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# Transpiration and moisture evolution in packaged fresh horticultural produce and the role of integrated mathematical models: A review

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## Abstract

Transpiration has various adverse effects on postharvest quality and the shelf-life of fresh fruit and vegetables (FFV). If not controlled, the water released through this process results in direct mass loss and moisture condensation inside packaged FFV. Condensation represents a threat to the product quality as water may accumulate on the product surface and/or packaging system, causing defects in external appearance and promoting growth of spoilage microorganisms. Thus, moisture regulation is extremely important for extending FFV shelf-life. This review focuses on transpiration phenomenon and moisture evolution in packaged fresh horticultural produce. It provides recent information on various moisture control strategies suitable for packaging of fresh horticultural produce. It also provides an evaluation on the role and application of integrative mathematical modelling in describing water relations of FFV for packaging design, as well as, an overview of models reported in literature.

**Keywords:** Moisture loss; packaging; humidity control; mathematical modelling; fresh produce; condensation

## 1. Introduction

Fresh horticultural produce are highly perishable commodities, as they remain metabolically active even after harvest. Fresh produce continues to lose water due to transpiration and respiration process. This turns produce shelf-life into a race against the clock for growers, processors, and retailers to maintain quality and reduce food loss (Mahajan, Caleb, Singh, Watkins, & Geyer, 2014). This water loss is usually associated with economic loss since it causes a decrease in saleable mass, due to shrivelling of the product (Caleb, Mahajan, Al-Said, & Opara, 2013; Veraverbeke, Verboven, Van Oostveldt, & Nicolaï, 2003b). In addition, moisture loss of the fresh produce can accumulate on the product surface and/or packaging system, causing defects in external appearance and promoting growth of spoilage microorganisms (Kang & Lee, 1998; Linke & Geyer, 2013). This leads to quality deterioration and flavour loss. Hence, it is important to remove or avoid moisture condensation on the product in order to maintain quality and prevent the growth of spoilage-causing microorganisms (Powers & Calvo, 2003).

According to Fonseca, Oliveira, and Brecht (2002) the goals of postharvest technology are to maintain freshness quality and reduce losses in the postharvest value chain of fresh fruit and vegetables (FFV). Temperature control and modification of atmosphere are important factors to extend a products shelf life (Fonseca et al., 2002). Nevertheless, besides these two factors the control of storage or in-package relative humidity (RH) is of critical importance (Tano, Oulé, Doyon, Lencki, & Arul, 2007). For example, Rux et al. (2015) investigated the transpiration behaviour of mushroom under different temperature and RH, and determined the effect of salt embedded humidity-regulating tray on in-package humidity and condensation behaviour. The authors reported that the humidity-regulating tray absorbed part of the water vapour produced by mushroom during the 6 d of storage, but its regulatory capacity was not efficient to avoid in-package moisture condensation. Therefore, understanding the physiological response of individual fresh horticultural produce towards optimum packaging/storage system design with adequate humidity control is one of the keys to achieving the postharvest technology goals.

Furthermore, mathematical modelling plays an important role in predicting the physiological response of FFV under different storage conditions. Mathematical models offer the possibility to describe characteristic changes in biological systems as a function of different environmental conditions, without the need to access these conditions in real time (Castellanos & Herrera, 2015). This makes it possible to optimise packaging design under different storage conditions for FFV (Kang & Lee, 1998), and to estimate the packaging requisites for specific fresh produce (Caleb et al., 2013; Sousa-Gallagher, Mahajan, & Mezdad, 2013).

In this context, the aim of this article is to provide a comprehensive review regarding the transpiration phenomenon and moisture evolution inside packaged fresh horticultural produce. The role and application of integrative mathematical modelling in describing water relations of fresh horticultural produce for packaging design is discussed. In addition, an overview of the various moisture control strategies, mathematical models reported in literature, and future prospects is presented.

## 2. Transpiration phenomenon in fresh horticultural produce

Transpiration is a critical physiological process for FFV (Xanthopoulos, Athanasiou, Lentzou, Boudouvis, & Lambrinos, 2014). Once separated from the mother plant, FFV cannot replace water from the plant and/or soil and depend on their own water content for transpiration and organic substrate for respiration (Caleb et al., 2013). Transpiration phenomenon involves three main stages: i) moisture is transported as liquid and vapour from intercellular spaces to and through the skin of the product; ii) moisture is evaporated from the outer surface layer of the product; and iii) convective mass transfer of the moisture to the surroundings (Becker & Fricke, 2001; Veraverbeke, Verboven, Van Oostveldt, & Nicolaï, 2003a). In terms of plant physiology there are four FFV components involved in the transpiration process this include: a) intercellular air spaces, through where water vapour diffuses inside the FFV; b) cuticle, responsible for the transpiration in which liquid water moves to the cell walls on the cuticle side of epidermal cells; where it can evaporate and the vapour is then diffused across the cuticle; c) stomata, through where water vapour diffuses in order to reach the boundary layer; and, d) boundary layer, which is located at the leaf surface and is the final component encountered by diffusing water vapour (Nobel, 2009).

Transpiration is driven by a concentration difference and can be described in terms of water activity differences across the membrane, moisture concentration and water vapour pressure differences between a product´s surface and its surrounding (Becker & Fricke, 2001; Veraverbeke et al., 2003a, 2003b). Based on this definition, there should theoretically be no potential for transpiration phenomenon at 100% RH (i.e. saturated storage condition) and constant temperature since there is no water vapour pressure difference. However, this is not the case for saturated conditions as transpiration occurs due to the heat generated by the respiration process (Becker & Fricke, 1996; Sastry, Baird, & Buffington, 1977; Tano, Kamenan, & Arul, 2005). Recently, Mahajan et al. (2016) investigated the moisture loss behaviour of three different FFV and a dummy evaporation sphere stored at 13 °C, 100% RH. Results showed that despite water vapour saturation the three tested products lost mass at 100% RH, while no mass was lost from the evaporating sphere. These results agree with the hypothesis that respiratory heat can significantly influence moisture evolution from FFV under saturated conditions. This implies that transpiration in packaged fresh produce continues where water vapour saturation is commonly observed. It also indicates that the transpiration process under saturated conditions is a complex process that involves different heat components including respiratory heat generated by the product; evaporative cooling effect on the product´s surface; convective heat transfer between the product and its surrounding environment.

**2.1. Potential effect on postharvest quality of fresh horticultural produce**

Transpiration phenomenon causes both water loss and evolution of free water from FFV, which may lead to formation of moisture condensation on the surface of product and/or packaging material. The free water, also known as moisture, facilitates the growth of fungal and bacterial pathogens (Holcroft, 2015; Linke & Geyer, 2013). Water loss results in direct mass loss, shrivelling, gloss reduction, limpness and wilting of horticultural produce. As the produce continues to lose water, its appearance, quality, shelf life, profitability, and consumer appeal diminishes (Holcroft, 2015; Thompson, Mitchell, Rumsay, Kasmire, & Crisosto, 1998).

Water loss affects FFV in different degrees. According to Holcroft (2015), leafy vegetables wilt after approximately 3 - 5% of water loss, while for nectarines shrivelling occur after 19% of water loss. There is extensive literature stating the maximum permissible water loss (%) for a wide range of FFV (Kays & Paull, 2004; Robinson, Browne, & Burton, 1975; Thompson et al., 1998). For instance, the maximum permissible mass loss for grape and nectarine is 5% and 21%, respectively (Kays & Paull, 2004). For summer squash the permissible mass loss is 24%, while for broccoli and carrot with leaves it is 4% (Thompson et al., 1998). Also, fresh produce response to transpiration such as biochemical, microbiological, and physiological changes contribute to quality degradation. These responses are usually temperature dependent and affect transpiration of FFV and low RH can raise transpiration damage leading to dehydration, increased respiratory intensity, and loss of product quality (Castellanos &

Herrera, 2015). Therefore, optimum temperature and RH should be maintained for each product in order to extend shelf-life and maintain products quality.

### 2.2. Transpiration measurement

Water loss from FFV, also known as moisture loss or transpiration phenomena, is often expressed as the percentage change in mass of the original or initial product mass. The quantity of water loss over a given period of time is considered as the water loss rate, also referred to as rate of moisture loss or transpiration rate (TR) (Maguire, Banks, & Opara, 2001). Calculation of the TR based on moisture loss per unit time is the most used and reported method to describe transpiration phenomenon in fresh horticultural produce (Caleb et al., 2013; Castellanos & Herrera, 2015; Mahajan, Oliveira, & Macedo, 2008a; Shirazi & Cameron, 1993; Sousa-Gallagher et al., 2013).

However, there are two main possible approaches to calculate TR of fresh produce. The first approach is by gravimetric measurement of change in product mass over time. The second approach is based on theoretical determination of TR, via the Fick's law of diffusion. It is worth mentioning that the gravimetric measurement of TR is used by many authors to find other parameters, such as the transpiration coefficient and/or tissue and boundary layer resistance that better describes the transpiration phenomenon (Linke, 1997; Sastry & Buffington, 1983; Thompson et al., 1998).

