Innovations in modified atmosphere and humidity packaging applied to fresh produce: a case study on strawberries

vorgelegt von

M.Sc.

Graziele Grossi Bovi Karatay

ORCID: 0000-0001-8610-6583

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1. Gutachter: Prof. Dr.-Ing. habil. Cornelia Rauh

2. Gutachter: Prof. Dr. Uwe Schmidt

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Preface

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1. Bovi, G.G., Caleb, O.J., Herppich, W.B., & Mahajan, P.V. (2018). Mechanisms and modeling of water loss in horticultural products. Reference Module in Food Science, Elsevier, pp. 1-5.

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3. Bovi, G.G., Caleb, O., Linke, M., Rauh, C., & Mahajan, P. (2016). Transpiration and moisture evolution in packaged fresh horticultural produce and the role of integrated mathematical models: A review. Biosystems Engineering, 150, 24-39.

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4. Bovi, G.G., Rux, G., Caleb, O.J., Herppich, W.B., Linke, M., Rauh, C., & Mahajan, P.V. (2018). Measurement and modelling of transpiration losses in packaged and unpackaged strawberries. Biosystems Engineering, 174, 1-9.

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   Publisher's version included in Chapter 3 (pp 44-52)

5. Bovi, G.G., Caleb, O.J., Klaus, E., Tintchev, F., Rauh, C., & Mahajan, P.V. (2018). Moisture absorption kinetics of FruitPad for packaging of fresh strawberry. Journal of Food Engineering, 223, 248-254.

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   Publisher's version included in Chapter 4 (pp 54-60)

6. Bovi, G.G., Caleb, O. J., Ilte, K., Rauh, C., & Mahajan, P. V. (2018). Impact of modified atmosphere and humidity packaging on the quality, off-odour development and volatiles of 'Elsanta' strawberries. Food Packaging and Shelf Life, 16, 204-210.
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7. Bovi, G.G., Caleb, O.J., Rauh, C., & Mahajan, P.V. (2019). Condensation regulation of packaged strawberries under fluctuating storage temperature. Packaging Technology and Science; 1-10.
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Summary

Fresh produce are unique among food products as they remain metabolically (e.g. respiring) and physically active (e.g. transpiring) and their shelf and storage life are shortened as consequence of these processes. Both transpiration and respiration plays an important role in water loss and in the postharvest quality of horticultural products. Transpiration is a process driven by the water vapour pressure difference between the product and its surrounding atmosphere, whereas respiration is a complex metabolic process comprising several different pathways that produce metabolites, carbon dioxide (CO_2), biochemical energy, reduction equivalents and, finally, water from the oxidation of atmospheric oxygen (O_2) at the expense of stored sugars, organic acids, lipids or fat. According to Food and Agricultural Organization (FAO), fresh produce have the highest wastage rates (45 %) in comparison to any other food product, almost half of all fresh produce produced are wasted. Appropriate packaging has been shown to slow down such physiological and metabolic processes and consequently prolonging the shelf life of fresh product. Modified atmosphere packaging (MAP) has been and still is extensively used for this purpose. However, current MAP design considers the respiration rate of product as the only important parameter for deciding target gas barrier properties of packaging materials. Nevertheless, besides O_2 and CO_2 regulation, it is also important to take into consideration the in-package humidity, in order to avoid condensation inside MAP systems.

Condensation represents a risk to the product quality as water may accumulate on packaging material and/or product surface resulting in defects in external appearance and promoting growth of spoilage microorganisms. Thus, humidity regulation is extremely important to further extend shelf life of fresh produce. Moreover, for the selection of the most appropriate packaging strategy that takes into consideration moisture regulation; modified atmosphere and humidity packaging (MAHP) application is required. For MAHP application it is essential to know how much water is released by the product and through the packaging system. Water loss in horticultural products is commonly measured by quantifying the amount of water released by the product per unit of time, known as the transpiration rate (TR). Based on this context, experiments on a single unpackaged strawberry were performed at 4, 12 and 20 °C; and 76, 86, 96 and 100 % RH. Water loss was also investigated as a function of the number of strawberries (1, 3, 6 and 15) and package volume (0.8, 1.4 and 2.3 L) at 12 °C. Experiments showed that different numbers of packaged strawberries in a fixed package size behaved differently; the TR of one strawberry was

2.5 times higher than of 15 strawberries. The key finding was that headspace played an important role in water loss of packaged strawberries. Therefore, TR measurements of single strawberries measured in large chambers with unrestricted surrounding air flow conditions are not suitable to estimate water loss from packaged fresh produce. Hence, two different TR models were developed: i) a model as a function of temperature, RH and mass transfer for an unpackaged single strawberry and ii) a model based on degree of filling for packaged strawberry. The latter model has potential application towards the selection of optimal moisture control strategies for packaged strawberries.

Moreover, this research focused on strategies to avoid/reduce in-package condensation by moisture and/or humidity regulation approaches in MAHP systems. Two feasible and innovative moisture regulation approaches were studied. The first approach consisted of packages fitted with a rectangular window of highly water permeable film (33, 66 and 100 % of total upper package area). The films used as windows were cellulose-based NatureFlex™ polymeric film and Xtend® breathable film, while Propafilm™ was used as control. The second approach involved the use of moisture absorbing pads, namely FruitPad, containing different contents of fructose (0, 20 and 30 %) as an active ingredient for moisture absorption. FruitPads were exposed to different storage conditions and moisture absorption kinetics was gravimetrically determined over 5 days of storage. FruitPad with 30 % fructose showed highest amount of moisture absorption (0.94 g of water per g of pad) at 20 °C and 100 % RH. The Weibull model combined with the Flory-Huggins model adequately described changes in the moisture content of the FruitPad ($R^2 = 0.93 - 0.96$).

Furthermore, to mimic retail practices, high water permeable films (NatureFlex™ and Xtend®) and FruitPads with different fructose contents (0, 20, 30, 35 and 40 %) were assessed under dynamic storage conditions and performance of the package design was evaluated. Package design performance was evaluated in terms of headspace gas composition, mass loss, condensation, physico-chemical changes and visual and ortho-nasal quality evaluation. Results showed that both strategies were efficient in reducing water vapour condensation, as compared to the control packages; however, this was at the expense of higher product mass loss. Percentage mass loss of packaged strawberries ranged from 0.6 % to 4 % and was 33 % for unpackaged.

Overall results of this thesis showed that the use of high water vapour permeable films as windows, instead of packing the entire product in such film, was advantageous as it can be

customised according to the specific physiological properties of each packaged fresh produce. Thus, avoiding excessive mass loss of product. FruitPads were also promising as they do not only absorb the water in direct contact with fresh produce but also water vapour from the package headspace. In addition, similar to the high water permeable film as windows it was possible to avoid excessive mass loss of product by selecting the appropriate fructose content. Overall, the potential of using the two innovative moisture control strategies for packaging of strawberry in MAHP systems is reflected in the different parts of this PhD thesis. The experimental data obtained from this research deepened the understanding of how the physiological processes of strawberries, temperature management, and package geometry affected the in-package humidity and condensation. These results provided substantial contributions to the scientific knowledge on MAHP as well as to the packaging industry by aiding in the selection of most adequate moisture control strategy to be used.

Zusammenfassung

Frische gartenbauliche Produkte nehmen unter den Lebensmitteln eine besondere Stellung ein, denn sie leben auch nach der Ernte weiter, sie bleiben stoffwechselaktiv, atmen und transpirieren. Dies wiederum verkürzt bzw. beeinflusst ihre Haltbarkeit und ihre Lagerungsqualität. Sowohl Transpiration als auch Atmung spielen eine wichtige Rolle beim Wasserverlust; sie beeinflussen auch in hohem Maße die Nacherntequalität von Gartenbauprodukte. Die Wasserdampfflüsse der Transpiration werden dabei durch den Wasserdampfpartialdruckgradienten zwischen dem Produkt und der umgebenden Atmosphäre angetrieben. Die Atmung dagegen ist ein sehr komplexer Stoffwechselprozess, der mehrere Teilschritte umfasst. Dabei werden auf Kosten von eingelagerten Zuckern, organischen Säuren, Lipiden oder Fetten unterschiedlichste Stoffwechselzwischenprodukte sowie Kohlendioxid (CO_2), Reduktionsäquivalente, biochemische Energie und schließlich, unter Oxidation von Luftsauerstoff (O_2), Wasser gebildet. Wie Analysen der Ernährungs- und Landwirtschaftsorganisation der Vereinten Nationen (FAO) zeigten, haben diese Frischprodukte die höchsten Verlustraten (45 %) unter allen Lebensmitteln. Beinahe die Hälfte des produzierten Obst und Gemüses landet auf dem Müll! Optimierte, spezifische Verpackungen können die Stoffwechselprozesse jedoch verlangsamen und damit die Haltbarkeit der Produkte entsprechend erhöhen. Verpackungen in denen sich eine modifizierte Atmosphäre einstellt (modified atmosphere packaging, MAP) wurden und werden in diesem Zusammenhang intensiv genutzt. Bisher werden die Verpackungssysteme ausschließlich auf ihr Vermögen zur Verringerung der Atmungsaktivität hin designt. Folglich werden auch nur die entsprechenden Diffusions- bzw. Gasbarriereeigenschaften als wichtiges Auswahlkriterium für das zu wählende Verpackungsmaterial angesehen. Jedoch ist es sehr wichtig, nicht nur die jeweiligen Sauerstoff- und Kohlestoffdioxidkonzentrationen in der Verpackung zu beeinflussen, auch die gezielte Regulation der Luftfeuchtigkeit, d. h. des Wasserdampfgehaltes in der Verpackung ist von großer Bedeutung, um eine Kondensation in den MAP-Systemen zu vermeiden.

Eine Kondensation von Wasserdampf kann eine Bedrohung für die Produktqualität darstellen, da sich das Wasser auf dem Verpackungsmaterial, vor allem aber auch auf der Produktoberfläche anhäufen kann. Dadurch wird das Erscheinungsbild der Produkte verschlechtert; aber vor allem wird das Wachstum von Mikroorganismen und damit der Verderb der Produkte verstärkt. Eine Kontrolle und Regulation der Luftfeuchtigkeit in der Verpackung ist daher extrem wichtig, will man die Haltbarkeit der Frischprodukte weiter verlängern. Für die Wahl der optimalen Strategie

für die Regulation der Luftfeuchtigkeit in einer MA-Verpackung ist es absolut essentiell, die Wasserdampfabgabeeigenschaften, d. h. die Transpirationseigenschaften der jeweiligen Produkte genau zu kennen. Die Wasser(dampf)verluste und somit die Transpirationsraten (TR) der gartenbaulichen Produkte werden oft durch Messung des Masseverlusts pro Zeiteinheit erfasst. In diesem Zusammenhang wurden im Rahmen dieser Arbeit Experimente an einzelnen unverpackten Erdbeeren durchgeführt, die bei 4, 12 und 20 °C bzw. bei 76, 86, 96 und 100 % gelagert wurden. Das tatsächliche Ausmaß der Wasserdampfabgabe wurde auch in Abhängigkeit von der Anzahl der Früchte (1, 3, 6 und 15) in Packungen mit unterschiedlichem Volumen (0,8, 1,4 und 2,3 L) untersucht, die jeweils bei 12 °C gelagert wurden. Diese Versuche zeigten, dass eine Variation der Anzahl der Früchte in einer Verpackung mit definiertem Volumen die Transpirationseigenschaften und damit den Gesamtwasserverlust deutlich beeinflusst. Eine einzelne Erdbeere transpiriert zweieinhalb Mal so viel wie 15 Früchte. Die wichtigste Erkenntnis aus diesen Versuchen war aber, dass der Luftraum über den Früchten generell eine essentielle Rolle bei den Wasserverlusten der verpackten Früchte spielt. Somit sind die an unverpackten Einzelfrüchten bei ungehinderter Luftumströmung ermittelten Transpirationsraten nur ganz bedingt nutzbar, um die Wasserverluste von verpackten Frischprodukten abzuschätzen. Aus diesem Grund wurden weiterhin zwei unterschiedliche Transpirationsmodelle entwickelt. Das erste Modell als Funktion von Temperatur, relativer Luftfeuchtigkeit und Massentransfer für eine unverpackte einzelne Erdbeere und dem ersten Fickschen Diffusionsgesetz, während das zweite den Füllungsgrad der Packung mit Erdbeeren mit einbezieht. Diese Modelle besitzen nicht nur für Erdbeeren ein großes Potential zur effektiven Selektion der optimalen Kontrollstrategie der Luftfeuchtigkeit in den Verpackungen.

Darüber hinaus fokussierten sich die Forschungsarbeiten auf die Kontrolle der Luftfeuchte in MA-Verpackungen, um eine Kondensation zu vermeiden bzw. zumindest zu reduzieren. Dabei wurden zwei mögliche innovative Strategien zur Feuchteregulation näher untersucht; i) die Nutzung von Plastikfolieneinsätzen mit hoher Permeabilität für Wasserdampf in der Umverpackung und ii) kontaktlos feuchtigkeitsaufnehmende Absorptionskissen (FruitPad). Bei dem ersten Ansatz wurden die Verpackungen mit unterschiedlich großen (33, 66 bzw. 100 % der gesamten Verpackungsoberseite) rechteckigen Einsätzen aus Folienmaterial mit hoher Permeabilität für Wasserdampf versehen. Diese Einsätze bestanden aus zellulosebasierender NatureFlex™ Polymerfolie bzw. aus atmungsaktiver Xtend® Folie, während Propafilm™ Folie

für die Kontrollen bzw. für die restliche Umverpackung genutzt wurde. In dem zweiten Ansatz wurden „FruitPads" verwendet, die unterschiedliche Gehalte an Fruktose (0, 20 und 30 %) als aktive Bestandteil zur Absorption der Feuchtigkeit enthielten. Die FruitPads wurden unterschiedlichen Lagerbedingungen ausgesetzt und die Wasserabsorption gravimetrisch über fünf Tage bestimmt. Dabei zeigten die FruitPads mit 30 % Fruktose mit 0,94 g H_2O pro g Padmaterial bei 20 °C und wasserdampfgesättigter Atmosphäre die höchste Wasserabsorption. Mit einem Weibull-Modell, kombiniert mit dem Flory-Huggins-Model, konnten die Änderungen im Wassergehalt der FruitPads sehr gut beschrieben werden (R^2= 0,93–0,96).

Die relevanten Eigenschaften der wasserdampfdurchlässigen Folien (NatureFlex™ und Xtend®) und der FruitPads mit den unterschiedlichen Fruktosegehalten (0, 20, 30, 35 und 40 %) wurden weiterhin unter dynamischen Lagerbedingungen untersucht und die Verpackungseigenschaften analysiert. Die Leistung der Verpackung wurde hinsichtlich der Gaszusammensetzung im Kopfraum, der Kondensation im Inneren sowie des Massenverlusts, der physikalisch-chemischen Veränderungen und der visuellen/ortho-nasalen Qualitätsbewertung der verpackten Erdbeeren bewertet. Der prozentuale Massenverlust lag dabei zwischen 0,6 und 4 % und Vergleich zu unverpackten Erdbeeren mit 33 %.

Zusammenfassend ergaben die Resultate dieser Experimente, dass die Nutzung von wasserdampfdurchlässigen Folienbereichen im Vergleich zum vollständigen Verpacken der Produkte in solchen Folien den Vorteil einer einfachen Anpassung der Verpackung an die produktspezifischen Transpirationseigenschaften hat, wodurch übermäßige Wasserverluste vermieden werden können. FruitPads zeigten sich ebenso vielversprechend, da sie bei direktem Kontakt mit den Früchten das Wasser ebenso absorbierten wie den Wasserdampf aus dem Verpackungsvolumen. Ähnlich wie bei den wasserdampfdurchlässigen Folienbereichen ist es mit den FruitPads möglich, durch die Wahl geeigneter Fruktosegehalte übermäßige Wasserverluste der Produkte zu vermeiden. In den unterschiedlichen Abschnitten dieser Dissertation werden die Nutzungspotentiale zweier innovativer Techniken zur Feuchtigkeitskontrolle in MAHP-Verpackungen am Beispiel von Erdbeeren detailliert behandelt. Die in diesen Experimenten erzielten Ergebnisse vertiefen das Verständnis der Einflüsse von Fruchtphysiologie, Temperaturmanagement und Verpackungsgeometrie auf die Feuchtigkeit und die Kondensation in Verpackungen. Diese Ergebnisse leisten damit einen wesentlichen Beitrag zum wissenschaftlichen Verständnis der MAHP und helfen der Verpackungsindustrie bei der Wahl

der optimalen Technik für eine effektive Kontrolle und Regulation der Feuchtigkeit in Fruchtverpackungen.

Acknowledgement

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List of abbreviations and symbols

Abbreviation	Description
FAO	Food and Agriculture Organization
UN	United Nations
MAP	Modified atmosphere packaging
MAHP	Modified atmosphere and humidity packaging
IP	Intelligent packaging
AP	Active packaging
MA	Modified atmosphere
RR	Respiration rate
RH	Relative humidity
TR	Transpiration rate
PP	Polypropylene
BOPP	Bi-axially oriented polypropylene
DOF	Degree of filling

Symbols	Meaning
O_2	Oxygen
CO_2	Carbon dioxide
H_2O	Water
M_{TOT}	Total mass losses
M_{WAT}	Water mass loss
M_{SUB}	Substrate mass loss
M_{ETH}	Ethylene mass loss
M_{VOL}	Emitted volatile organic compounds mass loss
NaCl	Sodium chloride
$CaCl_2$	Calcium chloride
KCl	Potassium chloride

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1. Introduction

1.1 Problem statement and motivation

Coping with the demand of securing global food safety and combating global hunger for the growing population that is expected to reach 9.8 billion by 2050 is one of the global challenges to be faced by humanity in the upcoming years. The challenge seems to be even harder to face when one third of all edible parts of food produced is lost or wasted, this corresponds to 1.3 billion tons of food per year (FAO, 2011). Due to environmental constraints, such as depleting of agricultural land and resources (e.g. water and energy), simply producing more food is not a feasible solution. On the other hand, an obvious solution is to reduce food losses and waste, and therefore maximize the use of food that is already produced. This will reduce the environmental impacts of waste as soil pollution is lessened. Moreover, it is a sustainable solution as it does not make use of any additional land and resources. In addition, it will directly contribute to achieving the United Nations' (UN) ambitious goal to halve per capita global food waste by 2030, and to the UN Sustainable Development Goal number 2 of zero hunger. This goal aims not only at ending hunger but at ensuring that everyone have access to nutritious, safe and sufficient food all year round (UN, 2015).

Fresh produce are known to provide valuable sources of essential nutrients such as vitamins, minerals, antioxidants and complex carbohydrates (Lee et al., 1995). Recklessly, from all food that is being wasted and lost, fresh produce, inter alia roots and tubers, have the highest wastage rates (45 %) of any food product. Almost half of all fresh produce produced are simply wasted (FAO, 2011). Such high wastage rate is due to the fact that fresh produce are unique among food products as they remain metabolically (e.g. respiring) and physically (e.g. transpiring) active and their shelf and storage life are shortened as consequence of these processes (Mahajan et al., 2014; Zagory and Kader, 1988). Therefore, there is a need to understand the physiological aspects of fresh produce in order to provide optimal solutions for extending shelf life and minimize postharvest losses.

As illustrated in Figure 1, there are three main paths that can be taken into account to tackle the problem of food loss and waste (Porat et al., 2018). The first is the technological path, which focuses on the development of effective preservation technologies that are capable of inhibiting fresh produce losses (Lee et al., 1995). The second is through consumer behaviour studies, which include consumer awareness campaigns, advertisements and instruction on how to do appropriate

home storage of fresh produce, among others. Lastly, the third is through policy and legislative measures, such as application of tax levies and fees on generation of food waste, revisions of food safety regulations and changes in marketing quality standards (Porat et al., 2018).

