, CFD tool has been applied to modeling heat transfer during forced-air cooling, with successful prediction on cooling rates of cellular foods, the tool still lacks the capability to model and analyze quality degradation.

In addition, as forced air cooling technique is gaining much research attentions, modification of air flow pattern and optimization of vent design of packaging systems to improve cooling uniformity and reduce energy consumption have been reported (Gong et al., 2021; Jia et al., 2021). This development increases cooling uniformity, reduces cooling time, resulting in lower energy consumption and weight loss during forced-air cooling of strawberry (Nalbandi and Seiiedlou, 2020) and apple (Gong et al., 2021).

3.3 Modified atmosphere vacuum cooling (MAVC)

For decades, VC is used as fast cooling technique for porous food items to achieve desired cooling goals. VC has been applied as an effective technique for cooling certain types of FFVs to prolong their storage life (He et al., 2013a; He et al.,2013b; McDonald and Sun, 2000; Song et al., 2016). In the last decade, VC has been successfully applied in conjunction with modified atmosphere method for some fresh vegetables to improve the cooling efficiency by elevating concentration of carbon-dioxide (CO_2) and reducing oxygen (O_2) level, thereby lowering the activity of microorganisms. Recently, researches have highlighted the potential of modified atmosphere vacuum cooling (MAVC) for leafy vegetables (Zhu et al., 2018), for which MAVC is beneficial to provide optimum gas composition, control the growth of micro-organisms, thus maintaining the quality of products that are cooled under MAVC. Meanwhile, products (such as mango, tomato and okra) with thick barrier to moisture transfer from the surface, or low ratio in the surface area and the mass, are not suitable for MAVC, hence limited its application. MAVC, as the name implies, is based on gaseous modifications and liquid evaporation (through a pressure-refrigerating system) to produce a cooling effect. The difference between MAVC and VC techniques is that for the MAVC, the cooling effect is done by evaporating some water from produce under controlled atmosphere, rather than by evaporating water from the product directly (Zhu et al., 2019). MAVC is novel among others emerging cooling techniques. It consists of cylinders, gas mixer, gas tank and VC chamber, as shown in Figure 1.

Gas optimum compositions of 7% O_2, 7% CO_2, and 86% N_2have been successfully applied to vacuum cooled three different leafy vegetables including flowering cabbage, Chinese cabbage and green cabbage from ambient temperature to 4°C (Zhu et al., 2018). The conditions achieved preservation of color, vitamin C and reduced the rate of respiration of the three leafy vegetables during storage at 4°C for 21 days. However, leaf morphology does not affect gas retention during MAVC, whereas intercellular spaces of leaves affect the cooling process and the final quality. So far, MAVC has been successfully applied to remove field heat of horticultural products in China and the United States in the recent years, and proved to be effective method for cooling mushroom and cabbage.



(1) – cylinders, (2)-gas mixer, (3)- gas tank, and (4)- vacuum cooling chamber

Figure 1 A typical set up diagram of MAVC system

4 Emerging cooling technologies

Solar cooling (SC) is an emerging technique for cooling FFVs. SC consists of solar collectors and cooling unit. SC can be achieved using the thermal energy of the sun as an energy source (Henning, 2012; Islam and Morimoto, 2011). The technique is becoming widespread in preservation of fresh food materials because of its eco-friendly characteristics (Kumar et al., 2018). Studies on the performance of SC have been consistently investigated and are available in the literatures (Aljabair et al., 2019; Núñez et al., 2007; Ruziewicz et al., 2015; Singh et al., 2017). Some experimental and numerical studies based on evaporative cooling were performed on SC of horticultural produces (Heleyleh et al., 2014;Samuel et al., 2016;Chinenye and Manuwa, 2014). In all the investigations, there exist satisfactory results in terms of efficiency and the cost. Moreover, the available literatures that focus on the SC processes of FFVs have reported that the technique enhances energy and reduce its dependence on the electric power supply. Ruziewicz et al.(2015) performed an experiment on hybrid solar-powered cooling system with traveling wave acoustic refrigeration to enhance the preservation of FFVs. In general, there are three main SC techniques viz: (1) concentrating SC system, (2) photovoltaic SC system, and (3) geothermal cooling system.

Concentrating solar cooling (CSC) involves solar tracking device that can collect maximum radiation to enhance cooling process, particularly in temperate region where solar energy resources are abundant or rural areas where electricity is not frequent and expensive (Plessis et al., 2015). This technique is relatively expensive when compared to conventional cooling methods and further research and development is required on this emerging technology for food cooling process. Alternative ways to enhance the effectiveness of CSC is consideration of, either the elements of the main component, or the entire design.

On the other hand, photovoltaic (PV) technique enables sun energy to be directly converted into electrical power for use in cooling process. Sharma and Mansuri(2017) reported that a PV cooling system can maintain FFVs temperature at 10°C-15°C below ambient, as well as at a relative humidity of 90%, depending on the season.

Typically, the efficiency of a PV cooling system is dependent on numbers of factors including the location and areas of the panels, and cooling requirements (Lal et al., 2013). The choice of appropriate panel area and characteristics is often based on the energy demand and the cooling load (Samuel et al., 2016). When applied in greenhouse vegetable cooling, larger PV panels can cause extensive shade, promote plant stress in hot climates, affecting plant quality Obura et al., 2015). But when PV panels are installed and applied properly with cooling system, they can preserve FFVs. Al-Ibrahim et al.(2006)used a PV panel of 14.72 kW for evaporative cooling, and satisfactorily cool a 9 x 39 m greenhouse. Similarly, Ganguly et al.(2010) demonstrated that SC plant that consist a fan, pad evaporative system, and PV panels, provided the coolness required for a 90 m^2 greenhouse. With these benefits, the PV panel forms a remarkable mean for powering cooling systems in a sustainable way. Nowadays, the use of PV panel-assisted cooling technique has expanded thanks to the decrease in the photovoltaic equipment cost. The positive results of the PV panel-assisted cooling technique allow this sustainable technology to be promptly implemented worldwide.

Furthermore, geothermal cooling technique is one of the main emerging cooling techniques for FFVs. The technique consists of underground pipes dung inside the earth at depth up to 100 m (Rabbi et al., 2019). The technique uses the relatively stable low-temperature earth surface as heat exchanger medium to deliver cooling in warm or hot food materials, usually fluids or materials that has flow characteristics (Rabbi et al., 2019). The earth-air heat exchanger techniques are scantly reported and studies that will guarantee its use in the food industry need urgent attention.

5 Conclusion

A wide range of cooling techniques exist to maintain and extend shelf life of FFVs. Specific techniques may only be applicable to certain types of products and the effectiveness of existing techniques on quality issues need to be assessed. Postharvest cooling techniques, such as hydrocooling, forced air cooling and MAVC are the emerging cooling techniques for preservation of FFVs. Some recent technologies like SC systems based on CSC, PV and geothermal are available. Research on these technologies is continuing on a range of FFVs. Research in SC represents a new era where solar energy is applied in a dynamic way, recognizing that the response of plants to varying climatic conditions, mainly temperature, radiation and humidity, change in response to the applied SC method. To date, use of SC is limited but the application of sun energy to the postharvest preservation may open new opportunities. For instance, the development of a mobile SC device can allow better matching between the demand for cold storage and the transportation system, in a situation where the field is farther away from cold storage. Future research in development of mobile or portable SC system will not only improve efficacy of postharvest preservation but also address the transportation and energy issues.

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Author contributions

KPA conceptualized, wrote, and edited the manuscript

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