#### 2.2.1. Gravimetric approach

The most commonly reported method for measuring TR is by the gravimetric approach, also known as the mass loss approach, which involves periodically weighing the produce at a given temperature and RH. TR can be directly calculated per unit surface area ($TR_s$) (Eq. 1) and/or per unit of initial mass ($TR_m$) (Eq. 2) of the produce:

$$TR_s = \frac{M_i - M_t}{t \, . \, A_s} \tag{1}$$

$$TR_m = \frac{M_i - M_t}{t \, . \, M_i} \tag{2}$$

where $M_i$ is the initial mass of the product; $M_t$ is product mass at a determined time (t); and $A_s$ is the initial surface area of the product. Usually $TR_s$ is commonly expressed in mg cm$^{-2}$ h$^{-1}$ or mg cm$^{-2}$ s$^{-1}$ and $TR_m$ in g kg$^{-1}$ h$^{-1}$, mg kg$^{-1}$h$^{-1}$ or mg kg$^{-1}$s$^{-1}$.

Different experimental methods have been reported for the measurement of TR by the mass loss approach (Fig. 1). In some setups, the balance was located outside the experimental container, which limits continuous measurement of product mass loss. In these cases the product has to be taken out of the container to be measured and opening of the container can result in disturbance of internal atmosphere and RH if it is not carried out with caution (Xanthopoulos et al., 2014). In the experiment conducted by Kang and Lee (1998), the chamber was equipped with gas control to maintain the desired oxygen ($O_2$) and carbon dioxide ($CO_2$) concentration in order to incorporate the effect of modified atmosphere as one of the parameters of TR for apples and minimally processed cut vegetables. A novel setup was considered by Mahajan et al. (2016) in their study. The authors included an additional infrared temperature sensor to monitor the products' surface temperature and a sensor for the surrounding environmental conditions.

### 2.2.2. Theoretical approach

It is well established that transpiration can be visualised as the interaction between a driving force for mass loss and resistance (Becker & Fricke, 1996, 2001; Leonardi, Baille, & Guichard, 2000; Sastry, 1985; Sastry & Buffington, 1983). This interaction is expressed mathematically as:

$$\boldsymbol{TR_m} = \boldsymbol{k_t} \,.\, (\boldsymbol{P_s} - \boldsymbol{P_\infty}) \tag{3}$$

where $TR_m$ is transpiration rate, mass basis (mg kg$^{-1}$s$^{-1}$); $k_t$ is transpiration coefficient assumed constant for a specific product (mg kg$^{-1}$ s$^{-1}$ MPa$^{-1}$); $P_s$ is water vapour pressure at the evaporating surface of the product (MPa); and $P_\infty$ is ambient water vapour pressure (MPa). In this mathematical equation the driving force for transpiration is represented by ($P_s$ - $P_\infty$), which is also known as the water vapour pressure deficit (VPD), and the resistance represented by the inverse of the transpiration coefficient ($k_t$). The $k_t$ can be divided into two terms, as follows:

$$\frac{1}{k_t} = \frac{1}{k_s} + \frac{1}{k_a} \tag{4}$$

where $k_s$ is skin mass transfer (transpiration) coefficient (mg kg$^{-1}$ s$^{-1}$ MPa$^{-1}$) and $k_a$ is air film mass transfer (mg kg$^{-1}$ s$^{-1}$ MPa$^{-1}$), also known as convective mass transfer coefficient or external mass transfer coefficient. Combining Eq. 3 with Eq. 4 yields:

$$TR_m = \frac{P_s - P_\infty}{\frac{1}{k_s} + \frac{1}{k_a}} \tag{5}$$

What differ among authors in using Eq. 5, are the factors and assumptions that are considered important or negligible in order to calculate $k_s$ and $k_a$. In Sastry and Buffington (1983), these coefficients were represented by $k_s = \frac{\tau}{\delta\varphi}$ and $k_a = \frac{1}{h_d}$, where $\delta$ is the diffusion coefficient of water vapour in air; $\tau$ the product skin thickness; $\varphi$ is fraction of product surface covered by pores; and $h_d$ is convective mass transfer coefficient. In contrast, Fockens and Meffert (1972) expressed skin mass transfer coefficient as $k_s = \frac{\xi_1 \beta}{R_D T}$ and air film mass transfer as $k_a = \frac{\xi_2}{1/\beta + \mu s/\delta}$, where $\xi_1$ is a fraction of surface behaving as a free water zone (non-dimensional); $\beta$ is a convective mass transfer coefficient (m $s^{-1}$); $R_D$ is a universal gas constant (J $kg^{-1}$°$C^{-1}$); $T$ is the ambient temperature (°C); $\xi_2$ fraction of surface behaving as porous membrane (non-dimensional); $\mu$ is resistance factor (non-dimensional); $s$ is skin thickness (m); and $\delta$ is diffusion coefficient of water vapour in the air ($m^2$ $s^{-1}$).

Different ranges of transpiration coefficients are shown in Table 1. Limitations of using transpiration coefficients are that they are restricted to certain range of experimental conditions; and often product specific. For example, there is a significant difference in transpiration coefficient of carrot ranging from 106 to 3250 mg $kg^{-1}$ $s^{-1}$ $MPa^{-1}$, based on various assumptions adopted in the calculation (Linke & Geyer, 2001). Also, different experimental methods are used for determining the transpiration coefficient, which results in different values even for the same product (Sastry & Buffington, 1983). However, Eq. 3 is a simple mathematical equation that can be used to predict the TR of a specific product. In order to use this equation details on transpiration coefficient of the specific product and the calculated water pressure difference between the FFV and surrounding environment are required. To determine the ambient water vapour pressure, psychrometric charts, which relate temperature, RH and water vapour pressure can be used.

A similar approach to determine the TR of FFV is by the use a known tissue and boundary layer resistance. Figure 2 presents the dynamics of water loss rate during the postharvest storage of FFV in this approach at constant heat and mass transfer conditions, and under pre-defined experimental conditions. The first section is characterised by the atmospheric evaporation of free surface water from the product. In this case the intensity of transpiration is solely dependent on the boundary layer resistance. However, when free water is no longer on the surface, water is transported from inside the produce to the surface, but with an additional resistance due to internal membranes, called tissue resistance. This additional resistance is evident by the decrease in the slope of water loss rate over time as shown in the second section. At this point, the water potential of the produce is also reduced, as shown in the third section (Linke, 1997). The reduction in water potential is important because the flow of liquid and/or gaseous water out of a produce, tissue or plant cell, as well as the rate of water movement directly depends on the water potential gradient between the produce, tissue, or plant cell and the surroundings (Gomez Galindo, Herppich, Gekas, & Sjoholm, 2004: Nobel, 2009). Water potential can be defined as the free energy of water within the respective system, such as produce, tissue, plant cell, or solution compared to that of pure water (Rodov et al., 2010). Thus, water potential is indicative of the true water deficit of a system (Herppich, Mempel, & Geyer, 1999). In addition, in plant physiology, water potential is generally accepted as the best parameter to describe actual tissue water status (Herppich, Mempel, & Geyer, 2001).

In this approach the resistances in the water vapour pathway can be determined by using a modified Fick´s law in terms of resistances, as shown in Eqs. 6 and 7, while taking into consideration the conditions presented in section 1 and 2 (Fig. 2).

$$TR_s = \frac{x_p - x_A}{r_B + r_T} \tag{6}$$

where $TR_s$ is transpiration rate, area basis (mg cm$^{-2}$ s$^{-1}$); $x_P$ is volume related water content of air in the intercellular spaces in the centre of the produce (mg cm$^{-3}$); $x_A$ is volume related water content of the air unaffected by the produce (mg cm$^{-3}$); $r_B$ is boundary layer resistance in the water vapour pathway (s cm$^{-1}$); and $r_T$ is tissue resistance in the water vapour pathway (s cm$^{-1}$), which includes tissue and skin of the fruit or vegetable. However, the tissue resistance approach becomes negligible when produce surface is wet and therefore the following equation is valid:

$$TR_s = \frac{x_{ps} - x_A}{r_B} \tag{7}$$

where $x_{ps}$ is the water content of the air at the produce surface, mg cm$^{-3}$ (Fig. 3). Tissue resistance is determined by the nature of the plant tissue, which is exclusively dependent on the internal properties of the product, such as the water activity and sugar. Other factors influencing tissue resistance of horticultural produce include pre-harvest conditions and postharvest handling practices (Linke, 1997).

On the other hand, the boundary layer resistance is determined by the form of FFV epidermal layer. It is dependent on external parameters such as shape, dimensions, and surface structure of the product, as well as environmental conditions such as air flow conditions and surface temperature of the produce. For the determination of the boundary layer resistance the water loss rate has to be measured under natural convection. Once boundary layer resistance is known, tissue resistance can be determined by Eq. 6, as long as the centre of the produce is water saturated. In Table 2 it is possible to visualise different tissue resistance found by Linke and Geyer (2000). The boundary layer resistance for single produce items at unrestricted natural convection and room temperatures was in the range between 1 and 4 s cm$^{-1}$ for small and bigger FFV, respectively. Both theoretical approaches for estimating TR, via transpiration coefficient or tissue resistance, have specific limitations due to the different values found in the literature. However, they are very useful tools to calculate the TR of FFV since no experimental data is required.