Figure 1. Possible pathways to reduce food loss and waste

Among these pathways, the technological pathway is the most used. Among the technologies are advances and optimization in logistic, and in packaging and storage of fresh produce. Advances in logistic are, in turn, directly related to the optimization of storage and packaging systems. Nowadays, it is also linked to adoption of digitalization systems. Amidst advances in storage technologies include ethylene, gas composition and cold chain management, the use of sensors and dynamic controlled atmosphere storage facilities, humidity regulation, and use of anti-microbial agents (Lee et al., 1995; Mahajan et al., 2014; Porat et al., 2018). Lastly, among packaging technologies are modified atmosphere packaging (MAP), modified atmosphere and humidity packaging (MAHP), intelligent packaging (IP) and active packaging (AP) (Gaikwad et al., 2018).

The beneficial effects of application of MAP technology on fresh produce as well as the ideal modified atmosphere (MA) conditions for a wide variety of fresh produce have been reviewed in numerous studies (Kader, 1986; Kader et al., 1989; Lee et al., 1995). Even though the benefits of MAP technology are known this technology is still not yet fully applied in practice. This was

confirmed by analysing packaged strawberries sold in two different supermarkets in the Potsdam area, Brandenburg, Germany (Table 1).

Table 1. Practiced packaging and storage conditions of strawberries in the Potsdam area, Brandenburg, Germany

Parameters analysed	Supermarket 1	Supermarket 2		
	1	1	2	3[*]
O_2 (kPa)	17.1	20.7	20.7	20.7
CO_2 (kPa)	4.6	0.0	0.0	0.0
Declared mass (g)	500	300	500	1000
Strawberry mass (g)	499.9	308.7	507.0	1137.7
Package dimensions (cm)	19 x 10.5 x 5	19 x 11 x 4	18.5 x 11.5 x 8	29.5 x 19.5 x 4.5
Type of package	Plastic clamshell tray and film cover	Paper-based tray and film pouch	Plastic clamshell tray with plastic lid	Wooden container covered with paper and film cover
# of perforations	0	18 ($\varnothing$ = 7.5 mm)	12 (Area = 87.9 mm^2)	18 ($\varnothing$ = 8.33 mm)
Condensation	yes	no	no	no
Refrigeration	no	no	no	no

= Number; $\varnothing$ = diameter of perforation. [*]Contained the following message on the packaging film: "to maintain the quality please store in the refrigerator".

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These results showed that all the strawberries analysed were packaged without making use of any of the available improved packaging systems (e.g. MAP, MAHP or AP). The lack of use of such improved systems, as well the absence of refrigeration, might lead to accelerated spoilage and subsequent food waste whereas if MAP/MAHP/AP would have been applied it could have full potential to extend shelf life further.

MAP design considers the respiration rate (RR) of the product for deciding target gas barrier (O_2 and CO_2) properties of packaging materials. Nevertheless, besides O_2 and CO_2 regulation, it is also important to control in-package humidity, in order to avoid high relative humidity (RH) that might lead to condensation inside MAP systems (Dennis, 1986; Giuggioli et al., 2015; Kader et al., 1989). In-package condensation might result in defects in external appearance, accelerated fungal decay, and negative perception by consumer (Holcroft, 2015; Linke and Geyer, 2013; Yildirim et al., 2018). This has led to a paradigm shift from research focusing on MAP to integrated MAHP systems. MAHP application is product specific; therefore, a deep understanding of how the physiological processes of fresh produce (e.g. how much water is released by the product), temperature management, moisture control strategy, and package geometry and design affects the in-package humidity and condensation should be studied in detail for each fresh produce. Nevertheless, most of the studies carried out on MAHP so far simply evaluate the performance of a specific moisture control strategy applied to fresh produce packaging under fixed conditions (e.g. package design and temperature). In that context, the overall aim of this study was to enhance the knowledge about, and to improve the techniques of MAHP. For that, this thesis focused on developing a model for water loss and evaluating the design and effectiveness of two feasible and innovative moisture control strategies, in reducing condensation, at fixed and under fluctuating storage temperature, using strawberries as a case study.

Based on the background information provided, the research questions for this PhD thesis's were formulated as follows:

- Transpiration rate (TR) models have been widely reported in the literature, mainly for unpackaged products with unrestricted air flow. Can these models be applied to predict water loss of packaged products?

- Total mass loss of product accounts for transpiration due to water vapour deficit as well as for substrate utilization in the respiration process. Is it possible to separate the two aspects in order to accurately quantify water loss?

- Fructose is highly hygroscopic and known for its high moisture absorption capacity. Can this active compound be integrated into pads (inner layer) for regulating moisture inside packages containing fruits?

- Highly water permeable films are commercially available but are they really suitable for packaging of fresh produce in terms of controlling moisture condensation and minimizing product mass loss?

- Can the two innovative techniques of MAHP addressed in this PhD thesis control the in-package relative humidity and reduce condensation under fluctuating temperature?

Based on these research questions hypotheses were formulated for this PhD work:

- Models for TR for unpacked products cannot be used for packaged fresh produce as the environmental conditions differ to a great extent;

- The commonly used calculation to express substrate loss is not valid for packaged fresh produce;

- Fructose has good potential as an absorbent, when incorporated to pads, to absorb headspace water vapour;

- The limited fixed area of highly water vapour permeable film used as a window on a package can help to prevent excessive product mass loss while lessening/avoiding condensation; and,

- Fructose integrated into FruitPads and highly water vapour permeable films have good potential for controlling in-package humidity and reducing condensation under fluctuating storage temperature.

1.2 Objectives

To accomplish the aim of this study and to answer the research questions and test the above stated hypotheses the following objectives were set and structured into chapters:

- To provide a comprehensive/theoretical background on packaging design, transpiration and the role of integrated mathematical models in MAHP design (Chapter 2);

- To evaluate the transpiration processes of packaged and unpacked strawberries and develop transpiration rate predictive models for packaged and unpackaged strawberries (Chapter 3);

- To investigate the moisture absorption kinetics of FruitPad containing different contents of fructose and develop a predictive model for the FruitPad moisture absorption (Chapter 4);

- To propose a specific design with dual functionality of film as window on a package for controlling gas and water vapour independently, and moisture control with application and experimental validation for strawberries (Chapter 5); and

- To investigate the impacts of fluctuating storage temperature on the performance of moisture regulation strategies for packaged strawberries (Chapter 6).

1.3   Thesis outline

This thesis is structured into seven chapters.

Chapter 1 is the introductory chapter that states the problems and motivation of the thesis. In addition, it highlights the PhD thesis's research questions and hypotheses and sets the PhD thesis's objectives.

Chapter 2 provides the theoretical background on packaging in general and specifically on the regulation of humidity in fresh produce packaging by MAHP design. It provides a review of the mechanisms and modelling of transpiration process in horticultural products. Moreover, this chapter extensively reviewed moisture evolution in packaged fresh horticultural produce and the roles of integrated mathematical models.

Chapter 3 provides comprehensive knowledge on the mechanistic basis of transpiration and respiration processes and their interaction. Moreover, it provides information on the contribution of these processes to the water loss of packaged and unpackaged strawberries. Finally, it provides mathematical models for water loss of packaged and unpackaged strawberries. Moreover, it highlights the potential application of the TR model for packaged strawberries, based on degree of filling (DOF), towards the selection of optimal moisture control strategies for strawberries.

Chapter 4 reports on the analyses of moisture absorption kinetics for FruitPads embedded with different contents of fructose (0, 20, and 30 %) with further application of such pads in packaging

of fresh strawberries. Moreover, it presents a model that predicts changes in the moisture content of the FruitPads with respect to storage and humidity.

Chapter 5 investigates the effects of packages containing windows (33, 66 and 100 % of total upper package area) of highly water permeable films (Xtend® and NatureFlex™) on the odour profile, condensation, gas composition, and postharvest quality attributes of strawberries stored under MAHP.

Chapter 6 evaluates the humidity regulating properties and the performance of different packaging design systems, namely highly water vapour permeable films (NatureFlex™ and Xtend®) and FruitPad of different fructose contents (0, 20, 30, 35 and 40 %), for strawberries under fluctuating temperatures (between 10 °C and 20 °C) for 5 days. Package performance was evaluated in terms of headspace gas composition, mass loss, condensation, physico-chemical changes, and visual and ortho-nasal quality evaluation.

Chapter 7 provides a comprehensive discussion and conclusions on findings obtained from this PhD thesis. The future perspectives on MAHP and condensation control measures were equally proposed based on the conclusions drawn from this study.

2. Theoretical background and literature review

2.1 Packaging

In the early times there was little need for packaging as humankind consumed food immediately and on the spot; and when containers were needed, nature and natural materials were used. However, the need for transportation of food and water for longer distances, the needs and concerns of people, competition in the marketplace, changed lifestyles, as well as discoveries and inventions led to further packaging developments (Figure 2) (Berger, 2002).

Figure 2. Developments in packaging

Nowadays, packaging plays a fundamental role in the supply chains of various products: electronics, food, industrial materials, garden products, consumer household items, among others. Primarily, it was developed with the aim of protecting its content from contamination and environmental damage, as well as to facilitate transport and storage of products (Berger, 2002). Nevertheless, it has also been used for decades as a retail marketing tool and as an interface to market the product to the final consumer (Sara, 1990). In the case of food products, the role of packaging goes beyond product protection and advertisement. Food packaging aids in preserving food quality and safety from growers to consumers (Gaikwad et al., 2018). Consumers increasing awareness of the importance of eating healthy and safe, high quality non or minimally processed food has led to improved food packaging systems for fresh produce (Giuggioli et al., 2015). Some of the improved packaging systems are modified atmosphere packaging (MAP), modified atmosphere and humidity packaging (MAHP), intelligent packaging (IP) and active packaging (AP) (Figure 3).

There is a rapidly growing interest in application of such packaging technologies to fresh produce evidenced from the growing literature within the last decade. This increase can be seen through a

keyword-based search, using 'AND' as a connector between keywords, on all databases of Web of Science (Table 2). Possible reasons contributing to the growth of this market is the increasing demand for convenience and ready-to-eat food, especially in the emerging economies.

Figure 3. Main aim of improved packaging systems

Table 2. Number of articles found on web of science databases on March 2019

Keywords	Number of articles		Percentage change (%)
	Before 2009	After 2009	
MAP	1652	2250	36.2
MAP AND fresh produce	192	254	32.3
MAHP	75	134	78.7
MAHP AND fresh produce	15	32	113.3
AP	2274	5478	140.9
AP AND fresh produce	17	88	417.6
IP	245	699	185.3
IP AND fresh produce	2	10	400.0

As evidenced by literature, from the available improved packaging systems, MAP is the most studied for fresh produce. MAP aims in minimizing the physiological and microbial decay of fresh produce by placing them in an atmosphere that is different from air composition (Kader et al., 1989; Rahman, 2007). The most commonly used packaging material for MAP applications is polypropylene (PP) film with varying numbers and sizes of perforations matching with

respiration rates (RR) of products (Robertson, 2012). Currently, MAP design considers the product respiration as the only important parameter for deciding target gas barrier properties of packaging materials (Caleb et al., 2013b; Castellanos et al., 2016). Nevertheless, besides O_2 and CO_2 regulation, it is also important to take into consideration the in-package humidity, in order to avoid condensation inside MAP systems (Dennis, 1986; Kader et al., 1989). Condensation, in turn, creates an ideal ground for microbial growth and should be avoided (Lee et al., 1995; Linke and Geyer, 2013; Rodov et al., 2010). Therefore, control of in-package humidity, in order to prevent moisture condensation, must also be taken into consideration while selecting packaging materials for MAP, MAHP and AP application. Such consideration will help to prevent/minimize condensation, maintain the freshness and extend shelf life of fresh produce along the supply chain, thereby reducing postharvest losses (Rodov et al., 2010).

2.2 Modified atmosphere and humidity packaging

Modified atmosphere packaging is a packaging technology with potential to extend shelf life of fresh produce by reducing the metabolic reaction rates as a result of changes on the surrounding atmosphere (Castellanos et al., 2016). MAP has been used as a supplement and in some cases even as a substitute, for refrigeration aiming at shelf life extension during transport and retail (Kader et al., 1989; Shirazi and Cameron, 1992). Among the benefits of using MAP technology are increased shelf life, economic losses reduction, increased transportation distances, product water loss reduction and product quality maintenance (Rennie and Tavoularis, 2009; Robertson, 2012). MAP systems rely on the interaction between the respiration of the product and the permeability of the packaging material to mainly O_2 and CO_2 (Caleb et al., 2013a; Kader et al., 1989; Lee et al., 1996).

Films, commonly used for MAP (e.g. PP) , usually have a low water vapour permeability and, thus, a high resistance to water vapour transfer, which by far exceeds the "diffusion pressure" exerted by the amount of water vapour normally released by fresh produce transpiration into the package (Lee et al., 1996; Lu et al., 2013; Rodov et al., 2010; Ryall and Pentzer, 1982). This leads to high in-package humidity, which in turn potentially may lead to condensation. Condensation may represent a threat to fresh produce safety and quality. As water may accumulate on packaging and/or product surfaces leading to defects in external appearance (Dennis, 1986), and/or promotes growth of spoilage microorganisms, and pronouncedly limits their shelf life (Kader, 1986; Kang and Lee, 1998; Linke and Geyer, 2013). In addition,

consumers perceive condensation as negative, thus it reduces the attractiveness of buying/consuming the product (Yildirim et al., 2018). Moreover, condensation on packaging films could modify their permeability to gases and, eventually, lead to anaerobic conditions (Lee et al., 1996). Therefore, alternatives to reduce or, at least, to control condensation is paramount in order to reduce deterioration and increase shelf life of packed fresh produce (Gaona-Forero et al., 2018).

This led to an extension of the term MAP to MAHP, which means 'modified atmosphere and humidity packaging'. In addition to the MAP concept, MAHP systems also aim at regulating/controlling the in-package humidity, thus taking the water vapour permeability of the packaging material into consideration. It is worth mentioning that MAP and MAHP systems can also be considered as active packaging (AP). The European Regulation (EC) No 450/2009 defines AP as packaging systems that are designed to "*deliberately incorporate components that would release or absorb substances into or from the packaged food or the environment surrounding of food*" (European-Commission, 2009). Hence, MAHP systems can make use of substances to absorb the in-package moisture and in this case they are also AP systems. The main challenge of MAHP applications is in finding the balance between creating the optimal atmosphere and reducing/preventing condensation, thereby, minimizing product mass loss to as lower as possible (Gaona-Forero et al., 2018; Mahajan et al., 2014).

Moreover, temperature management is of extreme importance as even minor temperature fluctuation occurring during handling and distribution might lead to condensation (Lee et al., 1996). The impact that temperature fluctuation exerts in the packaging system depends on the magnitude and duration of the fluctuation. For example, a small package (e.g. MAP or MAHP) is more affected due to its lower mass load and void volume, as compared to bulk packages because the heat transfer in such condition is much slower (Lee et al., 1996). In that sense, the application of MAHP to fresh produce that are commonly marketed in smaller packages is highly recommended. In addition to that, it makes much sense to shift from MAP to MAHP in case of highly transpiring fresh produce such as berry fruits, leafy greens, mushrooms and others (Ben-Yehoshua et al., 1998; Rodov et al., 2010).

Strategies applied to reduce condensation have progressed over the years and are moving towards more effectivity and flexibility so that they can be applied to any fresh produce (Figure 4). As it is a hard task to secure constant temperature during the entire supply chain of fresh produce, it is

useful that moisture absorbing systems are added to packaging systems of fresh produce (e.g. water absorbers). A wide range of moisture absorbers for food application has been recently reviewed by Gaikwad et al. (2018) and specifically for fresh produce application in Bovi and Mahajan (2017) (Chapter 2.4 of this thesis) and in Bovi et al. (2016) (Chapter 2.5 of this thesis).

Past	Present			Future	
Macro-perforations	Individual Shrink-wrapping	Highly water permeable films	Water contact absorber	Water non-contact absorber	Humidity windows of highly water permeable films
• Big holes • Reduce condensation • But no MAP	• Minimal headspace and temperature differences between product and film • But only suitable for spherical or cylindrical products	• Suitable for MAP applications (e.g. Xtend and NatureFlex) • But excessive mass loss	• Remove excess liquid (e.g. meat) • But only absorbs water in direct contact	• Attracts and holds water molecules (e.g. humidity regulating trays and FruitPads) • Absorbs water vapor in the headspace	• Suitable for MAP applications • Reduces mass loss as compared to use of packaging such films for 100% of packaging

Figure 4. Progress of MAHP technologies

Moreover, in order to select suitable strategies to regulate moisture it is essential to quantify how much water is lost by the product through transpiration. In that sense, it is essential to understand the mechanisms involved in the process of water loss (i.e. transpiration) (Chapter 2.3 of this thesis). In addition, it is very helpful to know the role integrated models for transpiration can play on the selection of moisture control strategies by predicting water loss (Chapter 2.5 of this thesis).

2.3   Mechanisms and modelling of water loss in horticultural products

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Mechanisms and Modeling of Water Loss in Horticultural Products

Graziele G Bovi[a], **Oluwafemi J Caleb**[b], **Werner B Herppich**[a], **and Pramod V Mahajan**[a], [a] Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany; and [b] Agricultural Research Council (ARC), Stellenbosch, South Africa

Introduction

Fresh horticultural products have a limited shelf-life as they continue their metabolic activity even after harvest. They keep on losing water due to transpiration and indirectly due to mitochondrial respiration. Harvested horticultural products can no longer replace the lost water from the soil and their water balance is inevitably negative (von Willert et al., 1995). Consequently, they depend on their own reservoir of stored water. To some degree, these water resources are supplemented by the water metabolically produced in the respirational end-oxidation in mitochondria. Water loss from horticultural products is directly related to economic loss since it causes a reduction in saleable mass and deterioration of external appearance due to wilting and shriveling of the product. As long as the produce continues losing water, its shelf life, quality and consumer appeal further decreases (Bovi et al., 2016; Linke and Geyer, 2013).

Transpiration is a process driven by the water vapor pressure difference between the product and its surrounding atmosphere. It comprises three fundamental stages (Fig. 1): i) water is diffused, mainly in water vapor form, from intercellular zones to the surface of the product; ii) water is evaporated from the exterior surface layer of the product; and iii) convective mass transfer of the water vapor to the neighboring environment (Becker and Fricke, 2001; Bovi et al., 2016; Veraverbeke et al., 2003). Respiration is a complex metabolic process comprising several different pathways that produce metabolites, carbon dioxide (CO_2), biochemical energy, reduction equivalents and, finally, water from the oxidation of atmospheric oxygen (O_2) at the expense of stored sugars, organic acids, lipids or fat (Caleb et al., 2016a). Consequently, both transpiration and respiration plays an important role in water loss and in the postharvest quality of horticultural products. Transpiration plays a direct role whereas respiration plays an indirect role by suppling additional water which can be lost in the transpiration process.

Modeling of water loss in horticultural products is a useful tool in predicting the physiological response of fresh produce under different storage conditions without the need of directly measuring the respective parameters in real time (Castellanos and Herrera, 2015). Nowadays, the use of predictive mathematical models is a common practice to aid in the development of optimum storage and packaging systems for horticultural products. However, most of the reported models do not use an integrative approach, but are restricted to independent respiration and transpiration models. Nevertheless, the addition of the respiration process to transpiration
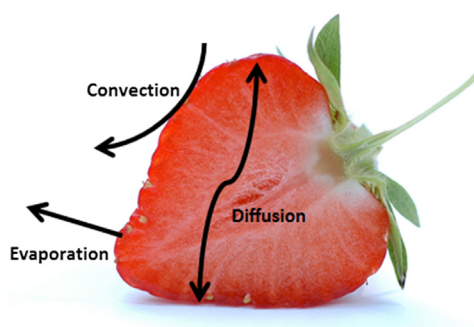

Figure 1 Mechanisms involved in the transpiration process in horticultural products: water diffusion, evaporation and convective mass transfer.

models (Mahajan et al., 2016; Song et al., 2001, 2002; Xanthopoulos et al., 2017) were already reported in the literature. In this context, the aim of this article is to provide a comprehensive review on existing mathematical models for describing water loss of horticultural products. In addition, factors affecting water loss in horticultural products are highlighted and recent techniques for measuring transpiration and respiration are discussed.