### 2.3. Factors affecting transpiration

#### 2.3.1. Intrinsic factors

Fresh produce shape and size, expressed as surface area-to-volume or surface area-to-mass ratios, are major factors affecting the $TR_m$, especially the boundary layer resistance. Products with large surface area to mass ratios provide a considerable contact area with surrounding atmosphere. For example, horticultural products, such as leafy green vegetables and cauliflowers have higher $TR_m$, when compared to spherical produce such as oranges and tomatoes with lower surface area (Sastry, 1985). Similarly, morphological and anatomical characteristics of the FFV also have significant effect on TR, specifically on the tissue resistance. Surface structure for each FFV is unique and those which contain skin and/or a waxy coating such as apple, provide extra layers of resistance and therefore the water loss rate in this product is lower than for products without these structures such as mushroom (Sastry, 1985). The skin of FFV acts as a barrier to diffusion of water vapour (Maguire et al., 2001).

Purity level of water content in FFV can also affect the TR of the product. Water content in most FFV contains dissolved/soluble solids (i.e. total soluble solids). Literature has extensively shown that total soluble solids of FFV significantly differs (Beckles, 2012; Mahmood, Anwar, Abbas, Boyce, & Saari, 2012). Thus, vapour pressure at the evaporating surface is determined by Raoult´s law and is a little lower than the saturation water vapour pressure at the same temperature (Sastry, 1985). This effect is also known as the vapour pressure lowering effect since it causes a reduction in VPD and directly affects the TR.

Additionally, physiological condition, such as the maturity stage in fresh produce after harvest has been shown to significantly influence on TR. In general, immature and over mature fruit transpires more rapidly than optimally mature fruit due to the permeability of the skin to water vapour (Mishra & Gamage, 2007; Sastry, 1985). The developmental stages of the fruit therefore directly affect the tissue resistance of the product. However, factors are often eliminated as a variable on mathematical models of transpiration due to lack of a reliable quantitative maturity index (Sastry & Buffington, 1983).

### 2.3.2. Extrinsic factors

Impacts of factors such as temperature and RH on TR of fresh horticultural produce have been extensively investigated over the last decade. Mahajan et al. (2008a) found that by increasing the RH in the storage containers for whole mushrooms from 76% to 96%, TR decreased by 87% at 4 °C, whereas decreasing the temperature from 16 °C to 4 °C decreased the TR by 61% at 96% RH. Caleb et al. (2013) also showed that by increasing RH inside storage containers for pomegranate arils from 76% to 96%, decreased TR by 83.5% at 5 °C, while decreasing the temperature from 15 °C to 5 °C, TR decreased by 68.9%. Xanthopoulos et al. (2014) reported that the TR for grape tomatoes increased with temperature from 15 °C to 20 °C, while it decreased for RH 80% to 92%. These studies showed that humidity is the variable with the greatest effect on TR, and the magnitude of TR decrease is product dependent. Aguirre, Frias, Barry-Ryan, and Grogan (2009) expressed the visual quality of mushroom stored under different temperatures and humidity using VPD instead of the RH to avoid the interaction between temperature and RH. Although VPD is a conventional variable for refrigeration technology, package designers and food technologists usually employ the RH.

Airflow around fresh produce and/or through the packaged product, also have a significant influence on TR. Baltaci, Linke, and Geyer (2010) measured the water loss rate of artificial fruits (water filled evaporating spheres) inside a plastic box in three layers under natural convection and forced airflow (0.8 m $s^{-1}$). The authors showed that differences in TR were dependent on the produce position inside and airflow. They also found that TR was higher under forced airflow than under natural convective conditions. Air movement around the product prevents the development of a microenvironment with high-humidity build-up (Sastry, 1985), and this decreases the resistance of the air films to mass transfer.

Physical conditions and surface injuries such as cuts, bruises and scratches on the skin surface of FFV, tend to increase the TR, as they reduce the tissue resistance due to modification of the skin (Holcroft, 2015; Maguire et al., 2001). FFV have 2 to 3 times higher TR after harvest when compared to the steady state values due to the physical injuries caused by detachment from the mother plant (Sastry et al., 1977). However, during the storage period once the injuries are healed TR reduces to a lower and relatively steady value (Sastry, 1985).

Also, heat removed from the evaporating surface during transpiration causes a lowered surface temperature and therefore a decreased vapour pressure at the surface, reducing transpiration (Becker & Fricke, 1996). This effect, also known as evaporative cooling, is more noticeable at high water vapour pressure differences. In this situation evaporation has a considerable effect on the driving force and consequently on transpiration (Sastry, 1985). However, respiration increases the product´s surface temperature because of heat generation and this increases water vapour pressure at the surface, increasing transpiration (Becker & Fricke, 1996). This effect, also referred to as respiratory heat generation, is usually low for moderate water vapour pressure but can grow into a dominant factor at RH close to saturation. The respiration phenomena produces an additional mass loss due to carbon loss but it is considered negligible (Sastry, 1985).

## 3. Moisture evolution in packaged fresh horticultural produce

Packaging of FFV leads to accumulation of moisture in the headspace as it acts as an additional barrier for moisture transfer. The main source of this moisture is the product itself, however, temperature fluctuations along the supply chain also plays an important role for moisture evolution and condensation (Powers & Calvo, 2003). Factors affecting moisture transfer and RH in packaged fresh produce are water vapour permeability of the packaging films, transpiration and respiration of product, and storage conditions (Lu, Tang, & Lu, 2013). Therefore, selection of appropriate packaging materials is one of the essential steps for achieving optimum humidity conditions in packaged fresh produce.

The optimum humidity levels vary in each product, yet in order to reach the maximal postharvest life span it should be taken into account (Ben-Yehoshua & Rodov, 2002). For most FFV the storage conditions should be within 85% and 98% RH. Nonetheless, for products such as garlic and onion storage at RH higher than 70 to 75% at optimum temperatures results in excessive water absorption leading to rooting, mould development and sprouting (Rodov, Ben-Yehoshua, Aharoni, & Cohen, 2010). In the review by Paull (1999) the possible effects of temperature and RH on fresh commodity quality was extensively discussed. The author also provided a detailed summary of optimum RH and temperature as well as shelf life for a wide range of FFV.

Current modified atmosphere packaging (MAP) designs consider the respiration rate of products as the only important parameter when selecting target gas barrier properties. However, besides in-package gas composition, it is also essential to take into consideration the in-package humidity level. In order to avoid moisture condensation and accelerated growth of spoilage microorganisms (Caleb et al., 2013; Mahajan et al., 2014; Song, Lee, & Yam, 2001). The in-package humidity is determined by transpiration and respiration of the fresh produce and water vapour permeability of the packaging material. Most polymeric materials (polyethylene, polypropylene or polyvinyl chloride) used in MAP have lower water vapour permeability relative to the TR of fresh produce (Rux et al., 2016; Song et al., 2001). This leads to further development of MAP into a modified atmosphere and humidity package (MAHP) system, since evaporated water molecules from the produce are not effectively transmitted across the packaging film and prevail within the package. Hence, the challenge of designing an effective MAHP system is finding a solution to design optimal atmosphere and lessen the risk of in-package moisture condensation while still keeping produce mass loss as low as possible.

### 3.1. Moisture condensation dynamics

Condensation is the process in which water vapour turns into liquid form as a result of temperature differences (Joyce & Patterson, 1994). The temperature at which this process occurs is known as the dew point temperature (Holcroft, 2015). Condensate will be formed on any product that is at or below the dew point temperature of the surrounding air. For every temperature and RH combination at constant pressure, there is a specific and measurable dew point temperature and in order for condensation to appear the temperature has to fall only by a fraction of a degree (Joyce & Patterson, 1994). Therefore, dew point measurement is a very useful parameter to anticipate moisture condensation and develop control measures. It can be measured directly by means of special sensors or calculated from temperature and humidity following the known laws of psychometry. Condensation inside packaged fresh produce occurs when water molecules evaporated from the product surface do not transmit through the packaging film and stay within the package (Fig. 4). Horticultural produce specific shape, dimension and surface structure, as well as environmental parameters such as storage temperature, RH, and air flow conditions around the produce have a direct impact on the intensity of condensation process (Rodov et al., 2010).

Condensation inside packages of FFV represents a threat to the product quality and safety. It is almost inevitable to avoid moisture condensation in the entire postharvest supply chain due to temperature fluctuations. However, there are some recommendations that can be taken into account in order to minimise the condensation this include: i) storage of the product under strict temperature control; ii) maintenance of a continuous cold chain; iii) perform packaging operation under cold condition; iv) temperature conditioning of the packaging material; v) cool the product to above dew point temperature until they are packed and then cool it to the desired storage temperature; and, v) faster warming of cold fruit in order to reduce the time that the produce is wet (Holcroft, 2015).

Gottschalk, Linke, Mészáros, and Farkas (2007) developed a model that predicts the condensation and transpiration process on a single fruit under varying ambient conditions along storage time. The model was validated using eight fruits in an open container. Linke and Geyer (2013) determined the condensation dynamics and intensity within plastic film packaging for fruit under fluctuating external temperatures. Using packages of plums as a test case, the authors showed that moisture condensation process occurred with time-delayed and superimposed varying intensities on the surface of the fruit, inner film surface, and inner tray walls (Fig. 5). Moisture condensation in the inner film surface was mainly influenced by flow conditions, external temperature amplitude, and in the inner air volume. On the contrary, moisture condensation on fruit surface was caused primarily by temperature amplitude and cycle time. In summary, for the studied cycle time of 240 min, the condensate remained for 53%, 51% and 42% of the cycle time on the inner wall of the tray, plum surface and underneath film, respectively. Further detailed investigations are needed to evaluate and simulate moisture condensate formation via integrative mathematical modelling. Such model can be developed using water vapour related characteristics of packaging materials (water vapour permeability, macro and micro perforations), and physiological characteristics of product (respiration and transpiration) as well as external storage environment (temperature, humidity and air flow).

## 3.2. Moisture condensation control strategies

### 3.2.1 Moisture absorbers

This involves the use of various hygroscopic substrates or substances to attract and hold water molecules from the surrounding environment. Desiccant and papers pads are used to wrap fresh produce in order to mitigate moisture accumulation (Ozdemir & Floros, 2004). The use of these salts and polyols packages offers an alternative way to avoid moisture condensation inside the package. It has been shown to have beneficial effect on the shelf life of FFV by reducing microbial growth and preserving colour attributes. Mahajan, Rodrigues, Motel, and Leonhard (2008b) also developed a moisture absorber. Fast absorbing moisture absorbers such as calcium chloride ($CaCl_2$), potassium chloride (KCl) and sorbitol were mixed with a slow absorbing desiccant such as bentonite in different proportions. Overall results showed that the appearance of mushrooms improved when 5 g of mixed desiccant was packed in 250 g of mushroom punnet compared to those packed without desiccant.

Similarly, Azevedo, Cunha, Mahajan, and Fonseca (2011) designed desiccants with calcium oxide (CaO), sorbitol, and $CaCl_2$ in a range of 0.2 - 0.6 g of desiccant mass in varying proportions. The change in moisture content of each of the mixed desiccants was measured at regular intervals up to 5 d at 10 °C. Results showed that optimised desiccant mixture, which contained 0.5, 0.26 and 0.24 g $g^{-1}$of CaO, $CaCl_2$ and sorbitol, respectively, and had a moisture holding capacity of 0.813 g water $g^{-1}$. Additionally, absorption of excess moisture from the headspace, keeps RH inside the package low (Shirazi & Cameron, 1992). Also, the use of desiccants for FFV with high water activity might lead to excessive moisture loss. Hence, careful application of desiccants based on detailed research is needed.

### 3.2.2 Perforated films

Micro-perforated packaging films are commonly used in fresh produce packaging to enhance $O_2$ and $CO_2$ gas permeability and control moisture around FFV. Such packaging films have the advantage to avoid in-package anaerobiosis and therefore may extend the shelf-life and maintain quality of FFV (Jo et al., 2013; Hussein, 2015). Almenar et al. (2007) studied the behaviour of strawberries packaged with two continuous and three micro-perforated films (with different gas permeability) with the purpose of obtaining equilibrium atmospheres of diverse compositions. Results showed that micro-perforated films with one and three holes provided adequate $CO_2$ and $O_2$ equilibrium concentrations. However, micro-perforated films do not allow for effective diffusion of water vapour into the environment leading to saturated humidity, moisture condensation and deterioration of fresh packaged horticultural produce (Rodov et al., 2010).

Perforations in a polymeric film is based on a compromise principle since perforations affect the film´s permeability to $O_2$ and $CO_2$ to a higher extend than to water vapour. With macro-perforated packaging films, it is nearly impossible to achieve MA equilibrium, and prevent excessive mass loss and shrivelling of FFV. In ideal packaging, the humidity level should be low enough to prevent moisture condensation but sufficiently high enough to reduce product mass loss, while also having an optimal atmosphere (Rodov et al., 2010).

### 3.2.3 Individual shrink-wrapping

Individual shrink wrapping (ISW) is a passive form of MAP in which a polymer film with selective permeability to $CO_2$, $O_2$, ethylene and water is used to pack individual fresh produce in order to maintain its freshness (Dhall, Sharma, & Mahajan, 2012; Megías et al., 2015). The main advantages of this technology are reduced mass loss, minimised fruit deformation, reduced chilling injuries and decay (Dhall et al., 2012). Rodov et al. (2010) reported that shrink wrapping is also efficient in controlling moisture condensation due to a very small headspace volume and negligible temperature differences between the product and the film surface.

Rao, Rao, and Krishnamurthy (2000) studied the effect of MAP and shrink wrapping on the shelf life of cucumber. Results showed that shrink wrapping with polyethylene film can extend the shelf life of cucumber for up to 24 d at 10°C. Megías et al. (2015) studied the effect of ISW on the postharvest performance of refrigerated fruit from two zucchini cultivars that differ in their sensitivity to cold storage. Results indicated that ISW zucchini packaging led to improved tolerance to chilling simultaneously with a decrease in oxidative stress, respiration rate and ethylene production. Despite the positive results, this approach is limited to spherical or cylindrical products (e.g. cucumber) because if any part of the product is not in contact with the film then it will lead to moisture accumulation (Rodov et al., 2010).

### 3.2.4 Enhanced water vapour permeable films

Various polymers have been developed with relatively high permeability towards water vapour compared to the commonly used polymeric films such as polypropylene or polyethylene. These include co-extruded and bio-degradable polymeric films with enhanced water vapour permeability. Co-extruded films consist of blends of different hydrophilic polyamides with other polymeric and non-polymeric compounds. The different blends allow manufacturing materials varying in water vapour permeability, in accordance with required in-package RH levels (Rodov et al., 2010).

As an example, Aharoni et al. (2008) used a co-extruded packaging film Xtend® (StePac, Tefen, Israel) and reported that Xtend® can effectively modify both atmospheric composition and RH inside packaging containing various FFV. Similarly, cellulose-based NatureFlex™ (Innovia films, Cumbria, UK) polymeric films also held a good potential for application in packaging of fresh produce as it has a very high water permeability (200 g $m^{-2}$ $d^{-1}$ at 25 °C and 75% RH) as against the conventional polypropylene film with 0.8 g $m^{-2}$ $d^{-1}$ water permeability (Sousa-Gallagher et al., 2013). Also, water vapour transmission rate (WVTR) of cellulose based NatureFlex™ polymeric films has been shown to increase with the increase RH. Therefore, care must be taken in designing fresh produce packages, as excessively high water permeability can lead to higher product moisture and mass loss.

### 3.2.5 Humidity-regulating trays

Singh, Saengerlaub, Stramm, and Langowski (2010) reported on the application of humidity-regulating trays incorporated with varying concentrations of sodium chloride (NaCl) for fresh mushrooms. In this study, different percentages of NaCl were introduced into the polymer matrix of the film from which trays were produced. The authors found that the amount of water vapour absorbed by the tray is directly proportional to the percentage of salt incorporated in the trays. Rux et al. (2015) also reported the use of humidity-regulating trays for mushrooms. Trays were produced with NaCl (18% on a weight basis) between the outer barrier layer (polypropylene) and the inner sealing layer (polypropylene/ ethylene vinyl alcohol/ polyethylene). Results showed that humidity-regulating tray maintained a stable RH (93%) inside the package and it absorbed 4.1 g of water vapour within 6 d at 7 °C and 85% RH storage condition. Yet the absorbed water vapour was not enough to prevent water condensation in the package headspace.

Furthermore, Rux et al. (2016) optimised the humidity-regulating tray from a thermoformed multilayer structure: polyethylene (outside)/foamed hygroscopic ionomer (active layer) with 0 (T-0 tray) or 12 (T-12 tray) wt.-% NaCl/hygroscopic ionomer (sealing layer, inside). The amount of water absorbed was 7.6 and 13.2 g by T-0 and T-12 trays respectively, which indicates that the moisture absorbed by the tray was directly proportional to the amount of salt incorporated into the tray matrix. The addition of salt into polymer matrix of packaging tray represents a novel approach to control in-package humidity for fresh produce. However, further optimisation via mathematical modelling is required for product specific needs.

## 4. Application of integrative mathematical modelling concept

A packaging system for FFV consists of a respiring produce fully enclosed in a tray type package lidded with permeable film. Changes in the amount of water vapour content inside the package will be dependent on transpirational water loss from the product, water vapour transmitted through the packaging film and the water vapour absorbed by the active moisture control system. As a result the following unsteady-state mass balance equation may be used to describe the rate of change of water vapour in the headspace as a function of time:

$$\left\{\begin{matrix}\text{Water vapour evolution}\\ \text{in a package}\end{matrix}\right\} = \left\{\begin{matrix}\text{Transpirational water loss}\\ \text{from the product}\end{matrix}\right\} - \left\{\begin{matrix}\text{Water vapour transfer}\\ \text{through packaging film}\end{matrix}\right\} - \left\{\begin{matrix}\text{Water vapour absored by the active}\\ \text{moisture control system}\end{matrix}\right\} \quad (8)$$

There is a wealth of published information on modelling of moisture evolution in fresh produce (Lu et al., 2013; Mahajan et al., 2016; Rennie & Tavoularis, 2009; Song et al., 2001), yet no systematic study has been conducted to bring all the theoretical models together in a ready to use format. Hence, the sub-sections below present an overview of published models related to product transpiration, water vapour permeation in perforated packaging system and active moisture control systems.