Measurements of Water Loss in Horticultural Products

Water loss in horticultural products is commonly measured by quantifying the amount or the mass of water lost per unit of time, called transpiration rate (TR). There are many approaches to measure water loss via transpiration analyses of horticultural products, nevertheless, the two most used approaches are: the gravimetric measurement and the theoretical determination via the Fick's first law of diffusion (Becker and Fricke, 1996; Bovi et al., 2016; Sastry, 1985).

Gravimetric Approach

This approach was first introduced in the late 1920s and is called "Stocker's rapid weighing method" (Stocker, 1929). Nowadays, it is commonly called the mass loss approach and it involves measuring the mass of the horticultural product at regular intervals. The results of this measurement can be expressed as the changes of mass per unit time and per unit surface area (TR_s) (Eq. 1), and/or per unit of initial mass (TR_m) (Eq. 2):

$$TR_s = \frac{m_i - m_t}{t \cdot A_s} \tag{1}$$

$$TR_m = \frac{m_i - m_t}{t \cdot m_i} \tag{2}$$

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 surface area of the product. It is worth mentioning that this approach neglects the additional mass loss due to substrate use by respiration. As a consequence, TR may be slightly overestimated; nevertheless, this approach has been widespread used in horticulture to quantify water loss.
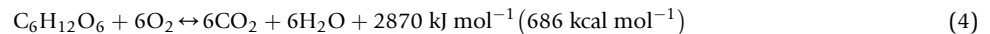
Theoretical Approach

A simple mathematical equation based on Fick's first law of diffusion can be used to estimate TR of a specific product and thus, predict its water loss (Eq. 3).

$$TR_m = k_t \cdot (p_i - p_a) \tag{3}$$

where TR_m is transpiration rate, mass basis; k_t is transpiration coefficient of the horticultural product; p_i is internal water vapor partial pressure assumed to be equivalent (or close) to saturation water vapor pressure at produce tissue temperature; and p_a is ambient water vapor partial pressure (Becker and Fricke, 2001; Sastry and Buffington, 1983). Furthermore, it is important to state that liquid water changes phase inside the horticultural product, nevertheless, the relevant diffusion area for the transpiration to happen is the product's surface.

Role of Respiration in Water Loss

Through the respiration process horticultural products consume O_2 and their own organic reserves (i.e. carbohydrates, lipids, and organic acids available in the fresh produce), and release CO_2, water, and heat (Eq. 4) (Fonseca et al., 2002).

$$C_6H_{12}O_6 + 6O_2 \leftrightarrow 6CO_2 + 6H_2O + 2870 \text{ kJ mol}^{-1} (686 \text{ kcal mol}^{-1}) \tag{4}$$

In this equation, 192 g of O_2 is used to oxidize 180 g of glucose and as a result 264 g of CO_2, 108 g of H_2O, and 2870 kJ mol^{-1} is produced. The CO_2 diffuses out of the tissue, the water is incorporated into the aqueous solution of the cell, and from the 2870 kJ mol^{-1} produced a part is lost due to entropy and heat and the rest is used to produce 38 ATP molecules (Saltveit, 2004). The energy that is lost as heat can have a direct effect on tissue temperature, and thus on the water vapor partial pressure deficit (VPD) and therefore affects transpiration. Thus, in summary the roles of respiration in water loss of horticultural products are i) in supplying additional water, which can be lost in the transpiration process and ii) by influencing transpiration due to increase of product temperature, and therefore alteration of the VPD.

Furthermore, respiration can be estimated by either measuring the O_2 consumed or the CO_2 released by the produce. Respiration rates (RRs) are, among others, mostly given as mg of the respective gas exchanged per kg of produce fresh mass per hour. The relevant gas exchange is often measured in "closed" systems, but also "open" steady-state systems or "permeable" systems are used. More detailed information on each method can be found in von Willert et al. (1995) and Fonseca et al. (2002). Moreover, respiration activity can be affected by various pre-harvest and postharvest factors. These factors include the stage of maturity or

development of the horticultural product, its cultivar, harvest time, farming system, growing region, pre-treatment and climatic conditions during growth in preharvest. During postharvest, temperature, chilling stress, atmospheric composition (concentration of O_2 and CO_2), storage duration, and ethylene exposure are the major influencing factors (Caleb et al., 2016a).

Factors Affecting Water Loss in Horticultural Products

Many factors affect water loss of horticultural products during postharvest handling. These may include intrinsic factors such as shape, size, and structure, i.e. morphological and anatomical characteristics of the produce, its developmental stage, and others. In addition, extrinsic environmental factors are also very important (Table 1). The effects of ambient temperature and air humidity on water loss in horticultural products have been extensively reported over the last years. For instance, Xanthopoulos et al. (2017) reported that TR was found to be higher at 70% RH and 10 °C and lower at 95%, both at 0 and 10 °C, and the corresponding VPD was 0.522 and 0 kPa. Volpe et al. (2018) reported a decrease in water loss of fresh-cut iceberg lettuce by increasing RH from 76% to 100% at constant temperature and an increase in water loss by increasing temperature from 2 to 10 °C, at fixed RH. These results show that both variations in temperature and air humidity affect the VPD, and thus water loss. In addition, speed of airflow may also affect water loss resulting from the direct effects of air speed on the boundary layer conductance (Baltaci et al., 2010). Forced airflow (high air speed) may result in higher water losses than natural convection, i.e. extreme low air speed conditions. Moreover, injuries on the outer tissue layers may also increase water loss as they reduce the surface resistance by exposing internal produce tissue (Sastry, 1985). Furthermore, respiratory heat generation and evaporative cooling also affect water loss by modifying the VPD between the product and the environment. Mahajan et al. (2016) reported that heat of respiration increases surface temperatures of fresh mushrooms above that of the surrounding air, thereby increasing VPD (the driving force of transpiration) and allowing water losses even in a water vapor saturated environment. On the other hand, when ambient air humidity was below saturation, the VPD caused water evaporation from the product surface resulting in evaporative cooling.

Produce shape and size are also important factors affecting water loss. Products with large surface area to mass ratios provide a considerable large diffusion surface area, and thereby increase water loss (Sastry, 1985). Morphological and anatomical characteristics of the horticultural product also have a significant effect on mass loss. For instance, well-developed epidermal or peridermal tissues and/or a waxy surface (e.g. pomaceous or stone fruits) provide additional resistance against water diffusion compared to products without these structures (e.g. mushroom) (Sastry and Buffington, 1983). Lastly, the maturity stage in fresh produce after harvest has been shown to significantly influence mass loss mostly due to its effect on structure and thickness of these surface tissues. Consequently, immature but also over-mature fruit transpire faster than if optimally mature (Mishra and Gamage, 2007).

Modeling Water Loss in Horticultural Products

Modeling water loss in horticultural products is a challenging task; nevertheless, many attempts on modeling water loss have been made over the last two decades. Bovi et al. (2016) have compiled a summary of TR models developed before the year of 2016 and this article presents models developed over the last two years (Table 2). Castellanos et al. (2016) presented a mathematical model describing (i) the water vapor, O_2 and CO_2 concentration evolution in the in-package headspace, (ii) the product mass loss and (iii) the condensation of water in modified atmosphere system with perforations. The transpiration was considered the sum of water released from the product due to respiratory heat gain (heat transfer) and the difference in concentration between the product and its surrounding (mass transfer). This model was validated in a modified atmosphere packaging test and showed good predictability for mass loss evolution, accumulation of condensed water and changes in RH. Mahajan et al. (2016) developed a generalized mathematical model to predict TR as a function of temperature, RH of storage environment and respiratory heat generation under water vapor-saturated conditions. Murmu and Mishra (2016) developed TR models based on unsteady state energy balance equation and regression equation. These models were fitted to the TR of three banana cultivars. The authors reported that the energy balance model fitted the TR data better than the regression model at all the studied conditions. Furthermore, Xanthopoulos et al. (2017) quantified the water loss (TR_mnet) due to two sources, respiration (WL) and transpiration (TR_m), Eq. (5).

$$TR_m net = TR_m + WL \tag{5}$$

Table 1   Factors affecting water loss in horticultural products

Extrinsic factors	Intrinsic factors
temperature	shape, size, and structure
air humidity	morphological and anatomical characteristics
air flow	physiological condition (e.g. maturity stage)
physical condition (e.g. surface injuries)	
respiratory heat generation	
evaporative cooling	

Table 2   Summary of up-to-date water loss models applied for various horticultural commodities under different storage conditions

Proposed model equation	Storage conditions	Product	References
$TR = \frac{q}{\lambda} + k(a_{wi} - a_w)$	T^a: 12 RH^b: 75	Feijoa fruits	Castellanos et al. (2016)
$TR = k\,(a_{wi} - a_w)(1 - e^{-aT}) + 8.6\,RR\,e^{\frac{-Ea}{R}\left[\frac{1}{(T+273)} - \frac{1}{(Tr+273)}\right]}$	T^a:13 RH^b: 100	Mushrooms Strawberries Tomato	Mahajan et al. (2016)
$TR = \frac{Q_s\,RR\,M + h_s\,A\,(T-T_p) - M\,C_s\,\frac{dT_p}{dt}}{M\lambda}$	T^a: 10, 20, 30 RH^b: 70, 80, 90	Banana	Murmu and Mishra (2016)
$TR = 63.40 - 0.31\,x_1 - 5.29x_2$	T^a: 10	Banana Singapura	
$TR = -196.88 + 9.33\,x_1 - 71.71x_2 + 0.32x_1x_2$	T^a: 20		
$TR = 405.35 - 5.68\,x_1 - 73.723x_2 + 0.06x_1x_2 + 0.03x_1^2 - 7.81x_2^2$	T^a: 30 RH^b:70, 80, 90		
$TR = k\,e^{\left[-\frac{E_a}{R}\left(\frac{1}{T+273} - \frac{1}{T_r+273}\right)\right]}\left(a_{wi} - \frac{RH}{100}\right)$	T^a: 0, 10, 20 RH^b: 70, 80, 95	Pears	Xanthopoulos et al. (2017)
$\ln(TR) = \ln(a_k + b_k\,RH) - \left[\left(\frac{a_{E_a} + b_{E_a}\,RH}{R}\right)\left(\frac{1}{T+273} - \frac{1}{T_r+273}\right)\right]$	T^a:2, 6, 10, 14, 18 RH^b: 86,96, 100	Fresh oyster mushrooms	Azevedo et al. (2017)

TR is transpiration rate; q is effective respiration heat used in the water evaporation from the produce; λ is latent heat of moisture evaporation/vaporization; k is mass transfer coefficient; a_w is water activity of the surrounding environment; a_{wi} is water activity of the produce; a is a coefficient; Tr is reference temperature; RR is respiration rate of the product at Tr and 8.6 is the conversion factor for obtaining TR from the respiratory heat generation; Ea is activation energy; R is universal gas constant; Q_s is respiratory heat generation; M is the product weight at time (t); h_s is the convective heat transfer coefficient $\left(h_S = 1.32 \times 3600 \times 24 \times \sqrt[4]{\frac{T-T_p}{d}}\right)$; T_p is product surface temperature at time (t); C_s is product specific heat; and a_k, b_k, a_{E_a} and b_{E_a} are model constants.
[a]T is temperature (°C).
[b]RH is relative humidity (%).

where WL is the water loss due to respiration rate (g water $kg^{-1}h^{-1}$), and can be calculated by Eq. (6).

$$WL = 10 \cdot \frac{A}{B} \cdot RR \qquad (6)$$

where A = (108 g of water) × (9.02 g of sugar/180 g of sugar), B = (134.4 × 10^{-3} mL [CO_2]) × (9.02 g of sugar/180 g of sugar), and RR is the respiration rate (mL [CO_2]100 g^{-1} h^{-1}). Results showed that close to saturation (20 °C and 95% RH), the water loss due to respiration accounts for 39% of the water loss due to VPD. Finally, Azevedo et al. (2017) developed an empirical mathematical model to analyze the influence of time, temperature and RH on the mass loss rate of fresh oyster mushrooms. In this study, TR was modelled using an Arrhenius-type equation and the parameters of the model were described following a linear relationship with RH. Overall, modeling water loss is extremely important across fresh produce value chain as it can be applied as guiding tool for industries on management of water loss in storage and packaging of horticultural products.

Management of Water Loss in Packaged Horticultural Products

If not controlled, the water released by horticultural products results in water condensation inside packaged products, and this represents a risk to product quality (Bovi and Mahajan, 2017; Linke and Geyer, 2013). Thus, water loss management is essential for extending the shelf life of horticultural products as it can lessen the risk of spoilage microorganisms. Nevertheless, when it comes to selecting the most appropriate water loss management strategy there is always a dilemma in finding a balance between low or high humidity. On one hand, low humidity leads to excessive water loss and shrinkage, whereas on the other hand, high humidity promotes favorable conditions for microbial growth.

There is no simple solution to solving this dilemma as the most appropriate strategy is product specific and thus, every horticultural product should be analysed individually. Nevertheless, factors such as optimum RH and storage temperature for a specific product, perishability, time needed for the harvested product to reach retailers and consumers, and temperature fluctuation along the supply chain should be taken into account. Furthermore, some strategies for managing water inside packaged fresh produce are: i) micro-perforations (Ben-Yehoshua et al., 1998); ii) use of contact moisture absorbers (Mahajan et al., 2008; Song et al., 2001); iii) use of non-contact moisture absorbers (Bovi et al., 2018; Rux et al., 2016); and, iv) use of a packaging material with high permeability to water vapor (Caleb et al., 2016b; Volpe et al., 2018).

Conclusions

Water loss in horticultural products is complex as it involves factors such as product transpiration (directly) and respiration (indirectly). Nevertheless, modeling water loss has a great potential to be applied by industries as an aiding tool on the selection of water

control strategies. In addition, it allows prediction of the physiological responses of horticultural products under different storage conditions without the need of accessing these in real time.

Moreover, there is lack of studies addressing substrate loss in horticultural products. This is an important factor for the quantification of water loss, as usually substrate loss is neglected and the total mass loss of a product is considered as being water loss. Therefore, efforts should be made to include substrate loss due respiration process so that it can be subtracted from the total mass loss of horticulture products and thus, water loss in horticultural products could be quantified more precisely.

Acknowledgment

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Regulation of Humidity in Fresh Produce Packaging

Graziele G Bovi and Pramod V Mahajan, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany

Introduction

Packaging of fruits and vegetables plays a key role in maintaining quality and safety of the product, promoting their competitiveness, and making them available in a convenient format for easy transport and storage (Robertson, 2013). Appropriate selection of packaging materials offer a possibility to slow down the physiological processes of fresh produce, and thus extend their shelf life. One of the major problems with packaged fresh produce is condensation leading to excess free water inside the package. It is well known that the in-package humidity is influenced by respiration heat and transpiration of the fresh produce, as well as the water vapor permeability of the packaging material (Bovi et al., 2016). However, most polymeric materials used in fresh produce packaging have lower water vapor permeability relative to the transpiration rates of fresh produce. Therefore, most water molecules that evaporate from the produce do not escape through the film and remain within the package, enhancing the water vapor pressure in the package micro-environment. Under these conditions, even minor temperature fluctuations may result in in-package condensation, leading to produce sliminess, and acceleration of microbial growth (Linke and Geyer, 2013).

In-package condensation represents a threat to the product quality and safety as the free water stimulates growth of fungal and bacterial pathogens, and therefore results in decay and reduced shelf life (Bovi et al., 2016; Holcroft, 2015). In addition, condensation leads to defects in the external appearance, such as in the texture, skin color and surface structure (Linke and Geyer, 2013). However, there are moisture control strategies that can be taken into account in order to avoid/lessen condensation, regulate humidity, and absorb free in-package moisture. In this context, the aim of this article is to provide a comprehensive review of packaging materials and moisture absorbers currently available for regulating humidity in fresh produce packaging. Furthermore, the sources and causes of moisture in fresh produce packaging are discussed.

Sources and Causes of Moisture in Fresh Produce Packaging

The main sources and causes of moisture in packaged fresh produce are metabolic activity of fresh produce, e.g. respiration and transpiration, and temperature fluctuations during transportation along the supply chain.

Transpiration is the process by which water is lost through the surface of the produce driven by a concentration difference between the product's surface and the environment (Bovi et al., 2016; Veraverbeke et al., 2003). Respiration is a metabolic process that consists of the oxidative breakdown of organic reserves (i.e. carbohydrates, lipids, and organic acids available in the fresh produce) to carbon dioxide, water and energy (Fonseca et al., 2002). It is noteworthy that after harvest, fresh produce can no longer replace the water lost from the soil and therefore it depends solely on its own water content for these processes (Caleb et al., 2013). Therefore, it is important to have adequate humidity regulation inside fresh produce packaging in order to maintain the water loss of the product as low as possible.

Nevertheless, temperature fluctuations during handling, transportation, storage and marketing, as well as water vapor permeability of the packaging films, also play an important role in the in-package moisture evolution (Bovi et al., 2016). These aspects are not the source but the causes of moisture evolution in fresh produce packaging, as they are the main factors leading to condensation. Condensation inside packaged fresh produce occurs when water molecules evaporated from the product surface do not escape through the packaging film and condense within the package as a result of temperature differences (Linke and Geyer, 2013). The temperature
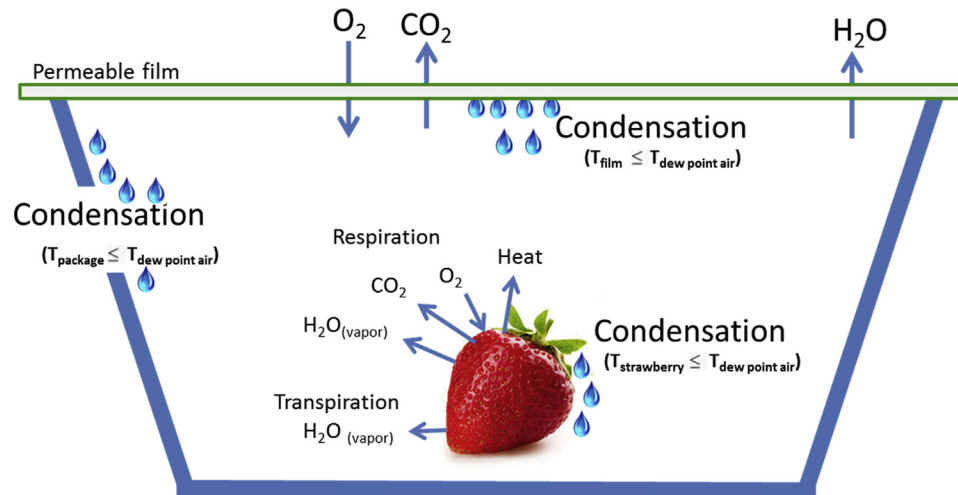
Figure 1 Moisture condensation dynamics.

at which condensation occurs is known as the dew point temperature and condensate is formed on any surface that is below or at the dew point temperature of the surrounding air as is shown in **Fig. 1** (Bovi et al., 2016; Holcroft, 2015).

In turn, condensation increases the in-package moisture content and consequently the in-package relative humidity (RH). RH is equal to the ratio (expressed as a percentage) of the partial pressure of water vapor present in the air to the saturation partial pressure at the environmental temperature (Powers and Calvo, 2003). It is noteworthy that there is a dynamic relationship between water vapor in the air and temperature. Air can hold less moisture at lower temperatures, and therefore when moist air is cooled, the decrease in temperature leads to an increase in RH (Holcroft, 2015). Therefore, adequate temperature control plays an import role in the regulation of humidity in fresh produce packaging as it affects RH directly. Furthermore, every horticultural product has an optimum storage condition for temperature and RH (**Table 1**).

Packaging Materials for Humidity Regulation

Selection of appropriate packaging materials is a key factor in regulating humidity as they play an important role in achieving optimum humidity conditions in packaged fresh produce. Most polymeric materials (polypropylene polyethylene, or polyvinyl chloride) used in modified atmosphere packaging (MAP) have low water vapor permeability (**Table 2**) and therefore, evaporated water molecules from the produce are not effectively transmitted across the packaging film and remain within the package, leading to in-package condensation (Rux et al., 2016; Song et al., 2001). Nevertheless, the use of perforated films, individual shrink-wrapping and enhanced permeable films help to lessen the risk of condensation occurring.

Perforated Films

Micro-/Macro-perforations are used in order to obtain higher gas and water vapor transmission through polymeric films. The number of perforations should be adjusted in order to match the equilibrium modified atmosphere (Joyce and Patterson,

Table 1   Optimum storage condition for some horticultural products

Fruits	Temperature (°C)	RH (%)	Vegetables	Temperature (°C)	RH (%)
Blackberry	−0.5–0	>90	Artichoke	0	> 95
Cherry, sweet	−1–0	>95	Asparagus	0–2	95–99
Kiwifruit	0	90–95	Broccoli	0	98–100
Lemon	7–12	85–95	Brussels Sprout	0	95–100
Passionfruit	7–10	90–95	Cabbage	0	98–100
Peache	−1–0	90–95	Carrot	0–1	98–100
Pineapple	7–12	85–95	Cauliflower	0	95–98
Raspberry	−0.5–0	> 90	Cucumber	10–12.5	95
Strawberry	0	90–95	Garlic	0	60–70
Watermelon	10–15	90	Lettuce	0	98–100

Gross et al. (2016, p. 202–599).

Table 2   Water vapor permeability of plastic films commonly used in modified atmosphere packaging (MAP)

Films	Water vapor permeability at 90%RH 25°C (mL cm cm^{-2} s^{-1} cm Hg^{-1})
Low density polyethylene (LDPE)	80
High density polyethylene (HDPE)	13
Polypropylene (PP)	57
Polyvinyl Chloride (PVC)	156–275

Robertson (2013, p. 108).

1994). It is well known that perforations have a beneficial impact on obtaining desirable gas and water vapor exchange rates within fresh produce packaging. Besides improving gas and moisture transfer, perforations have been reported to prevent in-package condensation and shorten cooling time (Fonseca et al., 2000; Hussein et al., 2015). Furthermore, perforation-mediated MAP can possibly reduce anaerobiosis and microbial growth related to moisture condensation (Hussein et al., 2015). Macro-perforations have been used to lower the in-package RH (Gross et al., 2016); however, they exclude the possibility of having modified atmosphere conditions within the packages as equilibrium modified atmosphere cannot be reached (Shirazi and Cameron, 1992).

Design of perforated mediated-MAP involves the use of mathematical models that are able to predict water vapor and gas permeability through the film as a function of perforations. Such models are useful in order to design adequate MAP (Hussein et al., 2015). For instance, Rennie and Tavoularis (2009) developed a mathematical model for perforation-mediated MAP that considers all the major biological and transport phenomena involved. It includes respiration, transpiration, condensation, heat transfer, and convective and diffusive transport of O_2, CO_2, H_2O and N_2. However, this model does not predict the in-package RH. Furthermore, various models for predicting gas and water vapor exchange through perforated film have been summarized in a recent review by Hussein et al. (2015).

Individual Shrink-Wrapping

Individual shrink wrapping (ISW) is a passive form of MAP used to pack individual fresh produce in order to maintain its freshness. The film usually used in this packaging technique is a polymer with selective permeability to CO_2, O_2, ethylene and water (Dhall et al., 2012; Megías et al., 2015). ISW satisfies the criteria of maintaining product's water content without increasing condensation as the film is closely in contact with the skin of the fruit (Joyce and Patterson, 1994). A study carried out by Rodov et al. (2010) showed that ISW is capable of controlling moisture condensation due to a minimal headspace volume and negligible temperature differences between the product and the film surface. Nevertheless, even though there are clear positive effects with this approach, it is limited to spherical or cylindrical products (e.g. cucumber, zucchini, and citrus) because if any part of the product is not in contact with the film then it leads to moisture accumulation (Joyce and Patterson, 1994; Rodov et al., 2010).

Enhanced Permeable Films

A wide range of films has been developed with relatively high permeability towards water vapor compared to the commonly used polymeric films such as polypropylene or polyethylene. For example, X-Tend® is a co-extruded film developed by StePac L.A. Ltd (StePac, Tefen, Israel). The water vapor transmission rate (WVTR) of this film (20-μm thick) is around 25×10^{-10} mol s^{-1}m^{-2} Pa^{-1}; the comparable value for low density polyethylene film is 1.2×10^{-10} (Rodov et al., 2010). Aharoni et al. (2008) reported that Xtend® can effectively modify both atmospheric composition and RH inside packages containing various fresh fruits and vegetables. Another example is the cellulose-based NatureFlex™ (Innovia Films, Cumbria, UK). The water permeability of this film is 200 g m^{-2} d^{-1} at 25 °C and 75% RH, which is very high compared to the conventional polypropylene film with a WVTR of 0.8 g m^{-2} d^{-1} (Sousa-Gallagher et al., 2013). Caleb et al. (2016) investigated the effects of using a window of NatureFlex™ film on polypropylene film on the postharvest quality of minimally processed broccoli branchlets. Their results indicated that the packages incorporated with cellulose-based composite film effectively prevented water vapor condensation on the film surface when compared to bi-axially oriented polypropylene and cling-wrapped commercial control. However, even though such films lessened the risk of condensation, better retained surface color and maintained quality attributes, due to its high WVTR, it resulted in excessive mass loss. More recently, Turan et al. (2017) developed a polyurethane film with a WVTR of 3830 g H_2O m^{-2} d^{-1} at 38 °C and 90% RH and moisture absorption of 0.2 g H_2O g^{-1} polymer at 25 °C and 98% RH. However, this film has not yet been tested for fresh produce packaging. Nevertheless, the challenge of using enhanced permeability films is finding a solution to design an optimal atmosphere and lessen the risk of in-package moisture condensation while still keeping produce mass loss as low as possible. Some authors such as Caleb et al. (2016) have used humidity windows instead of enhanced permeability film to cover the entire package in order to overcome this limitation.
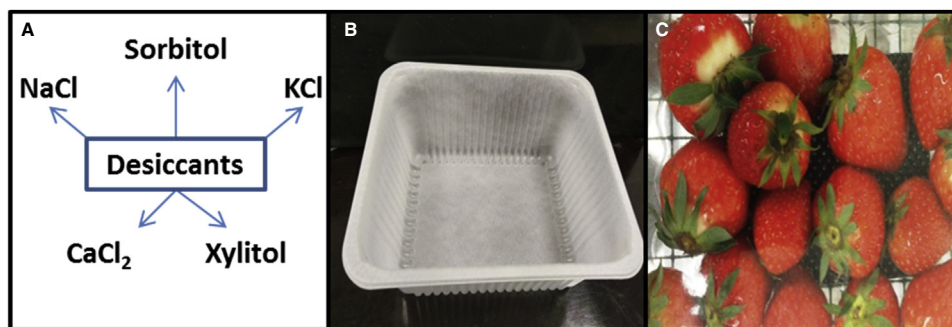
Figure 2   Moisture absorbers for humidity regulation. (A) Desiccants, (B) humidity regulating tray, and (C) package with pad and strawberries.

Moisture Absorbers for Humidity Regulation

Moisture absorbers absorb the in-package water vapor and/or free water, leading to a lowering of RH to a point at which condensation no longer occurs. Nevertheless, for the majority of fresh produce, low humidity is not appropriate as it can lead to excessive product weight loss. In a closed package, moisture absorbers absorb moisture from all sources, including the product. The quantity of water absorbed depends on (i) the type and amount of absorbent used; (ii) how strong the moisture is bound to the source; (iii) the amount of water that has already been absorbed by the absorber, and (iv) the temperature (Powers and Calvo, 2003). In the case of fresh produce packaging, the most commonly used moisture absorbers are desiccants and non-contact absorbers such as humidity regulating trays and pads (Fig. 2).

Desiccants

Another approach to regulate humidity can be through the use of desiccants. However, the selection of the appropriate desiccant and specification of the amount to be used is not as easy as it seems. The majority of the research carried out so far was based on a trial-and-error approach without using mathematical models. For instance, Ben-Yehoshua et al. (1983) used 5 g of $CaCl_2$ per fruit to control relative humidity between 80% and 88% in packages containing bell peppers. Shirazi and Cameron (1992) reported that 10 g each of dry sorbitol, xylitol, NaCl, KCl and $CaCl_2$ sealed with one mature green tomato fruit at 20 °C in simulated packages for 48 days resulted in stable relative humidities of approximately 75%, 80%, 75%, 85% and 35%, respectively. Song et al. (2001) studied the moisture sorption kinetics of xylitol ($C_5H_{12}O_5$) and sanwet IM-1000 (99% starch-grafted sodium polyacrylate) at 15 and 25 °C and developed a respiration-transpiration model to predict RH in the modified atmosphere system containing fresh produce and moisture absorbent. They reported that the moisture sorption increased with increasing temperature and the model prediction agreed well with the experimental data. Mahajan et al. (2008) developed a moisture absorber with high moisture holding capacity and slower rate of moisture absorption for the packaging of fresh mushrooms. Fast absorbing moisture absorbers such as $CaCl_2$, KCl and sorbitol were mixed with a slow absorbing desiccant such as bentonite in different proportions. However, none of the pure desiccants tested were found to be suitable for fresh produce as either they had low moisture holding capacity or did not have the ability to stay in the powder form for the longer period. Nevertheless, a drawback in the use of desiccants is that the system never comes to equilibrium, and the absorption process continues even after the dry powder desiccant has transformed into the liquid form (Mahajan et al., 2008).

Humidity-Regulating Trays

Humidity-regulating packaging trays were developed and patented by Langowski et al. (2008). They were developed by direct incorporation of the active substance (NaCl) in the packaging matrix. Trays were made from a thermoformed multilayer structure: polyethylene (outside)/foamed hygroscopic ionomer (active layer) with 0 (T-0) or 12 (T-12) wt% NaCl/hygroscopic ionomer (sealing layer, inside). Rux et al. (2015) assessed the impact of salt-embedded humidity-regulating trays on humidity and condensation behavior in mushroom packages at 7 °C and 85% RH. Results showed that the humidity-regulating tray maintained a stable RH (93%) inside the package and absorbed 4.1 g of water from the 11.4 g that were released from the mushrooms (4.5% of the total weight). Furthermore, Rux et al. (2016) investigated the moisture absorption kinetics of humidity-regulating trays and their application for fresh produce packaging. Results indicated that the humidity-regulating tray absorbed part of the water vapor produced by mushrooms during the 6 d of storage, but its regulatory capacity was not efficient enough to avoid in-package moisture condensation. Also, the headspace RH of trays was tested by covering the trays with 7 g of distilled water and a high barrier lidding film and found to be 89.8, 99.6 and 100% in the T-12, T-0 and control-PP trays, respectively. The T-12 trays containing fresh produce best regulated the in-package RH below 97% and maintained overall quality, but at the expense of slightly higher product weight loss (2–3 wt% for strawberries; 1 wt% for tomatoes) compared to the control-PP trays (0.3–0.6 wt%).

Pads

Pads generally consist of a lower and upper sheet of film and a core middle layer composed mainly of cellulose and an active ingredient that absorbs excess liquid in the package (Fang et al., 2017; Gouvêa et al., 2016). Due to the possibility of adding active and antimicrobial ingredients in the middle layer, absorbing pads are one of the most resourceful applications of active food packaging systems (Otoni et al., 2016). Although pads are mainly used in the meat industry, the use of such pads for fresh produce packaging has great potential in preserving the freshness of fruits and vegetables, as well as protecting them against mechanical injuries. McAirLaid's Vliesstoffe GmbH (Steinfurt, Germany) has a commercially-available pad named FruitPad. It consists of a 3-layer structure: upper film layer, active layer with cellulose, and lower film layer. The outer layers have micro-perforations in order to increase the moisture absorption. More recently, they have developed a new line of pads containing fructose. Fructose is hygroscopic and can absorb moisture from the package headspace. Therefore, it has potential to not only absorb free water in the tray but also to absorb excess water vapor from the package headspace, thereby avoiding condensation and maintaining humidity (White, 2014). However, there is not yet any information available on the in-package RH when using such pads.

A major challenge of humidity regulation in fresh produce packaging is finding a solution for creating an optimal humidity and reducing the risk of water condensation, while still maintaining produce weight loss as low as possible. The mathematical model proposed by Jalali et al. (2017) can be used to design the size and number of perforations in packaging materials to achieve both a modified atmosphere and desired humidity inside the package. Furthermore, the model can be improved by adding various active moisture control strategies such as humidity-regulating trays or active moisture absorbing pads. This can be done by incorporating in the mathematical model the moisture absorption kinetics of such active materials.

Conclusions

Moisture evolution in fresh produce packaging is complex as it involves many factors such as product transpiration, respiration, and permeability of packaging materials. Furthermore, it is compounded with temperature fluctuations along the supply chain leading to saturated humidity and moisture condensation inside the packaged fresh produce. Effective humidity regulation promises a great potential to further extend the shelf life of packaged fresh produce. Nevertheless, the challenge of using humidity regulators is always finding a balance between minimizing moisture condensation and keeping fresh produce mass loss as low as possible. Also, before selecting the most suitable strategy for moisture regulation, it is important to understand the physiological characteristics of the product. Furthermore, the use of predictive mathematical models can be valuable tools for selecting the most suitable strategy. The limitation is that such models are usually product specific due to fresh produce differences in transpiration and respiration, as well as different optimal/recommended humidity levels.

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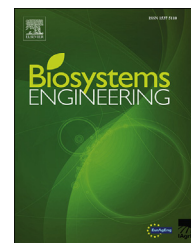
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Review

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

CrossMark

Graziele G. Bovi [a,b], *Oluwafemi J. Caleb* [a], *Manfred Linke* [a], *Cornelia Rauh* [b], *Pramod V. Mahajan* [a,*]

[a] Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering (ATB), Potsdam, Germany
[b] Department of Food Biotechnology and Food Process Engineering, Technical University of Berlin, Germany

ARTICLE INFO

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.

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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

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_∞	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})
δ	diffusion coefficient of water vapour in air (m^2 s^{-1})
τ, s	product skin thickness (m)
φ	fraction of product surface covered by pores (non-dimensional)
h_d, β	convective mass transfer coefficient(m s^{-1})
ξ_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)
ξ_2	fraction of surface behaving as porous membrane (non-dimensional)
μ	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})
F_w	water vapour flux through the perforated film (m^3 h^{-1})
α	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)
π	3.14 (non-dimensional)
R_h	radius of perforation (m)
N	number of pores (non-dimensional)
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 vapour (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)
ρ	gas mixture density (kg m^{-3})
ωH_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)
ωj	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_∞	is moisture holding capacity at equilibrium (g)
B	kinetic parameter (non-dimensional)

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., 2003b, 2003a). 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:

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

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

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 & Buffington, 1983; Sastry, 1985). This interaction is expressed mathematically as:

$$TR_m = k_t \cdot (P_s - P_\infty) \tag{3}$$

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_∞ 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 δ is the diffusion coefficient of water vapour in air; τ the product skin thickness; φ 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 $k_a = \frac{\xi_2}{\frac{1}{\beta} + \mu \frac{s}{\delta}}$, where ξ_1 is a fraction of surface behaving as a free water zone (non-dimensional); β 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); ξ_2 fraction of surface behaving as porous membrane (non-dimensional); μ is resistance factor (non-dimensional); s is skin thickness (m); and δ 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

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).

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

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.

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, Ben-Yehoshua, Aharoni, & Cohen, 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
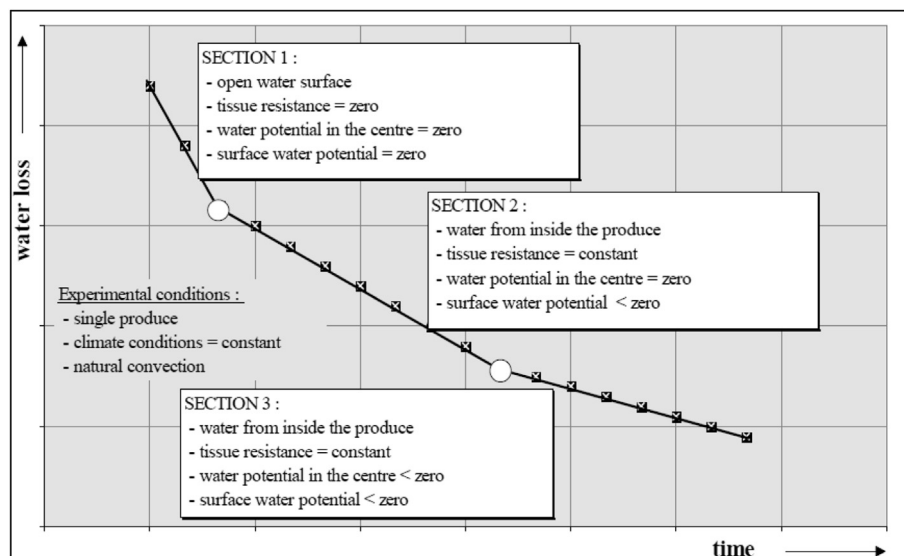

Fig. 2 — Sections describing the typical water loss of fruit and vegetables during postharvest storage (Adopted from Linke, 1997).
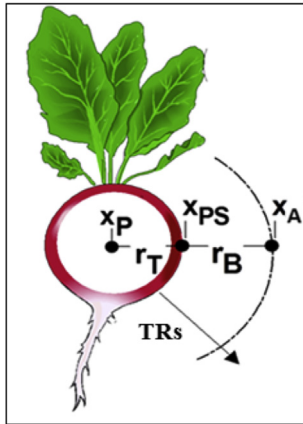
Fig. 3 – Basic relations for calculating tissue and boundary layer resistances (Adopted from Linke, 1998).

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

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 & Geyer, 2000; Linke & Geyer, 2001.			

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, Oliveira, and Macedo (2008) 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%–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 70–75% at optimum temperatures results in excessive water absorption leading to rooting, mould development and sprouting (Rodov et al., 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
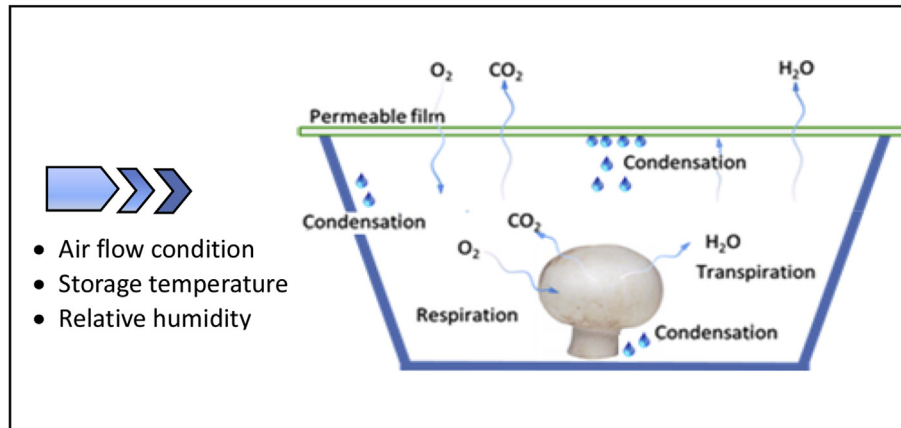
Fig. 4 – Condensation in packaged fresh produce and environmental parameters impacting the condensation process.