### 4.1. Moisture evolution due to transpiration

There are two approaches commonly used for the mathematical modelling of the transpiration phenomena. The first is based on the diffusion equations of Fick´s law (Leonardi et al., 2000; Maguire et al., 2001), and the second approach is based on heat and mass balances (Kang & Lee, 1998; Lu et al., 2013; Song, Vorsa, & Yam, 2002). The model presented by Sastry (1985) is the most basic form of a transpiration model: $TR = k_i\ (P_s\ -\ P_\infty)$. This model was applied primarily to storage situations where steady state conditions prevailed and the key assumption was that temperature of product evaporating surface is the same as its surrounding environment. However, an error is observed in the model at saturated environments (i.e. VPD = 0.0) as discussed previously. Therefore, a more complex diffusion model is required to predict transpiration under saturated and stagnant air flow conditions as observed inside packaged fresh produce.

Non-linear models for estimating TR based on Fick´s first law of diffusion have been reported in the literature, but very little work has been developed in this area, especially for the prediction of TR under MAP systems. There are at least two major reasons why the mathematical modelling of TR for MAP systems are not well developed this includes: i) modelling of this phenomena needs a complete understanding of the dynamic interactions between permeation through the packaging film and evaporation on produce surface as a result of the heat released from respiration; and, ii) existing models are limited to cooling process and bulk storage, which may not be suitable for MAP systems (Song et al., 2002).

It is noteworthy to mention that the difference between a $TR_m$ and $TR_s$ model is the unit of the $k_s$ coefficient. Some authors prefer to use it in terms of mass basis (Caleb et al., 2013; Sousa-Gallagher et al., 2013) since it is easier to determine the mass of product than its surface area, this makes it a more convenient unit (Sastry, 1985). Other authors emphasised on the significance of expressing transpiration per unit area (Linke, 1997; Xanthopoulos et al., 2014), because the area-based transpiration coefficient is not dependent on product mass. An alternative is the use of an area-based transpiration coefficient combined with a statistically determined correlation between surface area and mass for a specific FFV. This approach combines the accuracy of the area based coefficient with the convenience of a quick calculation of the product surface area from the mass.

Other approach for modelling TR is based on heat and mass balance between the produce and storage atmosphere and is also shown in Table 3. Kang and Lee (1998) developed a transpiration model to predict moisture loss of fresh produce under ambient and controlled atmosphere conditions. In this model the sum of heat energies transferred through natural convection from surrounding air and generated from respiration inside the produce was assumed to be supplied for evaporating moisture on produce surface. Song et al. (2002) proposed a respiration-transpiration model by applying simultaneous heat and mass transfer principles to known physiological behaviour of fresh produce in MAP. Their model applied the assumption that temperature inside the package was equal to the temperature on the surface of the produce and therefore external heat was negligible. Lu et al. (2013) developed a model for transpiration based on mass change of water vapour. Their model considered; respiratory heat generated by produce, heat absorbed by produce, heat absorbed by gas around the produce, heat absorbed by the package and heat change caused by gas transmission across the package.

Mathematical models for transpiration, which takes into consideration the various factors affecting TR, are important tools. They help select targeted package designs with optimum WVTR and help estimate fresh produce shelf life (Kang & Lee, 1998). Models that do not take into account all of the factors can in some cases be satisfactory, but may result in large errors in other cases (Sastry, 1985). However, models that take into account too many factors become complex with limited application flexibility, since some of the parameters may be product specific or not easily measurable. For instance skin thickness, pore fraction in the skin, geometry, thermal diffusivity, and surface cellular structure are factors not easily measured and/or determined (Kang & Lee, 1998). Therefore, an extremely detailed model might not be as useful and convenient as a well-designed simple model (Tanner, Cleland, Opara, & Robertson, 2002). Thus, the development of a successful and accurate mathematical model for transpiration depends on the parameters considered and the assumptions made. In addition, respiration plays an important role on the transpiration phenomena for packaged produce and it is important to take this into account when developing a TR model. Both Fick´s law and heat and mass transfer approach can incorporate this parameter.

### 4.2. Water vapour permeation in perforated packaging systems

Mathematical modelling of mass transfer through perforated packaging is commonly used and has been extensively reported in the literature. A detailed review on perforation mediated packaging systems was recently published by Hussein, Caleb, and Opara (2015). An example of the application of mathematical modelling for perforated packaging system can be found in the study reported by Fishman, Rodov, and Ben-Yehoshua (1996). The authors developed a mathematical model to study the influence of film perforations on water vapour flux through the perforated film (Eq. 9):

$$F_w = \propto (H_A - H)\left[\frac{SP_w}{L} + \frac{\pi R_h^2 N D_w}{L + R_h}\right] \qquad (9)$$

where $F_w$ is the water flux ($m^3$ $h^{-1}$); $\alpha$ is water vapour concentration under saturation vapour pressure which depends on temperature (non-dimensional); $H_A$ is RH in the ambient atmosphere (non-dimensional); $H$ is RH (non-dimensional); $S$ is film area ($m^2$); $P_w$ is water vapour permeability coefficient of the film found from film specifications ($m^2$ $h^{-1}$); $L$ is film thickness (m); $\pi$ is 3.14 (non-dimensional); $R_h$ is radius of perforation (m); $N$ is number of pores (non-dimensional); and $D_w$ is the diffusion coefficient of water vapour in air ($m^2$ $h^{-1}$).

The overall model showed that perforation had more effects on $O_2$ concentration than on RH. Although this model was designed for mango fruit; the proposed equations could still be valid for other commodities if appropriate transpiration coefficients are inserted. Ben-Yehoshua, Rodov, Fishman, and Peretz (1998) applied the model developed by Fishman et al. (1996) and evaluated the effects of perforation on MAP with bell peppers and mangoes. The results showed that perforating the film affects $O_2$ and $CO_2$ concentrations as well as moisture condensation, but not the in-package RH. Lee, Kang, and Renault (2000) developed a model for estimating changes in the atmosphere and humidity within perforated packages of fresh produce. The model was based on mass balances of $O_2$, $CO_2$, nitrogen gas ($N_2$), and water ($H_2O$) and included respiration, transpiration and terms for gas and water vapour transfer through perforations and films. The water vapour exchange rate through the film was modelled based on Fick´s law. Similarly, Techavises and Hikida (2008) developed a model based in Fick´s law that included atmospheric gas ($O_2$, $CO_2$ and $N_2$) and water vapour exchanges in MAP with perforations. The proposed model showed good prediction of gas concentrations and RH when compared with experimental results. The differential equation used to obtain the volumetric changes inside a perforated MAP of respiring produce for water vapour is presented (Eq. 10):

$$\frac{d\,V_H(t)}{dt} = n_p D_H + A_f K_H \left(P_H - P_T \frac{V_H(t)}{V_T(t)}\right) \qquad (10)$$

where $n_p$ is number of perforations (non-dimensional); $D_H$ is effective permeability of one perforation to water vapour ($10^{-6}$ $m^3$ $h^{-1}$ $kPa^{-1}$); $A_f$ is surface area of the film package ($m^2$); $K_H$ is water vapour transpiration rate of film to water vapour ($10^{-6}$ $m^3$ $m^{-2}$ $h^{-1}$ $kPa^{-1}$); $P_H$ is partial pressure of water vapour outside the package (kPa); $P_T$ is total pressure inside the package (kPa), equal to 101.325 kPa; $V_T(t)$ is total volume of gases inside the package at time t ($10^{-6}$ $m^3$) and effective permeability ($D_H$) is a function of perforation diameter ($d$) in mm:

$$D_H = 2.98 \, x \, 10^{-2} d^2 + 5.37 \, x \, 10^{-1} d + 8.22 \, x \, 10^{-1} \quad (11)$$

The authors reported that Eq. 10 is valid for water and atmospheric gases in a temperature range of 5 to 25 °C and for film thickness smaller than 0.025 mm.

Rennie and Tavoularis (2009) also developed a space and time dependent mathematical model for perforation-mediated MAP. The authors considered respiration, transpiration, condensation, heat transfer (evaporative, convective, and conductive), and convective and diffusive transport of $O_2$, $CO_2$ and $N_2$ and $H_2O$ through the Maxwell-Stefan diffusion and the convection mass balance model (Eq. 12):

$$\rho \frac{\partial \omega H_2O}{\partial \mathrm{t}} + \nabla \left( -\rho \, \omega H_2O \, \sum_{j=1}^{n} \mathrm{Dij} \left( \nabla \mathrm{x} H_2\mathrm{O} + (\mathrm{x} H_2\mathrm{O} - \omega H_2\mathrm{O}) \frac{\nabla \mathrm{p}}{\mathrm{p}} \right) = -\rho \omega H_2O \cdot u \quad (12)$$

where $\rho$ is the gas mixture density (kg $m^{-3}$); $t$ is time (s); $\omega_{H_2O}$ is $H_2O$ mass fraction (non-dimensional); $Dij$ is the ij component of multicomponent Fick diffusivity ($m^2$ $s^{-1}$); $xH_2O$ is the mole fraction of water (non-dimensional); $p$ is the total gas mixture pressure (Pa); and $u$ is the velocity vector (m $s^{-1}$). Their model can be used for steady-state as well as for transient analysis of MAP in a wide range of conditions and is valid to model $H_2O$ transport in the ambient storage environment, the perforations and in the headspace.