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
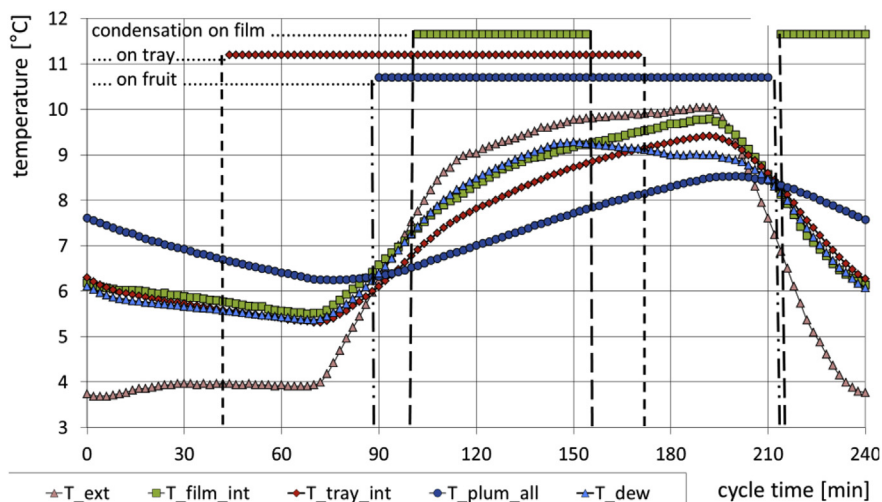

Fig. 5 – Condensation dynamics in plastic film packaging containing fresh plums (Adopted from Linke & Geyer, 2013).

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, Kim, An, Lee, & Lee, 2013; Hussein, Caleb, & Opara, 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 post-harvest 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:

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

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

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
$\dfrac{Q_r W + hA(T-T_p)}{\lambda}$	kg h⁻¹	T: 0 RH: 100	Apple	18.4[b] (normal air) 5.7[b] (1%O₂,1%CO₂) 8.7[b] (3% O₂, 3%CO₂)	Model was not validated; not tested in MAP (tested in controlled atmosphere)	Kang & Lee, 1998
		T: 10 RH: 82	Fresh-cut onion Fresh-cut green onion	447[b] (normal air) 363[b] (normal air)		
$\dfrac{Q_r W + WC_s\frac{dT_s}{dt}}{\lambda}$	kg h⁻¹	T: 15, 25 RH: 10, 60	Blueberry	NG	T inside the package was considered equal to the T_s	Song et al., 2002
$\rho \cdot K_i \cdot (a_{wi} - a_w) \cdot (1 - e^{-aT})$	mg cm⁻² h⁻¹	T: 4, 10, 16 RH: 76, 86, 96	Mushrooms	0.14–2.5[a]	Model not tested in MAP; does not consider RR	Mahajan et al., 2008
$K_i \cdot (a_{wi} - a_w) \cdot (1 - e^{-aT})$	g kg⁻¹ 24 h⁻¹	T: 5, 10, 15 RH: 76, 86, 96	Pomegranate arils	48–698[b]	Model not tested in MAP; does not consider RR	Caleb et al., 2013
	g kg⁻¹ h⁻¹	T: 5, 10, 15 RH: 76, 86, 96	Strawberries	240–1160[b]	Model does not consider RR	Sousa-Gallagher et al., 2013
$K_i \cdot e^{\left[-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right]} \cdot (a_{wi} - a_w)$	g kg⁻¹ h⁻¹ mg cm⁻² h⁻¹	T:10, 15, 20 RH: 70, 80, 92	Grape tomato	18–107[b] 0.012–0.058[1]	Model not validated; does not consider RR	Xanthopoulos et al., 2014
$\rho \cdot K_i \cdot e^{\left[-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right]} \cdot (a_{wi} - a_w)$ $K_i \cdot (a_{wi} - a_w) \cdot (1 - e^{-aT}) + 8.6 RR_{CO2,r} \cdot e^{\left[-\frac{E_a}{R}\left[\frac{1}{(T+273)}-\frac{1}{(Tr+273)}\right]\right]}$	mg kg⁻¹ h⁻¹	T:13 RH: 100	Mushrooms Strawberries Tomato	713[b] 122[b] 17.6[b]	Model was not validated	Mahajan et al., 2016

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; Tp-produce temperature; ʎ-latent heat of moisture evaporation/vaporization; C_s is specific heat of the produce, T_s 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.

[a] mg cm⁻² h⁻¹ (area based).
[b] mg kg⁻¹ h⁻¹ (mass based).

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)):

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

where F_w is the water flux (m^3 h^{-1}); α 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); π 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$_2$O) 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)):

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

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:

$$D_H = 2.98 \times 10^{-2} d^2 + 5.37 \times 10^{-1} d + 8.22 \times 10^{-1} \tag{11}$$

The authors reported that Eq. (10) is valid for water and atmospheric gases in a temperature range of 5−25 °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$_2$O through the Maxwell−Stefan diffusion and the convection mass balance model (Eq. (12)):

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

where ρ is the gas mixture density (kg m^{-3}); t is time (s); ωH_2O is H$_2$O mass fraction (non-dimensional); Dij is the ij component of multicomponent Fick diffusivity (m^2 s^{-1}); $x H_2O$ 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$_2$O 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$_2$H$_4$) and H$_2$O 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:

$$WVTR = 2.28 D^{1.72} L^{-0.72} e^{-\frac{12.62}{RT_s}} \tag{13}$$

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:

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

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$^{-1}_{dry\ matter}$ 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)):

$$P_{ab} = P_{sp} a_w \qquad (15)$$

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, Rodrigues, Motel, et al. (2008) 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)).

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

where M_t is the moisture absorbed (g) at a determined time t (d); M_∞ is moisture holding capacity at equilibrium (g); and β 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.

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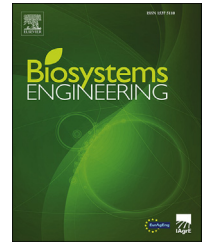# 3. Measurement and modelling of transpiration losses in packaged and unpackaged strawberries

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Research Paper

Measurement and modelling of transpiration losses in packaged and unpackaged strawberries

Graziele G. Bovi [a,b,*], *Guido Rux* [a], *Oluwafemi J. Caleb* [a,c],
Werner B. Herppich [a], *Manfred Linke* [a], *Cornelia Rauh* [b],
Pramod V. Mahajan [a]

[a] *Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany*
[b] *Department of Food Biotechnology and Food Process Engineering, Technical University of Berlin, Germany*
[c] *Division of Post-harvest and Agro-processing Technologies, Agricultural Research Council (ARC) Infruitec-Nietvoorbij, Stellenbosch 7599, South Africa*

ARTICLE INFO

Transpiration and respiration are physiological processes well-known as major sources of fresh produce mass loss. Besides causing impairment of external quality, it is associated with economic loss since it inevitably decreases saleable weight. To prevent postharvest mass losses, by improved modified atmosphere and humidity packaging, comprehensive knowledge on the mechanistic basis of both processes and their interactions is essential. The objective of this study was to evaluate the contribution of these processes on mass loss of packaged and unpackaged strawberries. Experiments on a single strawberry were performed at 4, 12 and 20 °C; and 76, 86, 96 and 100% RH. Mass loss was also investigated as a function of number of strawberries and package volume at 12 °C. A combined model based on Arrhenius equation and Fick's first law of diffusion for an unpackaged single strawberry and a model based on degree of filling was developed and validated with packaged strawberries. These models have potential application towards the selection of optimal moisture control strategies for strawberries.

1. Introduction

Modified atmosphere packaging (MAP) systems have been extensively used to reduce physiological activity of fresh produce by modifying in-package gas composition as well as to reduce mass loss by maintaining high in-package air humidity (Caleb, Mahajan, Al-Said, & Opara, 2013a). Most of the packaging materials used for MAP have low water vapour permeability, and, therefore, the water vapour released by the product due to transpiration remains trapped inside the package, often leading to undesirable condensation (Bovi, Caleb, Linke, Rauh, & Mahajan, 2016). Thus, in order to lessen in-package water vapour condensation it is essential to

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Nomenclature

DOF	Degree of filling
MAP	Modified atmosphere packaging
MAHP	Modified atmosphere and humidity packaging
RH	Relative humidity (%)
TR	Transpiration rate
RR	Respiration rate
VPD	Water vapour pressure deficit
TR_m	Transpiration rate on mass basis (g kg^{-1} h^{-1})
m_i	Initial mass of the product (g)
m_t	Product mass (g) at a determined time (t) in hours (h)
P_s	Saturation vapour pressure (kPa)
P_a	Actual vapour pressure (kPa)
T	Surrounding temperature (°C)
BOPP	Bi-axially oriented polypropylene
K_i	Mass transfer coefficient
a_{wi}	Water activity of the commodity
a_w	Water activity of the storage air
a	Model constant coefficient
M_{sub}	Mass loss due to substrate
TMLR	Total mass loss rate
$V_{product}$	Product's volume (mL)
$V_{package}$	Package's volume (mL)

shift the system design from MAP to modified atmosphere and humidity packaging (MAHP). The main challenge of MAHP is to reduce condensation while still maintaining produce water loss as low as possible (Rodov, Ben-Yehoshua, Aharoni, & Cohen, 2010). The design based on MAHP not only takes into account the gas composition but also the in-package air humidity and moisture control strategies to maintain desirable relative humidity (RH) and thus reduce condensation (Bovi & Mahajan, 2017).

In order to design appropriate MAHP it is essential to understand how much water is released by the product. Water loss in fresh produce is commonly measured by quantifying the amount or the mass of water lost per unit of time, the transpiration rate (TR). Many models based on Fick's first law of diffusion have been proposed to calculate the TR of a wide range of horticulture products such as strawberry (Sousa-Gallagher, Mahajan, & Mezdad, 2013), pomegranate arils (Caleb, Mahajan, Al-Said, & Opara, 2013b), whole mushroom (Mahajan, Oliveira, & Macedo, 2008), tomatoes (Xanthopoulos, Athanasiou, Lentzou, Boudouvis, & Lambrinos, 2014), and pears (Xanthopoulos, Templalexis, Aleiferis, & Lentzou, 2017). These models are efficient and valid for single unpackaged products, but their application in a dynamic system to estimate the TR of packaged products have not yet been tested.

Furthermore, the quantity of mass loss over a given period of time has long been accepted as being the TR of fresh produce. This was based on the assumption that mass loss due to the oxidative breakdown of organic reserves (substrate loss) and the effects that respiration exerts on TR, by generating metabolic heat and by supplying additional water that can be lost in transpiration, are negligible (Shirazi & Cameron, 1993;

Xanthopoulos et al., 2017). Recent studies, however, have pointed out the important role respiration plays on TR of fresh produce, under water vapour saturated environments which is normally seen in packaged fresh produce (Bovi, Caleb, Herppich, & Mahajan, 2018). For instance, Mahajan et al. (2016) developed a model to calculate TR based on respiration rate (RR). The authors calculated this effect on TR by multiplying RR with a conversion factor of 8.6 obtained from the respiratory heat and adding it to model of TR calculations based on Fick's first law of diffusion. Furthermore, the authors indicated that the heat of respiration increased the surface temperature of fresh mushroom above that of the surrounding air, thereby creating a water vapour pressure deficit (VPD) that may further drive transpirational water losses. In addition, Xanthopoulos et al. (2017) developed a model that analyses the contribution of transpiration and respiration on water loss using pears as a model product. Water loss indirectly resulting from respiration accounts for 39% of the total water loss as a result of water vapour pressure deficit at an air temperature of 20 °C and 95% RH.

The critical challenge in modelling TR and, consequently, water loss in fresh produce is that the parameters and/or coefficients of the model are product specific. Similarly, the appropriate moisture control strategy also needs to be product specific and has to be optimised considering the transpirational properties of each fruit or vegetable (Bovi, Caleb, Klaus, et al., 2018). This challenge implies that the respective physiological features of each type of fresh produce needs to be studied in detail and individually under each different storage condition and packaging system. In this context, the aim of this work was to develop a model to predict water loss from packaged fresh produce, with the potential application towards the selection of optimal moisture control strategies. With this aim, a comprehensive case study was carried out on the mass loss of packaged and unpackaged strawberries.

2.   Materials and methods

2.1.   Sample preparation

Freshly harvested strawberries were obtained from a commercial supplier (Obst und Gemüse Großhandle, Beusselstraße, Berlin) and immediately transported to the Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam, Germany. The strawberries were carefully sorted for uniformity in size and colour, and damaged, overripe and poor quality samples were discarded.

CO_2-based respiration rates (RR) of strawberries were determined by continuously monitoring rates of CO_2 production by a novel closed-system respirometer previously described by Rux, Caleb, Geyer, and Mahajan (2017). The respirometer consisted of acrylic glass cuvettes (8.2 l), each fitted with non-dispersive infrared CO_2 sensor (GMP222, Vaisala GmbH, Bonn, Germany). The RR was calculated as the amount of CO_2 per unit mass of the fruit per unit time (mg CO_2 kg^{-1} h^{-1}). Measurements were carried out for 6 h at 4, 12 and 20 °C.

2.2. Transpiration rate of single unpacked strawberries

The experimental setup consisted of four containers (190 l) located in walk-in cold rooms with adjustable temperature. Three temperatures (4, 12 and 20 °C) at four different RH were tested. The RH (%) inside each of the container was adjusted independently by using various saturated salt solutions made from analytical grade reagents of sodium chloride, potassium chloride, and potassium nitrate, for RH of 76, 86, and 96%, respectively, and pure distilled water was used for 100%. Two trays containing saturated salt solutions were placed inside each container and a wire mesh was placed above the trays to hold the petri-dishes containing the individual strawberries. TR was calculated by a gravimetric approach according to:

$$TR_m = \frac{m_i - m_t}{t \cdot \left(\frac{m_i}{1000}\right)} \qquad (1)$$

where TR_m is the transpiration rate on mass basis (g kg^{-1} h^{-1}), m_i is the initial mass of the product (g); m_t is product mass (g) at a determined time (t) in hours (h). A total of five repetitions were carried out for each treatment and the mass loss was measured daily using an electronic balance CPA10035 (Sartorius, Göttingen, Germany). The VPD for every temperature and RH was calculated according to the equation presented by Matyssek and Herppich (2017):

$$VPD = P_s - P_a \qquad (2)$$

where P_s is the saturation vapour pressure (Eq. (3)) and P_a is the actual vapour pressure (Eq. (4)).

$$P_s = \left[\exp\left(52.57633 - \frac{6790.4985}{T + 273.16} - 5.02808 \ln T + 273.16\right)\right] \qquad (3)$$

$$P_a = P_s \times RH \qquad (4)$$

where T is surrounding temperature (°C), RH is relative humidity (%), and P_s and P_a are given in kPa.

These equations were further used to calculate the linear variation of TR as a function of VPD. A regression analysis of the linear variation between TR and VPD, for every temperature, was carried out using Microsoft Excel (Office 2010, Microsoft, 116 Germany).

A second set of experiments was performed at 100% RH, i.e. at water vapour saturation, at 13 °C in a storage chamber (190 l), based on the methodology reported by Mahajan et al. (2016). A single strawberry was hung from the electronic scale using nylon. Distilled water was used in the storage chamber in order to maintain saturated air humidity. Mass loss from the strawberry was continuously monitored using an electronic balance connected to the data logger (ALMEMO 2490, Ahlborn, Holzkirchen, Germany) and its surface temperature was measured using an infrared temperature sensor AMIR 7842 (accuracy ±1% from value or ±1 K) (Ahlborn, Holzkirchen, Germany).

2.3. Transpiration measurement of packaged strawberries

Two separate experiments were performed in order to evaluate total mass loss of packaged strawberries. In the first experimental set-up, different number of strawberries (1, 3, 6 and 15) were placed inside closed polypropylene containers (0.93 l) weighing (12.26 ± 1.73 g), (40.33 ± 8.80 g), (78.57 ± 12.78 g) and (215.73 ± 49.01 g), respectively. A total of six repetitions were carried out and the mass loss of individual strawberries was measured daily using an electronic balance. This experimental data was then used to test the hypothesis that different numbers of strawberries packaged in the fixed size of a package (0.93 l) behave differently than a single strawberry.

In the second experiment, the mass loss of fixed amount of strawberries (200 ± 4 g) placed in packages with different volumes was evaluated. For this investigation, three different polypropylene packaging trays were used: a small (0.8 l), a medium (1.4 l), and a large (2.3 l); and the proportion of strawberry per package size (strawberry volume: package volume) was 1:4, 1:7, and 1:12, respectively. All packages were filled with strawberries and covered with bi-axially oriented polypropylene (BOPP) PropafilmTM RGP25 (25 mm thickness; permeability rate to O$_2$, 8.5 × 10^{-12} mol m^{-2} s^{-1} Pa^{-1} at 23 °C and 0% RH; water vapour, 5.7 × 10^{-6} mol m^{-2} s^{-1} Pa^{-1} at 23 °C and 85% RH, Innovia Films, Cumbria, UK). The covering film on the trays was perforated with 6, 5, and 4 micro-perforations of diameter 0.82 mm, for the small, medium, and large tray, respectively. These perforations were made in order to maintain the package atmosphere close to air and reduce condensation. Packages were stored for 5 d at 12 °C and the mass loss of strawberries was measured gravimetrically.

2.4. Model development and experimental validation

A combined model based on Arrhenius equation and Fick's first law of diffusion for unpackaged single strawberries and a model based on degree of filling (DOF) for packaged strawberries were developed (see Section 3.3). Experimental data obtained at all combinations of temperature, RH, and packaging systems studied were used to estimate the values of the coefficients.

For the validation of the model based on DOF, strawberries were pre-cooled to the study temperature of 12 °C for 3 h, and packed (15 strawberries of 200 ± 10 g) in polypropylene trays (16 × 12 × 5 cm), in the proportion of strawberry and package of 1:4. The trays were covered with BOPP and perforated with 6 micro-perforations of diameter 0.82 mm. Packages were stored for 5 d at 12 °C. Headspace gas composition (O$_2$ and CO$_2$ concentrations) inside each package was monitored daily using a CheckMate 3 gas analyser (PBI Dansensor, Ringsted, Denmark). Mass loss was determined by weighing the strawberries at the beginning of the experiment and after storage. Five replicates were carried out.

2.5. Statistical analysis

The models parameters were determined by fitting the data by non-linear regression analysis and Solver tool in Microsoft Excel (Office 2010, Microsoft, Germany). Furthermore, the data obtained were submitted to analysis of variance (ANOVA) and Tukey's test with significance set at $p < 0.05$ using the Statistica software (version 10.0, StatSoft Inc., Tulsa, USA).

3.   Results and discussion

3.1.   Transpiration rate of single unpacked strawberry

At the lowest RH the TR was highest (Fig. 1) because the VPD, i.e. the driving force for transpiration, was generally highest. Raising RH at 20 °C from 76% to 96%, i.e. reducing VPD by approx. 83% lowered TR by only 43% from 1.28 to 0.73 g kg^{-1} h^{-1}. Similarly, with increase in air temperature higher TR was recorded when RH was kept constant. For instance, with the rise in temperature from 4 °C to 20 °C at 96% RH the TR increased more than 5 times (from 0.13 to 0.73 g kg^{-1} h^{-1}) although VPD increased only approx. threefold from 0.033 kPa to 0.094 kPa. These results indicate how both temperature and VPD, or less accurately RH, affect the transpiration. Similar results were found in Sousa-Gallagher et al. (2013). In their study the TR for strawberries varied from 0.24 to 1.16 g kg^{-1} h^{-1} (at 5, 10 and 15 °C and 76, 86 and 96% RH), whereas in the present study TR varied from 0.13 to 1.28 (at 4, 12 and 20 °C and same RH).

This was further highlighted by a comparison of residual transpiration rates in water vapour saturated air (100% RH), which pronouncedly increased 6.5-fold from 0.02 g kg^{-1} h^{-1} at 4 °C to 0.13 g kg^{-1} h^{-1} at 20 °C (Fig. 1). This clearly indicated that there remained a driving force for transpiration even when the air surrounding the strawberry was water vapour saturated. The driving force for such water loss resulted from a higher fruit body temperature due to heat generated by respiration, which was indeed more than five times higher at 20 °C that at 4 °C, from 30.26 to 153.18 mg CO_2 kg^{-1} h^{-1} (Fig. 1). The linear variation of TR as a function of VPD is shown in Fig. 2. At VPD = 0 kPa (i.e. 100% RH), there was a residual transpiration rate of 0.1737, 0.0675 and 0.0057 g kg^{-1} h^{-1}, at 20, 12 and 4 °C, respectively. This residual TR resulted from heat of respiration which showed estimated fruit surface temperature of 20.12 °C, 12.07 °C and 4.01 °C.
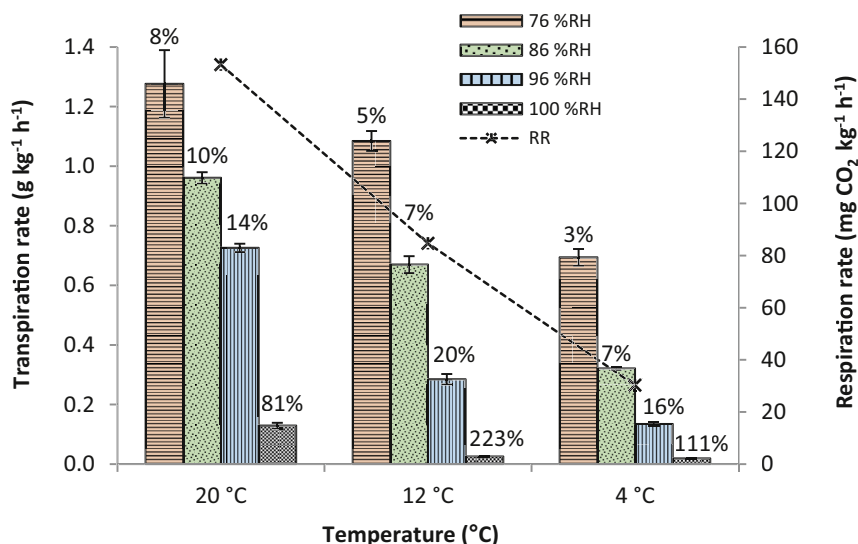

Fig. 2 — Experimentally determined transpiration rates (TR) of single unpackaged strawberry versus water vapour pressure deficit (VPD).

Comparison of the variations of surface temperature of a strawberry and the temperatures of the surrounding air allows visualisation of the effect of respiratory heat generation on strawberry mass loss (Fig. 3). Fruit temperature was indeed higher than that of the surrounding air. This fact implied that the heat of respiration of strawberry increased its surface temperature. In turn, this temperature difference led to an increase in water vapour pressure gradient for the mass transfer between the strawberry and its surrounding conditions and a continuous decline of fruit mass. Therefore, results from this study agree with the hypothesis that respiratory heat can significantly influence water losses from fresh fruit and vegetables under water vapour saturated conditions (Chau & Gaffney, 1990; Kang & Lee, 1998). This was also validated by Mahajan et al. (2016) using a mushroom and a spherical evaporation dummy apparatus (Linke, Schlüter, & Geyer, 2008), both stored under water vapour saturated conditions. The mushroom continuously lost mass while that of the evaporation sphere remained constant over time.

Fig. 1 — Transpiration rate of single unpackaged strawberry and respiration rate of strawberries under different storage conditions. The values on top of the bars represent the percentage (%) of mass loss due to substrate usage or consumption.
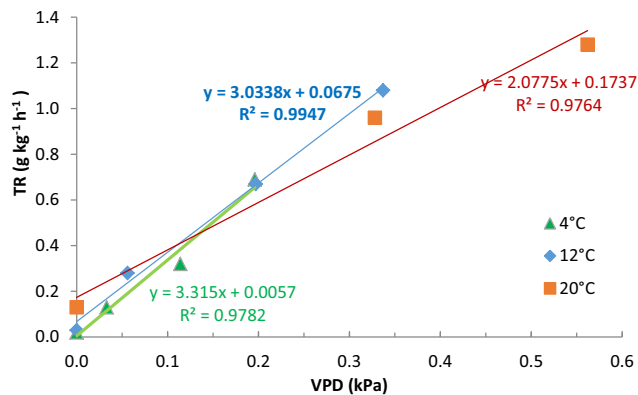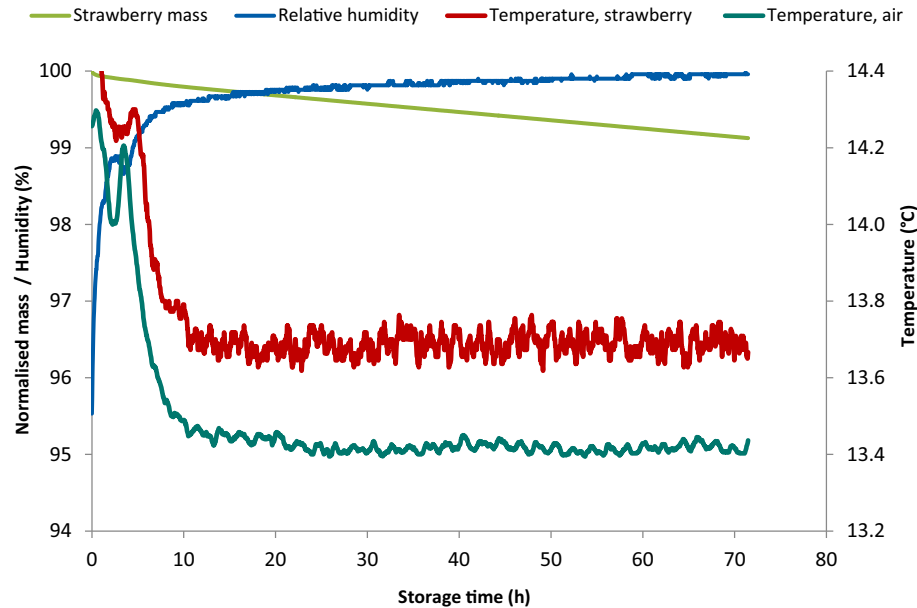
Fig. 3 – Impact of relative humidity on surface temperature and associated mass loss of a single strawberry.

3.2. Transpiration rate as a function of fruit quantity and package volume

This study showed that increasing the number of strawberries inside a package resulted in lower TR (Fig. 4a). When there was only a single strawberry in the package, the rate of mass loss was 0.068 g kg^{-1} h^{-1}, whereas with 15 strawberries mean mass losses were less than half that rate, 0.027 g kg^{-1} h^{-1}. Possible reasons for this reduction could be that: (i) with more strawberries in a package the fresh produce tends to stay closer to each other thereby reducing the effective surface area available for the transpiration and (ii) with more strawberries in the same package volume, saturation is reached more rapidly, and thus the period for decreasing the driving force for transpiration is effectively reduced.

It is well documented that the surface area available for water vapour diffusion plays an important role on fresh produce water loss (Sastry, 1985). Similarly, when strawberries are kept close together their overlapping area reduces the surface available for transpiration and, therefore, water loss is reduced. Furthermore, the time needed for the package to reach water vapour saturation is also important since when the saturation point is reached the TR decreases considerably. Thus, the package headspace plays an indirect, but important, role in water loss because the smaller the headpace, the quicker water vapour saturation is reached. The observations recorded on the effects of varying container volumes on total mass loss (Fig. 4b), confirmed the hypothesis that package headspace played a major role on mass loss. When the headpace was 0.6 l, mass loss was 0.019 g kg^{-1} h^{-1}; increasing the free headspace to 2.1 l (i.e. ≈ 350%) the rate of mass loss increased to 0.035 g kg^{-1} h^{-1} (185%). Therefore, in order to minimise mass loss from fresh produce it is important to minimise package headspace. Overall, these results showed that package headspace played an important role in

strawberry mass loss and, therefore, TR measurements of single strawberries measured in large chambers with unrestricted surrounding air flow conditions are not realistic to calculate water loss from packaged fresh produce.

3.3. Mathematical models

3.3.1. Unpackaged strawberries
Transpiration of fresh produce has been well studied with several reports have been published on mathematical modelling of transpiration rate as a function of extrinsic factors such as temperature, RH and air velocity (Bovi et al., 2016; Mahajan et al., 2008; Sastry & Buffington, 1983). One such model is described by:

$$TR = K_i(a_{wi} - a_w)(1 - e^{-a\,T}) \qquad (6)$$

where TR is transpiration rate, K_i is a mass transfer coefficient, a_{wi} is water activity of the commodity; a_w is water activity of the storage air, a is a model constant coefficient and T is temperature. This model was used to fit the experimental data at 76, 86, and 96% RH. The model parameters, as well as the comparison between the predicted and experimental data for single unpackaged strawberry are shown in Fig. 5.

As this model was developed for the range 76–96% RH, extrapolating to 100% RH (aw = RH/100) would lead to zero TR. This error originated from the assumption that the surface temperature is equal to the temperature of the surrounding air and there is no moisture loss due to respiration heat. Therefore, such model needs to be revised for 100% RH and the differences in temperature between the product and the surrounding air should be taken into account. Furthermore, mass measurements also consisted of substrate loss due to respiration. Such loss was calculated using the well accepted equation based on product respiration rate (Kays, 1991; Saltveit, 2004):
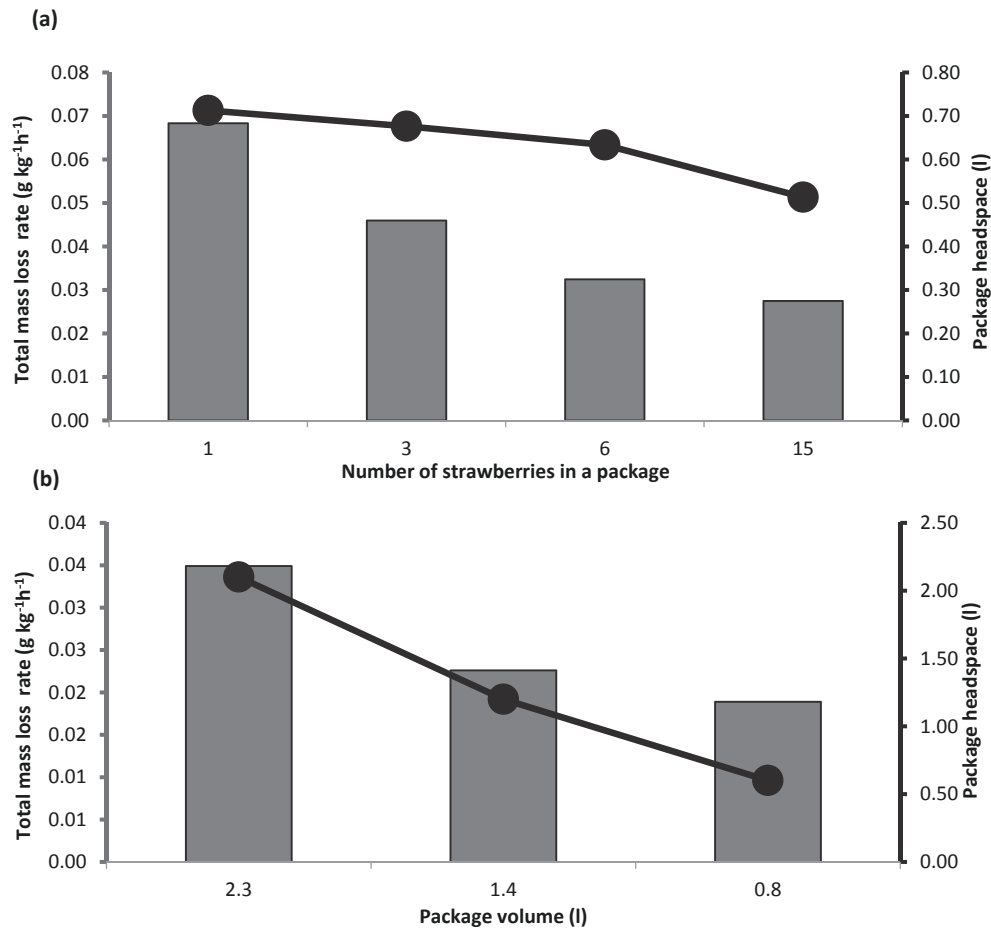
(a)

(b)

Fig. 4 — Effect of (a) number of packaged strawberries on total mass loss and (b) container volume on total mass loss of strawberries. The bars represent the total mass loss rate (g kg^{-1} h^{-1}) whereas the dots represent the package headspace (l).

$K_i = 6.42$
$a = 0.15$
$R^2 = 99.47$
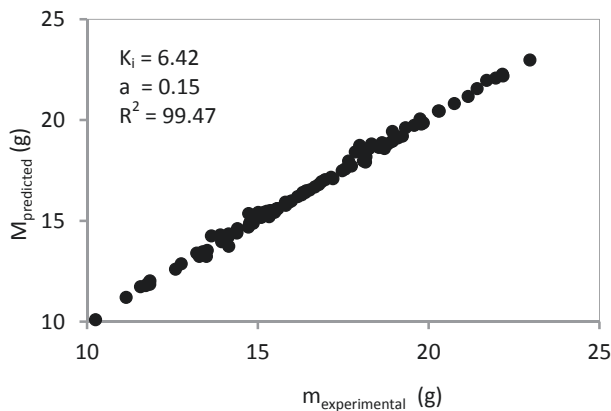
Fig. 5 — Description of changes in strawberry mass (g) for predicted versus experimental data, and the model parameters.

$$M_{sub} = RR \times \left(\frac{180}{264}\right) \qquad (7)$$

where, M_{sub} is the mass loss due to substrate, RR is the respiration rate in mg CO_2 kg^{-1} h^{-1} and the ratio 180/264

indicates that when glucose is the substrate, 180 g of this sugar is lost for each 264 g of CO_2 produced due to respiration reaction. However, this calculation does not take into consideration air humidity and, therefore, the calculated value of M_{sub} remained the same despite different water vapour pressure gradients under varying RH. Nevertheless, the calculations were performed and compared to the TR of a single unpackaged strawberries at different RH and temperatures (Fig. 1). The percentage contribution of substrate loss on TR at RH lower than 96% was between 3 and 20%. This indicated that the water vapour pressure gradient dominated the transpiration process. However, at saturated humidity (100%) as normally observed in packaged fresh produce, the contribution of substrate loss on transpiration rate of strawberry was very high (81—223%). It is established that the actual transpiration rate or mass loss of fresh produce constitutes not only substrate loss but also moisture loss due to heat of respiration which plays an important role in packaged produce (Bovi, Caleb, Herppich, et al., 2018; Saltveit, 2004). Therefore, this approach to calculating water loss based on substrate loss was not valid in the case of packaged fresh produce where RH is very high. Calculation of transpiration rate of packaged fresh produce either based on water vapour pressure gradient due to increase of surface temperature, heat

of respiration, substrate loss or carbon loss is still unresolved challenge and needs further attention.

Moreover, other mass flow components such as volatile organic compounds and ethylene, also passing the fruit skin, are usually considered as negligible. Nevertheless, it may be that they also play a role in total mass loss. In this context, the term total mass loss rate (TMLR) will be used in this study, instead of TR, when referring to fresh produce packed in high humidity environments as the mass loss due to substrate, and other mass flow components, might be much more considerable in high humidities.

3.3.2. Packaged strawberries

For packaged strawberries a TMLR model based on the DOF was proposed. The DOF (%) was calculated according to:

$$DOF = \frac{V_{product}}{V_{package}} \times 100 \qquad (8)$$

where $V_{product}$ is the product's volume (ml) and $V_{package}$ is the package's volume (ml). For the calculation of $V_{product}$ strawberry density was considered to be 1 g ml^{-1}.

The analyses of multiple packaged strawberries data showed that there was a negative linear relationship between TMLR and DOF. Therefore, this data was used to develop a simple TMLR model based on the DOF (Fig. 6). It is worth mentioning that this model was only valid when the lidding film used is BOPP as the use of films with different water vapour transmission rate would lead to different values of the TMLR. For instance, Bovi, Caleb, Ilte, Rauh, and Mahajan (2018) reported that strawberries packaged with NatureFlex, Xtend, and Polypropylene film lost 1.46, 0.41, and 0.27%, respectively, of the initial mass during storage conditions at 5 °C for 14 d. These results showed another challenge of modelling mass loss of packaged products as the permeability of the packaging material used is another important factor to be considered. Moreover, further studies need to be carried out in order to evaluate the effect of the number of micro-perforations on the TMLR of strawberries packaged in BOPP film.

3.4. Experimental validation using packaged strawberries

In-package gas composition varied between 17–21% for O_2 and 0–4% for CO_2 during 5 d of storage at 12 °C. After 2 d of storage, the in-package gas composition of all packages reached equilibrium-modified atmosphere and it effectively maintained O_2 and CO_2 concentrations of 17 and 4%, respectively. Almenar, Catala, Hernandez-Muñoz, and Gavara (2009) reported O_2 concentration of up to 14% for wild strawberries packed in containers covered with polyethylene terephthalate/polypropylene multilayer films with three micro-perforations stored at 10 °C for 4 d.

Furthermore, results showed that the micro-perforations led to saturated conditions within 1 h of packaging. This observation can be compared with larger size chamber, 190 l (Fig. 3), with a single strawberry where it reached the water vapour saturation after 10 h. This reinforced the hypothesis that lower headspace played a major role on TR as it was directly related to the time needed for a system to reach water vapour saturation. The TR of packaged strawberries was 0.03 ± 0.001 g kg^{-1} h^{-1}. The initial respiration rate of the packaged strawberries was 33.50 ± 1.45 mg CO_2 kg^{-1} h^{-1} and after 5 days of storage it was 54.12 ± 0.40 mg CO_2 kg^{-1} h^{-1}. Based on the average respiration rate of day 0 and day 5 (43.81 mg CO_2 kg^{-1} h^{-1}), the substrate loss for packaged strawberries was 0.03 g kg^{-1} h^{-1}. This indicates that the contribution of substrate loss on actual measured TR was 100%. Therefore, once again this calculation seems not to be realistic to calculate substrate loss due to respiration.