Li, Li, and Ban (2010) reported a model applicable to non-perforated and micro-perforated MAP films which simulates changes in concentrations of various gases, such as $O_2$, $CO_2$, ethylene ($C_2H_4$) and $H_2O$ inside MAP films over time based on Fick´s law of diffusion. While, Mahajan, Rodrigues, and Leflaive (2008c) developed a mathematical model to describe the changes in *WVTR* as a function of perforation diameter, length and storage temperature in perforation-mediated MAP:

$$WVTR = 2.28 \; D^{1.72} \; L^{-0.72} \; e^{-\frac{12.62}{RT_s}} \quad (13)$$

where $D$ is the perforation diameter (mm), $L$ is the perforation length (mm), $R$ is the universal gas constant (0.008314 kJ $mol^{-1}$ $K^{-1}$) and $T_s$ is the storage temperature (K). These studies present the potential role and application of integrated models in the design of perforation-mediated MAP systems for FFV. Their findings also highlight that research needs to develop more flexible and robust models.

### 4.3. Active moisture control systems

A possible solution to control humidity involves the use of moisture absorbers. In this case the package design requires, in addition to packaging specifications, the selection of appropriate desiccants and specification of the amount to be used. This respiration-transpiration model presented by Song et al. (2002) was thus developed into the new model presented by Song et al. (2001). The new model introduced the moisture sorption behaviour of the absorbent (m) as follows:

$$m = k_{sa}\, m_{ab}(P_i - P_{ab}) \tag{14}$$

where $m$ is moisture absorption rate of the absorbent (kg $h^{-1}$); $k_{sa}$ is the absorbent mass transfer coefficient that can be experimentally determined absorbent mass transfer coefficient ($kg_{water}\ kg_{dry\ matter}^{-1} h^{-1} atm^{-1}$); $m_{ab}$ is mass of dried absorbent (kg); $P_i$ is water vapour pressure inside the package containing absorbent (atm); and $P_{ab}$ is water vapour pressure on the surface of the absorbent (atm). Additionally, $P_{ab}$ is a function of moisture sorption characteristics of absorbents and can be estimated (Eq. 15):

$$P_{ab} = P_{sp}\, a_w \tag{15}$$

where $P_{sp}$ is saturated water vapour pressure at constant temperature (atm) and $a_w$ is the water activity of the moisture absorbent (non-dimensional), which can be experimentally determined as a function of moisture content. The modified model considered moisture sorption characteristics of absorbent and mass transfer coefficient between adsorbent and package headspace. The model was successfully validated with blueberries using two commercial desiccants, Sanwet (Hoechst Celanese, USA) and Xylitol (Sigma,USA). Although the model predictions were in agreement with experimental data obtained, the amount of condensation inside the packages was not quantified. Therefore, it is not possible to optimise the amount of absorber needed to absorb the excess moisture inside the packages.

Furthermore, Mahajan et al. (2008b) investigated the kinetics of moisture absorption for mixed desiccant ($CaCl_2$, KCl and sorbitol) at 4, 10, and 16 °C, at different humidity levels (76, 86 and 96%). Change in moisture content of the mixed desiccant with respect to storage time was fitted to a Weibull distribution model (Eq. 16).

$$M_t = M_\infty \left[1 - e^{\left(\frac{-t}{\beta}\right)}\right] \tag{16}$$

where $M_t$ is the moisture absorbed (g) at a determined time $t$ (d); $M_\infty$ is moisture holding capacity at equilibrium (g); and $\beta$ is the kinetic parameter, which defines the rate of moisture uptake process and it represents the time (d) needed to accomplish 63 % of the moisture uptake process. The moisture holding capacity was found to be dependent on RH, which increased from 0.51 to 0.94 g water $g^{-1}$ desiccant when RH was increased from 76 to 96%. Similarly, Rux et al. (2016) used a Weibull distribution to fit the moisture uptake data obtained from the individual humidity-regulating trays. The authors found that packaged produce with absorbers lost more mass than control samples. Their findings emphasised the importance of selecting the appropriate and correct amount of moisture absorber in order to prevent excessive mass loss and shrivelling of packaged product.

## 5. Conclusion and future research needs

Harvested horticultural produce are transported from farm to the final consumer. This process involves many challenges since the product continues both metabolic and physiological activities after harvest. Thus, strict control of temperature and RH along the supply chain and storage are decisive factors for maintaining quality of FFV. These factors govern the respiration and transpiration processes and consequently degradation of organic substrates and moisture loss. Appropriate packaging of FFV, under optimum storage conditions, offers a possibility to slow down the physiological processes and extend storage life. However, the control of moisture evolution inside packaged horticultural products is complicated due to numerous factors (intrinsic and extrinsic) and the complexity of their interactions. Therefore, application of integrated mathematical models for water relations presents a possible solution; to integrate different factors affecting moisture evolution inside packaged horticultural products. This is vital in order to match the high physiological product requirements and the mass balance of a packaging system in terms of water vapour inside and outside the package. It will provide a guiding tool for all the role players in food packaging industry on package system optimisation such as selection of packaging film, produce amount, package dimensions, perforation, and moisture control strategies; thereby eliminating the "pack-and-pray" approach commonly adopted by the food packaging industry.

## Nomenclature

| | |
|---|---|
| $TR_s$ | transpiration rate per unit surface area (mg $cm^{-2}h^{-1}$ or mg $cm^{-2}s^{-1}$) |
| $TR_m$ | transpiration rate per unit of initial mass (g $kg^{-1}h^{-1}$, mg $kg^{-1}h^{-1}$ or mg $kg^{-1}s^{-1}$) |
| $RH$ | relative humidity (%) |
| $M_i$ | initial mass of the product (mg, g or kg) |
| $M_t$ | product mass at a determined time (mg, g or kg) |
| $A_s$ | initial surface area of the product ($cm^2$ or $m^2$) |
| $t$ | time (s, h or d) |

| | |
|---|---|
| $k_t$ | transpiration coefficient (mg kg$^{-1}$s$^{-1}$ MPa$^{-1}$) |
| $P_s$ | water vapour pressure at the evaporating surface of the product (MPa) |
| $P_\infty$ | ambient water vapour pressure (MPa) |
| $k_s$ | skin mass transfer coefficient (mg kg$^{-1}$ s$^{-1}$ MPa$^{-1}$) |
| $k_a$ | air film mass transfer (mg kg$^{-1}$ s$^{-1}$ MPa$^{-1}$) |
| $\delta$ | diffusion coefficient of water vapour in air (m$^2$s$^{-1}$) |
| $\tau$, $s$ | product skin thickness (m) |
| $\varphi$ | fraction of product surface covered by pores (non-dimensional) |
| $h_d$, $\beta$ | convective mass transfer coefficient(m s$^{-1}$) |
| $\xi_1$ | fraction of surface behaving as a free water zone (non-dimensional) |
| $R_D$, $R$ | universal gas constant (J kg$^{-1}$°C$^{-1}$) |
| $T$ | ambient temperature (°C) |
| $\xi_2$ | fraction of surface behaving as porous membrane (non-dimensional) |
| $\mu$ | resistance factor (non-dimensional) |
| $x_P$ | volume related water content of air in the intercellular spaces in the centre of the produce (mg cm$^{-3}$) |
| $x_A$ | volume related water content of air unaffected by produce (mg cm$^{-3}$) |
| $r_B$ | boundary layer resistance in the water vapour pathway (s cm$^{-1}$) |
| $r_T$ | tissue resistance in the water vapour pathway (s cm$^{-1}$) |
| $x_{ps}$ | water content of the air at the produce surface (mg cm$^{-3}$) |
| $\mathrm{F_w}$ | water vapour flux through the perforated film (m$^3$ h$^{-1}$) |
| $\alpha$ | water vapour concentration under saturation vapour pressure (non-dimensional) |
| $H_A$ | relative humidity in the ambient atmosphere (non-dimensional) |
| $H$ | relative humidity (non-dimensional) |
| $S$, $A_f$, | surface area of the film (m$^2$) |
| $P_w$ | water vapour permeability coefficient of the film (m$^2$ h$^{-1}$) |
| $L$ | film thickness (m) |
| $\pi$ | 3.14 (non-dimensional) |
| $R_h$ | radius of perforation (m) |
| $N$ | number of pores (non-dimensional) |
| $\mathrm{D_w}$ | diffusion coefficient of water vapour in air (m$^2$ h$^{-1}$) |
| $V_H(t)$ | volume of water vapour inside the package at a determined time (10$^{-6}$ m$^3$) |
| $n_p$ | number of perforations (non-dimensional) |
| $D_H$ | effective permeability of one perforation to water vapor (10$^{-6}$m$^3$h$^{-1}$ kPa$^{-1}$) |

| | |
|---|---|
| $K_H$ | water vapour transpiration rate of film to water vapour ($10^{-6}m^3\ m^{-2}\ h^{-1}\ kPa^{-1}$) |
| $P_H$ | partial pressure of water vapour outside the package (kPa) |
| $P_T$ | total pressure inside the package (kPa) |
| $V_T(t)$ | total volume of gases inside the package at a determined time ($10^{-6}\ m^3$) |
| $d, D$ | perforation diameter (mm) |
| $\rho$ | gas mixture density ($kg\ m^{-3}$) |
| $\omega H_2O$ | $H_2O$ mass fraction (non-dimensional) |
| $Dij$ | ij component of multicomponent Fick diffusivity ($m^2 s^{-1}$) |
| $xH_2O$ | mole fraction of $H_2O$ (non-dimensional) |
| $\omega j$ | mass fraction of $H_2O$ (non-dimensional) |
| $p$ | total gas mixture pressure (Pa) |
| $u$ | velocity vector ($m\ s^{-1}$) |
| $L$ | perforation length (mm) |
| $T_s$ | storage temperature (K) |
| $m$ | moisture absorption rate of the absorbent ($kg\ h^{-1}$) |
| $k_{sa}$ | absorbent mass transfer coefficient ($kg_{H2O}\ kg_{dry\ matter}^{-1}\ h^{-1}\ atm^{-1}$) |
| $m_{ab}$ | is mass of dried absorbent (kg); |
| $P_i$ | is water vapour pressure inside the package containing absorbent (atm) |
| $P_{ab}$ | is water vapour pressure on the surface of the absorbent (atm) |
| $P_{sp}$ | saturated water vapour pressure at constant temperature (atm) |
| $a_w$ | is the water activity of the moisture absorbent (non-dimensional) |
| $M_t$ | is the moisture absorbed (g) at a determined time (days) |
| $M_\infty$ | is moisture holding capacity at equilibrium (g) |
| $B$ | kinetic parameter (non-dimensional) |

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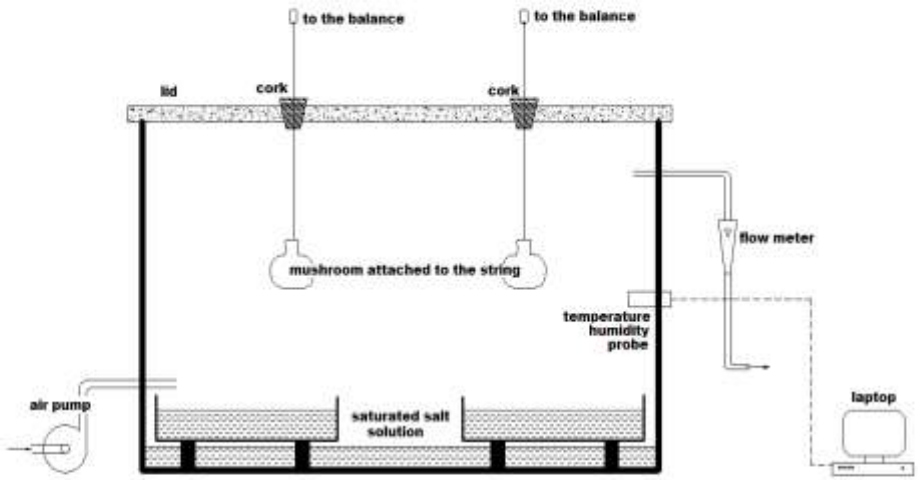
(A)

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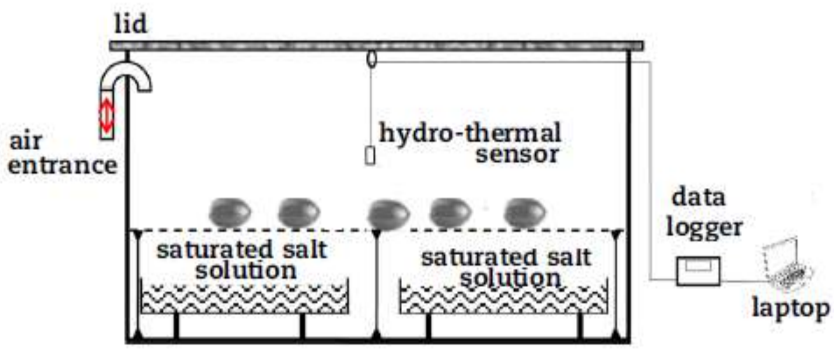


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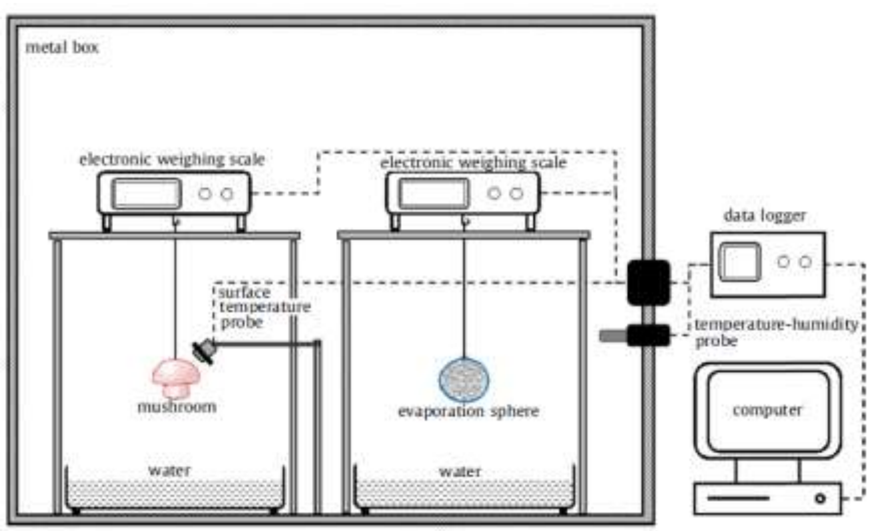


**Fig. 1.** Schematic representation of a typical experimental setup for used for non-continuous (A and B) and continuous (C) measurement of produce mass loss (Adopted from Mahajan et al. (2008a), Xanthopoulos et al. (2014), and Rux et al. (2015), respectively)

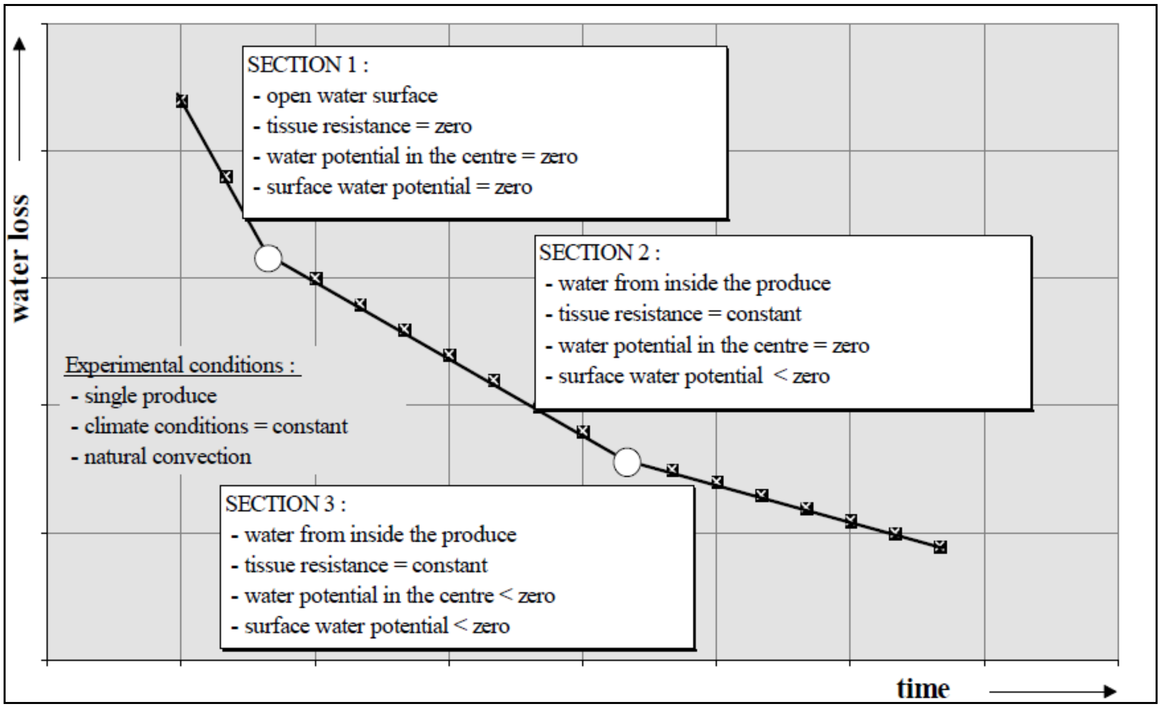


**Fig. 2.** Sections describing the typical water loss of fruit and vegetables during postharvest storage (Adopted from Linke, 1997)