Moreover, the model based on DOF was used to predict mass loss of packaged strawberries and was then compared with the experimental values (Fig. 7). The predicted mass loss of strawberries packaged with BOPP film was only 446 mg which was much lower than experimental value (717 mg). This experimental value of mass consisted of 20 mg condensation in the tray, 47 mg condensation on the film, and 649 mg transmitted through the micro-perforated packaging film.
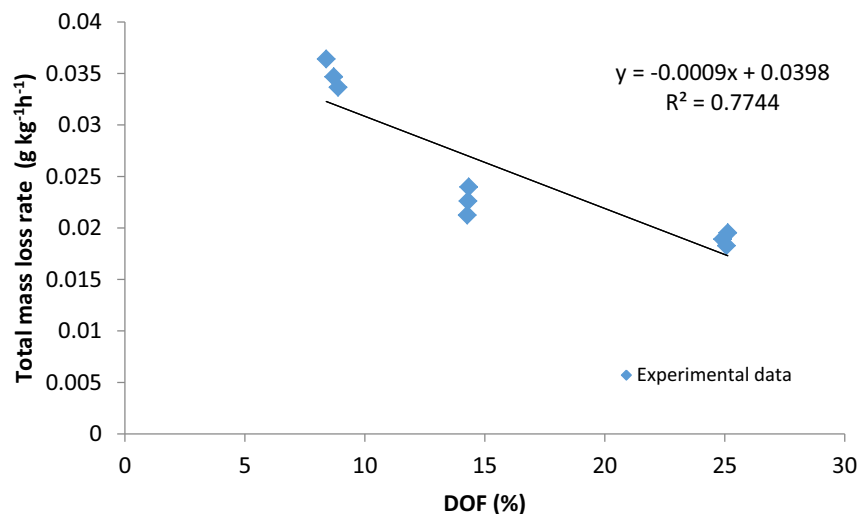

$$y = -0.0009x + 0.0398$$
$$R^2 = 0.7744$$

Fig. 6 — Total mass loss rate of strawberry packaged in containers of different volumes and proposed model based on percentage degree of filling (DOF).
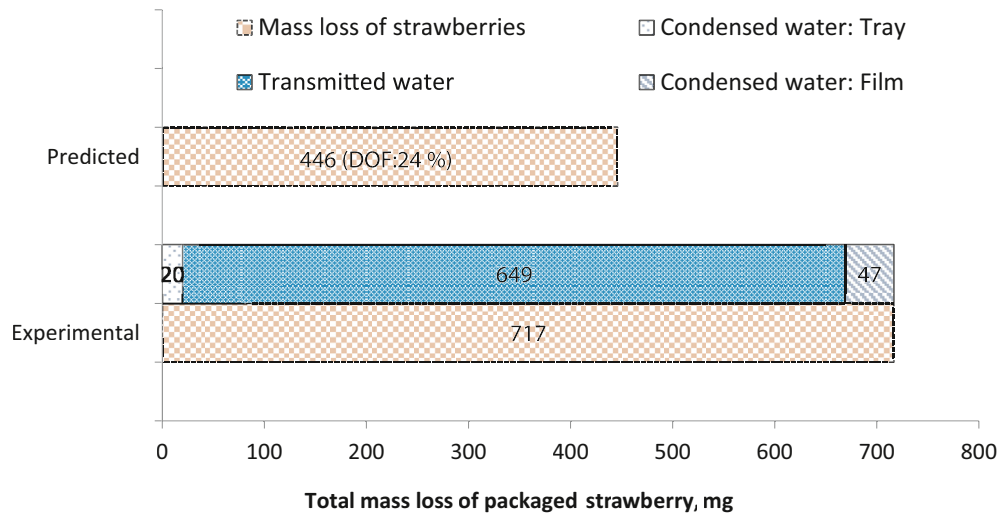
Fig. 7 — Experimental distribution of total mass loss in packaged strawberries after 5 d at storage and the predicted value of total mass loss at 24% degree of filling (DOF) at 12 °C.

This analysis showed that it is possible to use water loss predictive model, despite large error, to quantify the amount of moisture in the packaged fresh produce. Such analysis can be used for selection of packaging materials and other active moisture control strategies for controlling humidity and minimising condensation in packaged strawberries. This modelling could eliminate the "pack and pray" approach normally adopted for designing modified atmosphere and modified humidity packaging for respiring fresh products.

4.   Conclusion and future research needs

A key finding of this study is that headspace plays an important role in mass loss of packaged strawberries and, therefore, the development of a model based on the DOF seems to be an alternative to overcome the difficulties of developing water loss predictive models. Furthermore, the findings of this study raised up some points that should be taken into account for modelling of water loss, such as the deduction of substrate loss and consideration of the degree of filling. Nevertheless, the question of how to quantify substrate loss in packaged fresh produce still needs to be addressed.

Acknowledgement

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4. Moisture absorption kinetics of FruitPad for packaging of fresh strawberry

Moisture absorption kinetics of FruitPad for packaging of fresh strawberry

Graziele G. Bovi [a, c], Oluwafemi J. Caleb [a, b], Eylin Klaus [d], Filip Tintchev [d], Cornelia Rauh [c], Pramod V. Mahajan [a, *]

[a] Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany
[b] Post-harvest and Agro-processing Technologies, Agricultural Research Council (ARC), Infruitec-Nietvoorbij, Stellenbosch, South Africa
[c] Department of Food Biotechnology and Food Process Engineering, Technical University of Berlin, Germany
[d] McAirlaid's Vliesstoffe GmbH, Berlingerode, Germany

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ABSTRACT

This study analysed the moisture absorption kinetics of FruitPad embedded with different concentrations of fructose with further application of such pads in packaging of fresh strawberries. The FruitPad was exposed to different storage conditions (temperature and RH) and moisture absorption kinetics was gravimetrically determined over 5 days of storage. FruitPad with 30% fructose showed highest amount of moisture absorption (0.94 g of water/g of pad) at 20 °C and 100% RH. The Weibull model combined with the Flory-Huggins model adequately described changes in moisture content of the FruitPad with respect to storage time and humidity ($R^2 = 93-96\%$). The FruitPad containing fructose minimized in-package condensation compared to the pad without fructose. Weight loss of packaged strawberry was less than 0.9% which was much below the acceptable limit of 6% for strawberry.

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1. Introduction

Fresh fruits and vegetables (FF&V) have continuous metabolism as they keep losing water due to respiration and transpiration processes. If not controlled, water released through these processes results in moisture condensation inside packaged FF&V; since packaging acts as an additional barrier for moisture transfer (Bovi et al., 2016). In turn, condensation represents a risk to product quality as water may accumulate in packaging system and/or on product surface leading to defects in external appearance, quality deterioration, flavour loss, and promoting growth of spoilage microorganisms (Linke and Geyer, 2013). Thus, moisture regulation is essential for extending FF&V shelf life as it can lessen the risk of spoilage causing microorganisms growth, and therefore maintain product quality. Various strategies for controlling moisture inside packaged fresh produce have been reported: i) use of moisture absorbers inside the package (Mahajan et al., 2008); ii) use of a humidity-regulating tray that can actively absorb moisture (Rux et al., 2016); and, iii) use of a packaging material with a very high permeability for water vapour (Caleb et al., 2016).

Moisture absorbing pads are one of the most innovative and versatile applications of active food packaging systems. It is generally constituted of an upper and lower sheet of film coating and a core middle layer composed mainly of cellulose and an active ingredient that absorbs excess liquid (drip loss) present in the package. Pads can be divided into two main categories: water contact and non-contact absorber. The water contact absorber pad is commercially being used for packaging of meat products, such as fish, beef, and pork (Fang et al., 2017). These pads are useful, however; the excess moisture leached out from the product must be in direct contact with the active ingredient of the pad in order to be absorbed. Therefore, these pads are not suitable for fresh produce application as FF&V continue to respire and transpire and the water vapour released in these process remains inside the package headspace and not necessarily in direct contact with the pad. Thus, there is a need for novel and non-contact moisture absorbing pads that can not only absorb the water in direct contact with FF&V but also water vapour from the package headspace.

The idea of incorporating active hygroscopic NaCl between the two layers, like humidity regulating tray (Rux et al., 2016), was further applied to absorbing pads using fructose as an active ingredient. Fructose contributes to functional attributes when

applied to food and beverage. These include flavour enhancement, osmotic stability, humectancy, and freezing point depression (White, 2014). These functional properties may be attributed to physical and chemical properties of fructose itself or to the interaction of fructose with the food system. Fructose is hygroscopic and can absorb moisture from its environment. It begins to absorb water vapour at approximately 55% relative humidity (RH). Furthermore, fructose has good humectant properties and it can retain moisture for a long period of time, even at low RH (White, 2014). Therefore, fructose has a great potential of acting as a moisture absorber. The integration of fructose into the matrix of absorbing pad structures, as active substance, is promising as it can absorb free water in the tray and also absorb excess water vapour in the package headspace. In this context, the aim of this study was to investigate the moisture absorption kinetics of absorbing pads (namely FruitPad) matrix, embedded with varying concentrations of fructose as active ingredient for moisture absorption.

2. Materials and methods

2.1. FruitPad

The pad consisted of a 3-layer structure (Fig. 1). The top and bottom layers were made of polyethylene with 8 micro-perforations of 0.3 mm diameter per cm^2. The middle layer contained cellulose fibres (McAirLaid's Vliesstoffe GmbH, Steinfurt, Germany). These FruitPads (FruitPad00) were incorporated with two concentrations of fructose (20 and 30%, henceforth called FruitPad20 and FruitPad30, respectively in the manuscript) in the middle layer using the commercial production facilities of McAirlaid's Vliesstoffe GmbH. The remaining matrix consisted of 28% film and 52% cellulose (for 20% fructose pad), and 21% film and 49% cellulose (for 30% fructose pad).

2.2. Moisture absorption kinetics

Pad samples (10.3 × 7.5 cm), in triplicate, were stored in 190 L metal chambers at temperatures 4, 12, and 20 °C. The RH was maintained at 76, 86, 96 and 100% RH by using saturated salts solutions (Rux et al., 2016). The water vapour absorption of the FruitPad was gravimetrically determined by measuring increase in weight of the pads at regular intervals for 5 days using an electronic balance (Sartorius, Göttingen, Germany). The moisture content of the FruitPad was expressed as shown in Eq. (1).

$$M_t = \left(\frac{W_t - W_i}{W_i} \right) \tag{1}$$

where M_t is the moisture content of the FruitPad at time t (g water g^{-1} pad), t is time (h), W_i and W_t are the weight of the FruitPad (g) in the beginning and at time t, respectively.

Weibull model has been shown to be a suitable model to describe moisture absorption as a function of time (Mahajan et al., 2008; Rux et al., 2016), and therefore was used in this study, as a primary model, to describe the curves of moisture content versus time as shown in Eq. (2):

$$M_t = M_0 + (M_\infty - M_0) \, x \left[1 - e^{\left(\frac{-t}{\beta 1} \right)} \right] \tag{2}$$

where M_0 is the initial moisture content of the FruitPad (g water g^{-1} pad), which is zero as the FruitPad was dry, M_∞ is the moisture holding capacity (g water g^{-1} pad) at equilibrium, and β_1 is the kinetic parameter that defines the rate of moisture uptake process and represents the time needed to accomplish approximately 63% of the moisture uptake process. Furthermore, M_∞ can take infinite time to be measured; however, the Weibull model offers the possibility of estimating the M_∞ with experimental data of moisture content with time.

2.3. Packaging of strawberry

Strawberries (cv. Flair) were obtained from a commercial grower (Karls Erlebnis-Dorf Elstal, Germany). They were precooled to the study temperature for 3 h. Polypropylene tray (16 × 12 × 5 cm) was used to pack 15 strawberries of 260 ± 5 g. It was covered with bi-axially oriented polypropylene Propafilm™ RGP25 (25 mm thickness; permeability rate to O$_2$, 8.5 × 10^{-12} mol m^{-2} s^{-1} Pa^{-1} at 23 °C and 0% RH; water vapour, 5.7 × 10^{-6} mol m^{-2} s^{-1} Pa^{-1} at 23 °C and 85% RH). The lid film was
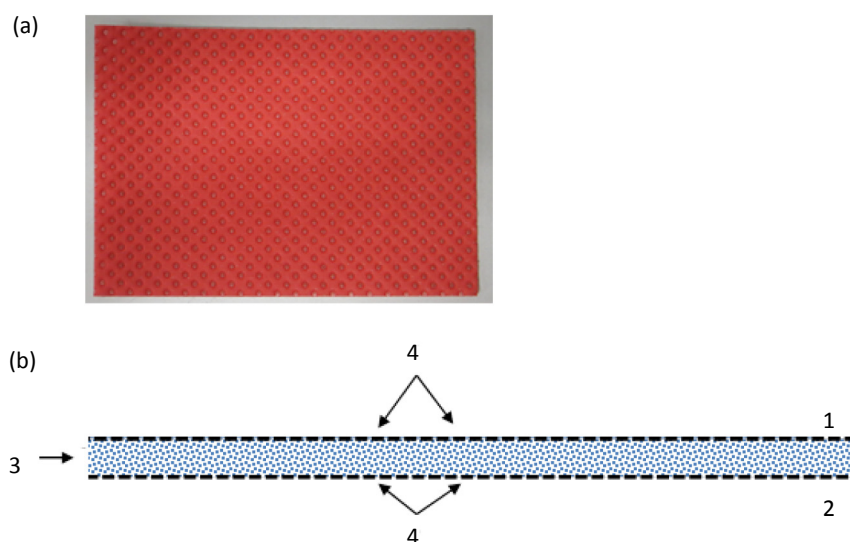

Fig. 1. Annotated diagram of FruitPad from McAirlaid's Vliesstoffe GmbH. (a) Upper view of the FruitPad (b) Schematic lateral view representation of the FruitPad: 1 - Top layer film, 2 - bottom layer film, 3 - active layer: fructose (blue) and cellulose (white), and 4 - micro-perforations.

perforated with 2 micro-perforations of diameter 0.7 mm. Packages were stored for 5 days at 12 °C. Packages were named FruitPad00 for the pad containing 0% of fructose, FruitPad20 for the pad with 20% of fructose, FruitPad30 for the package with 30% of fructose, and control for the package without FruitPad. Two replicates of each package were performed.

2.4. Package performance evaluation

Weight loss was determined by weighing the strawberries at the beginning of the experiment and after storage. The FruitPad absorption capacity was calculated by weight of the FruitPad on day 0 and day 5. The amount of water vapour condensed inside the package was quantified by weighing the package and film before and after the condensed water was removed.

2.5. Statistical analysis

The constants of all the presented models were obtained by fitting the experimental data into the equations by using regression analysis and Solver tool in Microsoft Excel (Office 2010, Microsoft, Germany). The statistical analysis was carried out using Statistica software (version 10.0, StatSoft Inc., Tulsa, USA).

3. Results and discussion

3.1. Moisture absorption kinetics

Moisture uptake increased significantly ($p < 0.05$) over storage time (Fig. 2). Generally, moisture uptake for all FruitPads was faster on the first day and substantially slower from day 2. FruitPad kept at higher humidities had higher moisture absorption capacity in comparison to lower humidities at the end of day 5. At 20 °C,
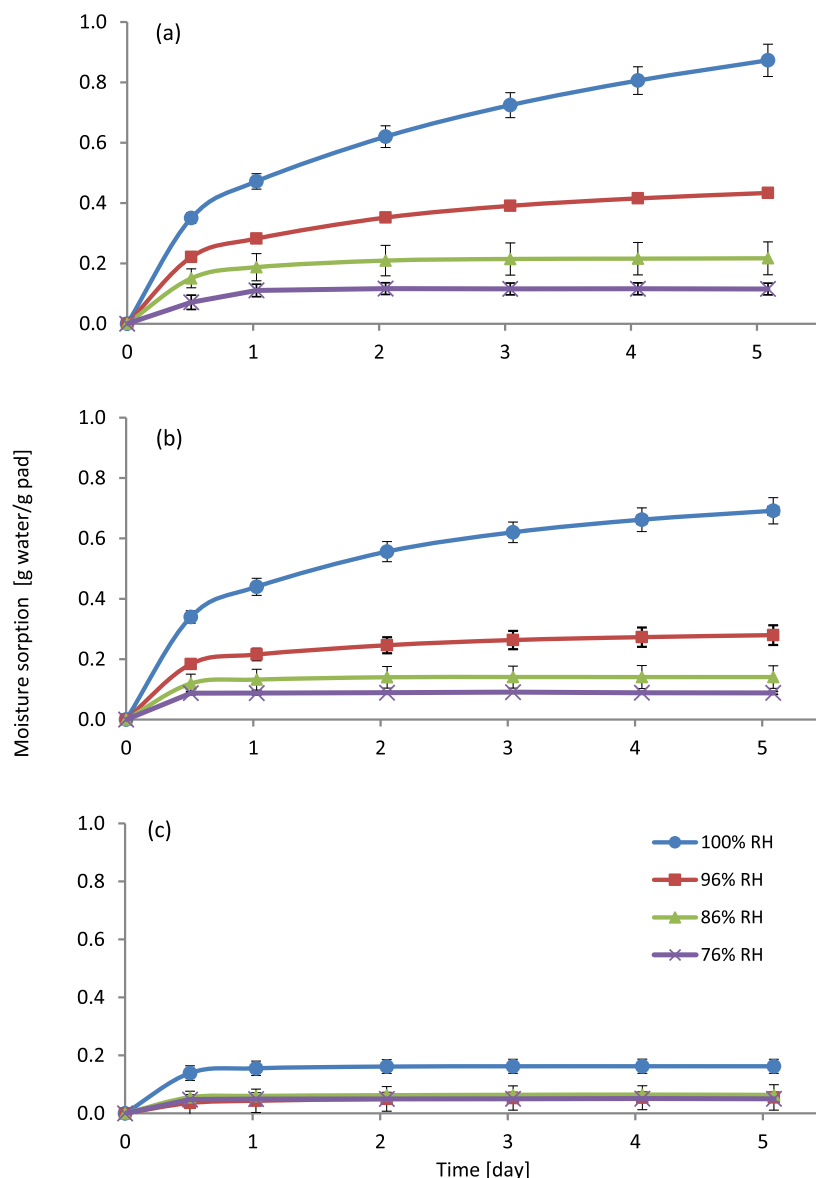

Fig. 2. Moisture sorption kinetics of FruitPad stored under different relative humidity at 12 °C and containing different concentration of fructose (a) FruitPad30 (30% of fructose), (b) FruitPad20 (20% of fructose), (c) FruitPad00 (0% of fructose). Error bars represent standard deviation (SD) of mean values (n = 3).

FruitPad30 absorbed 0.94 g water g^{-1} pad at 100% RH and 0.13 g water g^{-1} pad at 76% RH, an increase of 7.2 times on water uptake. Results are consistent with other studies reported as it is well established that there is higher moisture uptake at higher humidity for a diverse range of materials. For instance, Saberi et al. (2016) reported that the slope of the isotherms for a pea starch films was smaller at lower a_w (less than 0.60), and with a rising in a_w the slope increased quickly.