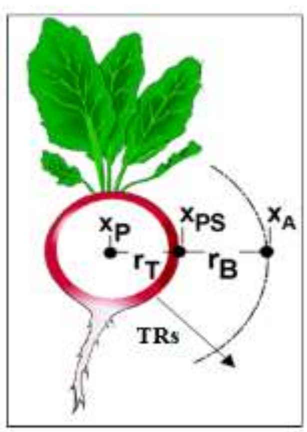


**Fig. 3.** Basic relations for calculating tissue and boundary layer resistances (Adopted from Linke, 1998)

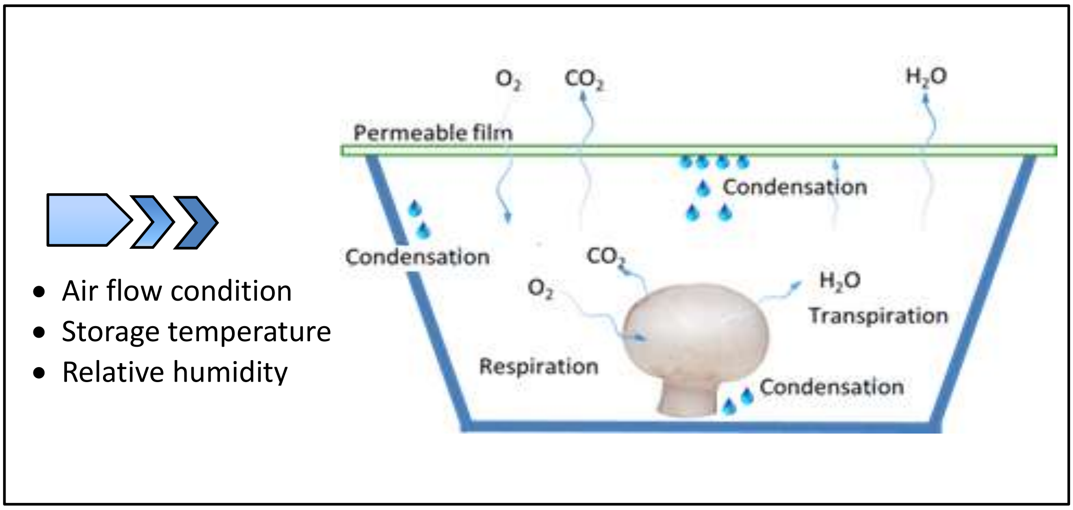


**Fig. 4.** Condensation in packaged fresh produce and environmental parameters impacting the condensation process

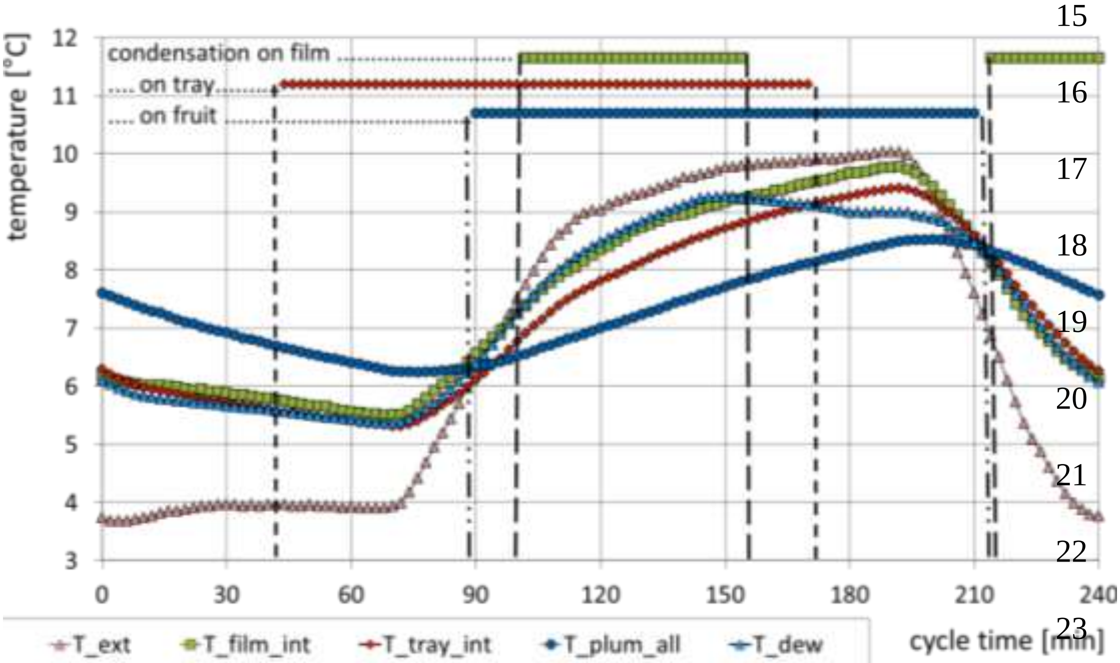


**Fig. 5.** Condensation dynamics in plastic film packaging containing fresh plums

(Adopted from Linke & Geyer, 2013)

**Table 1.** Range of transpiration coefficients for some fresh fruit and vegetables

| **Fruit** | **$k_t$ (mg kg $^{-1}$ s$^{-1}$ MPa$^{-1}$)** | **Vegetables** | **$k_t$ (mg kg $^{-1}$ s$^{-1}$ MPa$^{-1}$)** |
|---|---|---|---|
| Apple | 16 - 100 | Potato | 2 - 171 |
| Pear | 10 - 144 | Onion | 13 - 123 |
| Grapefruit | 29 - 167 | Tomato | 71 - 365 |
| Orange | 25 - 227 | Cabbage | 40 - 667 |
| Grapes | 21- 254 | Lettuce | 680 - 8750 |
| Plum | 110 - 221 | Leek | 530 - 1042 |
| Lemon | 139 - 229 | Carrot | 106 - 3250 |
| Peach | 142 - 2089 | Celery | 104 - 3313 |

Source: Thompson et al., 1998 compiled from Sastry et al., 1977

**Table 2.** Tissue resistance of single fresh fruit and vegetables after harvest at natural convection

| **Fruit** | **Tissue Resistance ($r_T$, s cm$^{-1}$)** | **Vegetables** | **Tissue Resistance ($r_T$, s cm$^{-1}$)** |
|---|---|---|---|
| Strawberries | 3 - 23 | Radish tubers | 0.25 - 1.5 |
| Plums | 23 - 38 | Carrots (without leaves) | 1 - 6 |
| Apples | 170 - 320 | White asparagus | 11 - 12.5 |
| | | Bell peppers | 35 - 80 |

Source: Linke and Geyer, 2000; Linke and Geyer, 2001

**Table 3.** Summary of transpiration rate models applied for various horticultural commodities under different storage conditions and their limitations.

| Proposed model equation | Unit | Storage conditions | Product | TR Range | Limitation | Reference |
|---|---|---|---|---|---|---|
| $\frac{Q_r W + h A (T - T_p)}{ƛ}$ | kg $h^{-1}$ | T: 0<br>RH: 100 | Apple | 18.4[2] (normal air)<br>5.7[2] (1%$O_2$,1%$CO_2$)<br>8.7[2] (3% $O_2$, 3%$CO_2$) | Model was not validated; not tested in MAP (tested in controlled atmosphere) | Kang and Lee, 1998 |
| | | T: 10<br>RH: 82 | Fresh-cut onion<br>Fresh-cut green onion | 447[2] (normal air)<br>363[2] (normal air) | | |
| $\frac{Q_r W + W C_s \frac{dT_{sp}}{dt}}{ƛ}$ | kg $h^{-1}$ | T: 15, 25<br>RH: 10, 60 | Blueberry | NG | T inside the package was considered equal to the $T_s$ | Song et al., 2002 |
| $\rho . K_i . (a_{wi} - a_w) . (1 - e^{-aT})$ | mg $cm^{-2}$ $h^{-1}$ | T: 4, 10, 16<br>RH: 76, 86, 96 | Mushrooms | 0.14 - 2.5[1] | Model not tested in MAP; does not consider RR | Mahajan et al., 2008 |
| $K_i . (a_{wi} - a_w) . (1 - e^{-aT})$ | g $kg^{-1}$ 24$h^{-1}$ | T: 5, 10, 15<br>RH: 76, 86, 96 | Pomegranate arils | 48 - 698[2] | Model not tested in MAP; does not consider RR | Caleb et al., 2013 |
| | g $kg^{-1}$ $h^{-1}$ | T: 5, 10, 15<br>RH: 76, 86, 96 | Strawberries | 240 - 1160[2] | Model does not consider RR | Sousa-Gallagher et al., 2013 |
| $K_i . e^{\left[-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right]} . (a_{wi} - a_w)$ $\rho . K_i . e^{\left[-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right]} . (a_{wi} - a_w)$ | g $kg^{-1}$ $h^{-1}$<br>mg $cm^{-2}$ $h^{-1}$ | T:10, 15, 20<br>RH: 70, 80, 92 | Grape tomato | 18 - 107[2]<br>0.012 - 0.058[1] | Model not validated; does not consider RR | Xanthopoulos et al., 2014 |
| $K_i . (a_{wi} - a_w) . (1 - e^{-aT}) + 8.6\, RR_{CO2,r} \; . \, e^{\frac{-Ea}{R}\left[\frac{1}{(T+273)} - \frac{1}{(Tr+273)}\right]}$ | mg $kg^{-1}$ $h^{-1}$ | T:13<br>RH: 100 | Mushrooms<br>Strawberries<br>Tomato | 713[2]<br>122[2]<br>17.6[2] | Model was not validated | Mahajan et al., 2016 |

[1] mg $cm^{-2}$ $h^{-1}$ (area based); [2] mg $kg^{-1}$ $h^{-1}$(mass based); T is temperature (°C), RH is relative humidity (%), RR is respiration rate $Q_r$-respiration heat of produce; W-produce weight; h-convective heat transfer coefficient; A-produce surface area; $T_s$-surrounding temperature; Tp-produce temperature; ƛ-latent heat of moisture evaporation/vaporization; $C_s$ is specific heat of the produce, $T_{sp}$ product surface temperature; ρ-water density; $K_i$-mass transfer coefficient; $a_w$-water activity of the container; $a_{wi}$-water activity of the commodity; a-coefficient; $E_a$-activation energy; R-universal gas constant; Tr-reference temperature; $RR_{CO2,ref}$ -respiration rate of the product at Tr and 8.6 is the conversion factor for obtaining TR from the respiratory heat generation, NG is not given.