Fig. 3 shows the effect of fructose concentration and storage RH on the total moisture content (M_t). FruitPad30 absorbed 0.94 g
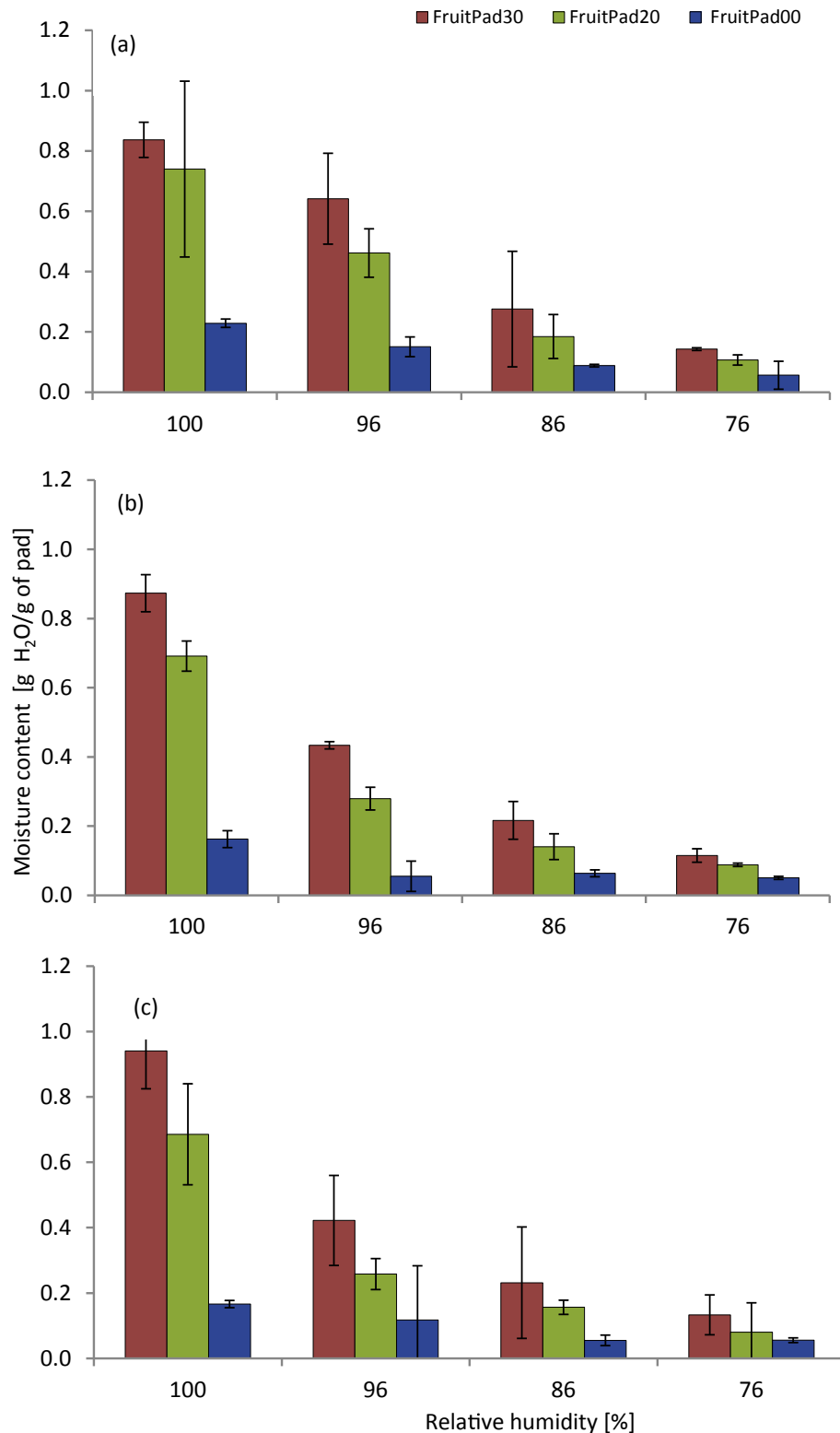

Fig. 3. Effect of fructose concentration and storage relative humidity on total moisture content (M_t) of FruitPad containing different fructose concentration (0: FruitPad00, 20: FruitPad20, and 30%: FruitPad30) stored at (a) 4 °C, (b) 12 °C and (c) 20 °C for 5 days. Error bars represent standard deviation (SD) of mean values (n = 3).

water g^{-1} pad while FruitPad00 absorbed 0.17 g water g^{-1} pad at the same humidity and temperature (100% RH and 20 °C). It is clear that the concentration of fructose, as well as the RH, had a significant impact on M_t. In addition, results showed that incorporation of fructose into the FruitPad increased the water vapour absorption of the pads. One of the reasons for this could be due to the high hygroscopic property of fructose. Fructose is highly soluble in water (3.75 g/mL at 20 °C) (Chemical Book, 2017). Hence, it keeps absorbing moisture even after the powder form of fructose turns into liquid form. The resultant fructose-water solution is very

Table 1
Estimated parameters of the primary model for FruitPad containing different concentrations of fructose (0%: FruitPad00, 20%: FruitPad20, and 30%: FruitPad30).

Absorbing pad	M_∞				β_1			
	RH: 76%	86%	96%	100%	76%	86%	96%	100%
FruitPad00	0.0499	0.0575	0.0886	0.1572	0.0010	0.0100	0.3447	0.0010
FruitPad20	0.0886	0.1398	0.2656	0.5515	0.0020	0.2741	0.5002	0.0020
FruitPad30	0.1073	0.1898	0.4118	0.6410	0.0030	0.0100	0.8172	0.0003

M_∞ is the equilibrium moisture and β_1 is a primary model constant. All parameters shown are at 12 °C.
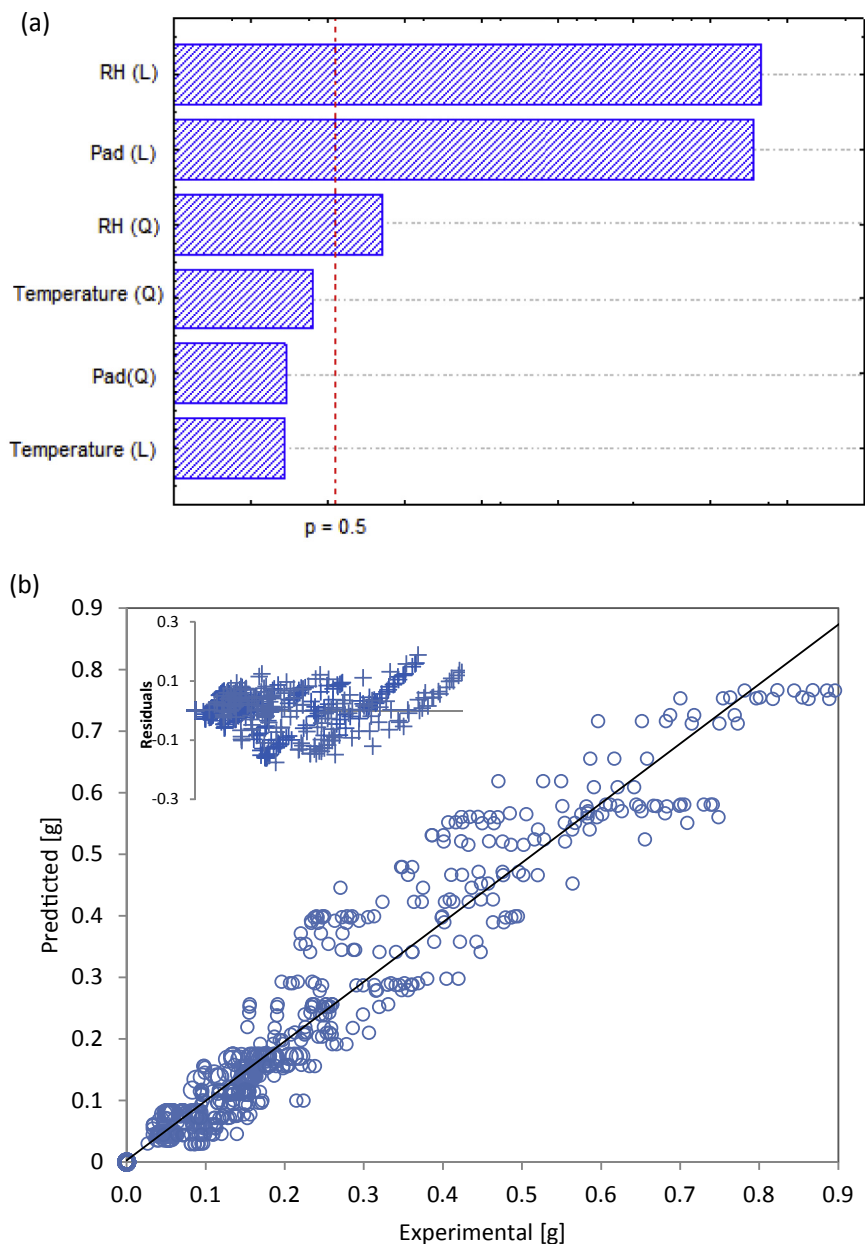

Fig. 4. Relevant statistical information (a) Pareto analysis of primary model and (b) Experimental vs predicted values of the equilibrium moisture content (M_∞) of the secondary model for all fructose concentrations (0%: FruitPad00, 20%: FruitPad20, and 30%: FruitPad30).

Table 2
Estimated parameters of the secondary model for FruitPad containing different concentration of fructose (0%: FruitPad00, 20%: FruitPad20, and 30%: FruitPad30).

Absorbing pad	Estimated coefficients			R^2 (%)
	A	B	β_2	
FruitPad00	0.00074	0.05445	0.28333	92.56
FruitPad20	0.00005	0.09371	0.77688	92.99
FruitPad30	0.00031	0.07817	1.09146	96.09

A, B, and β_2 are secondary model constants and R^2 is a coefficient of determination.

viscous (Silva et al., 2009), and can be easily retained by the cellulose fibres of the FruitPad. Therefore, the higher amount of fructose per gram of FruitPad, the higher is the potential for moisture absorption. Similar result was found in a study with humidity-regulating trays incorporated with salt as the active compound (Rux et al., 2016).

3.2. Model development

With the results obtained from the moisture absorption kinetics a primary model based on the Weibull model was developed for each FruitPad at each RH and temperature. Table 1 showed the primary model parameters obtained at 12 °C. As can be seen M_∞ was clearly affect by the increase in RH and fructose concentration. In addition, results showed that RH and fructose concentration had a significant impact ($p < 0.05$) on moisture absorption; however temperature did not (Fig. 4a).

As RH had an impact, the Flory-Huggins model (Eq. (3)) was then employed to relate the moisture holding capacity (g water g^{-1} pad) at equilibrium (M_∞) with RH (Saberi et al., 2016).

$$M_\infty = A \, x \, e^{(B \, x \, a_w)} \tag{3}$$

where a_w is the water activity (RH/100); and A and B are model constants.

Eq. (3) was then combined with Eq. (2) yielding in a secondary model (Eq. (4)), in order to express the influence of RH in M_∞.

$$M_t = M_0 + \left(A \, x \, e^{(B \, x \, a_w)} - M_0 \right) \, x \left[1 - e^{\left(\frac{-t}{\beta_2} \right)} \right] \tag{4}$$

Therefore, a secondary model for each fructose concentration was developed taking into account RH and fructose concentration and not the temperature effect. This model was then used to fit the experimental data at all RH and temperature for each fructose concentration. The secondary model parameters and the coefficient of determination (R^2) for each combination are shown in Table 2. Results showed that the Weibull model combined with the Flory-Huggins model adequately described changes in moisture content of the FruitPad with respect to storage time ($R^2 = 93$–96%). Predicting the moisture content of the FruitPad is of considerable importance when designing optimal packaging systems. Every fresh produce gives out different amounts of water due to the respiration and transpiration process; therefore, for every product there is a different requirement for selecting the most suitable moisture absorber (Bovi and Mahajan, 2017). For this reason it is important to know how much moisture each FruitPad can absorb so that retailers can choose which fructose concentration is more suitable for each given fresh produce. In addition, Fig. 4b shows the experimental vs predicted values of the equilibrium moisture content (M_∞) of the secondary model for all concentrations of fructose.

3.3. Package performance evaluation

Strawberry weight loss was significantly influenced by the FruitPad inside the package (Fig. 5). Tukey's test showed that there was no significant difference in weight loss between the control and the FruitPad00 sample, whereas significant difference in weight loss was observed between the control and pads embedded with fructose ($p < 0.05$). Overall, percentage weight loss were significantly below the recommended maximum acceptable of 6% (Nunes and Emond, 2007). This showed that MAP played a significant role in minimizing the weight loss of strawberries. Furthermore, it is noteworthy that weight loss includes both water and carbon loss. Water loss is attributed to transpiration, while carbon loss is due to respiration (Saltveit, 1996). However, in this study the carbon loss was considered as negligible and water loss via

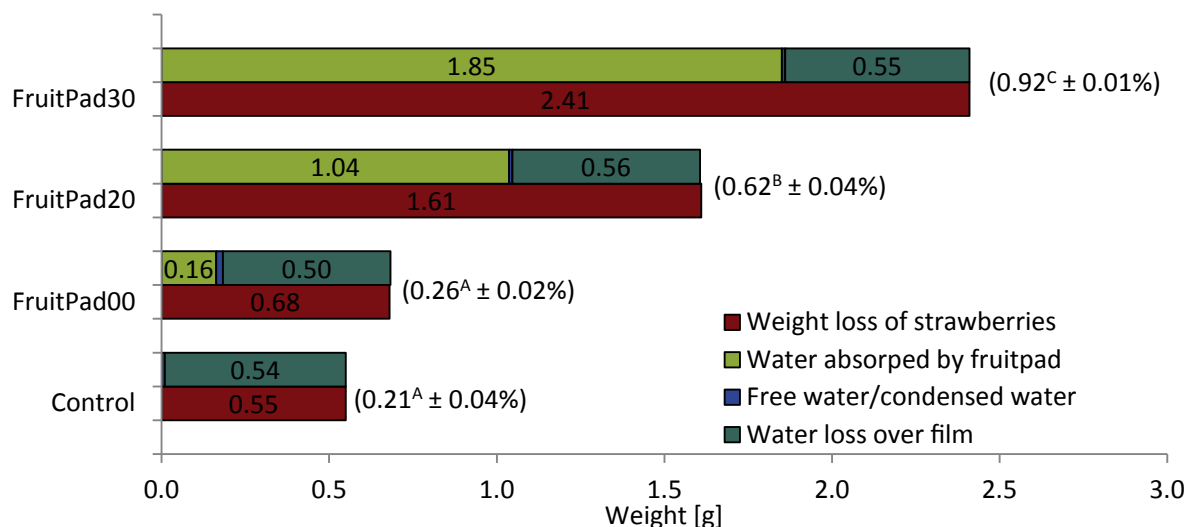**Fig. 5.** In-package moisture dynamics of strawberries packaged with FruitPad containing different fructose concentration (0: FruitPad00, 20: FruitPad20, and 30%: FruitPad30) stored at 12 °C for 5 days. The values in bracket represent the percentage mean values (mean value ± standard derivation, n = 2) for total strawberry weight loss. Different upper case superscript is significantly different based on Tukey test at p < 0.05.

transpiration was considered as the main driver of the weight loss.

In addition, the very low weight loss for MA-packaged strawberries samples could be attributed to the higher water vapour barrier property of the BOPP film, which resulted in a higher RH inside the package (Caleb et al., 2016). However, part of the moisture released by the product probably escaped the packaging material through the optimized film micro-perforations (based on preliminary study) for gas exchange. This contributed to very low condensation (less than 0.02 g) underneath the packaging film (Fig. 5), which was beneficial for maintaining the quality of the strawberries. Nevertheless, the use of pads did not avoid the formation of water condensation but it might have reduced the volume. The presence of water condensation could be attributed to the transpiration rate of the strawberries, which was higher than the absorption rate of the FruitPad.

Furthermore, water absorbed by the FruitPad was proportional to the concentration of fructose present in the FruiPad. The highest moisture gain was found in FruitPad30 (1.16 g of water g^{-1} of pad), followed by FruitPad20 (0.90 g of water g^{-1} of pad), and FruitPad00 (0.21 g of water g^{-1} of pad). This behavior was also observed in the moisture sorption kinetics of the FruitPad. Fructose has the functional attribute of hygroscopicity and humectancy, which means it has the ability to bind and hold moisture (White, 2014). Therefore, higher concentration of fructose leads to higher moisture uptake. This trend was also seen in the study carried out by Rux et al. (2016). In their study, humidity trays were developed with two concentrations of NaCl 0 wt% (T-0) and 12 wt% (T-12) as active compound of the humidity regulating trays and were tested with strawberries stored at 13 °C for 7 days. The total amount of strawberry moisture loss ranged from 1.6 to 7.9 g for strawberries, with the samples packed in the control-PP trays losing the least amount of water (1.6 g; 0.6% of total strawberry weight), followed by T-0 (6.0 g, 2.2% of total strawberry weight), and T-12 trays losing the most (7.9 g, 2.9% of total strawberry weight). These results also show that the use of NaCl as active compound leads to higher weight loss when compared to the use of fructose. In the present study the moisture loss by the strawberry was not higher that 0.92% of the total strawberry weight. Thus, this shows the possibility to further optimize strategies for in-package moisture absorption. For instance, it is possible to further develop humidity regulating packaging systems by incorporating different proportions and types of active compounds. Overall results showed that FruitPad containing fructose were effective in absorbing water vapour from the package headspace at 12 °C. Furthermore, concentration of fructose integrated into the absorbent pads is product specific and has to be optimised considering the transpiration rate of each fruit or vegetable. If fructose concentration is too high drying of the product surface can occur, and, if it is too low the effects of accumulated condensation will be significant.

4. Conclusion

This study showed that both fructose concentration and storage RH had an effect on the equilibrium moisture content of the FruitPad stored at different temperatures. The Weibull model in combination with the Flory-Huggins model adequately described the changes in moisture content of the pads with respect to storage time (R^2 > 93%). FruitPad containing fructose was effective in absorbing water vapour from the package headspace containing strawberries.
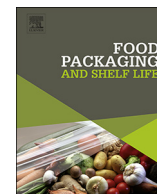
Acknowledgement

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5. Impact of modified atmosphere and humidity packaging on the quality, off-odour development and volatiles of 'Elsanta' strawberries

Impact of modified atmosphere and humidity packaging on the quality, off-odour development and volatiles of 'Elsanta' strawberries

Graziele G. Bovi[a,b,*], Oluwafemi J. Caleb[a,c], Kathrin Ilte[a], Cornelia Rauh[b], Pramod V. Mahajan[a]

[a] Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany
[b] Department of Food Biotechnology and Food Process Engineering, Technical University of Berlin, Germany
[c] Post-harvest and Agro-processing Technologies, Agricultural Research Council (ARC) Infruitec-Nietvoorbij, Stellenbosch 7599, South Africa

ABSTRACT

Development of off-odours, as well as visual quality of packaged fresh produce plays a crucial role in consumer's choice. In this context, this work investigated the odour profile, condensation, gas composition, and postharvest quality attributes of strawberries stored under modified atmosphere and humidity packaging at 5 °C for 14 days. The packages were fitted with fixed area (69, 126.5, and 195.5 cm^2) of different permeable membranes (NatureFlex, Xtend, and Propafilm). No significant changes were detected on the measured physicochemical quality attributes of strawberries and mass loss was below 1.5% across the different packaging systems. Package modification/design had an influence on in-package water vapour condensation, gas composition, and accumulation of secondary volatile organic compounds (acetaldehyde, acetone, ethanol and ethyl acetate).

1. Introduction

Fresh produce remains metabolically active even after harvest and continues to respire and lose water (Bovi, Caleb, Linke, Rauh, & Mahajan, 2016). This represents a challenge for the development of controlled atmosphere (CA) and modified atmosphere packaging (MAP) systems, since it leads to changes in the package atmosphere over time. Jo, Kim, An, Lee, and Lee (2013) developed a fresh produce container that combines the principles of MAP (atmosphere modification based on produce respiration) and CA (periodic adjustment of atmosphere composition). Their approach consists of a controlled container system fitted with a gas diffusion tube responding to real-time measured O$_2$ and CO$_2$ concentration. However, this approach addresses only to optimum gaseous composition and does not take into account the accumulation of water vapour. Water vapour evolution inside fresh produce packages often limits product´s shelf life due to the formation of condensation (Bovi & Mahajan, 2017). Condensation represents a risk to the product quality as water may accumulate on packaging system and/or product surface leading to defects in external appearance and promoting growth of spoilage microorganisms (Bovi et al., 2018; Linke & Geyer, 2013). Thus, the concept of a modified atmosphere and humidity packaging (MAHP) equipped with a humidity control window might represent an innovative approach to avoid or lessen the risk of condensation.

Besides condensation, visual quality, freshness aroma, and development of characteristic off-odour volatiles play a crucial role in consumer's choice, and this influences future decisions to purchase the product. Thus, the identification of characteristic off-odour volatiles during storage life of packaged fresh produce can serve as an indicator of product quality. Around 360 volatile compounds have been identified in the aroma of strawberry (*Fragaria x ananassa* Duch.), however, only a small portion (15–25) of these volatiles are important contributors to the aroma (Jouquand, Chandler, Plotto, & Goodner, 2008; Nielsen & Leufvén, 2008; Zabetakis & Holden, 1997). Some of these compounds include methyl and ethyl esters, furanones, C$_6$ aldehydes and other C$_6$ derivative compounds. In addition, strawberries may produce secondary volatile organic compound (VOCs), such as acetaldehyde, ethanol and ethyl acetate during storage. When these secondary volatiles are present in concentrations above their threshold limit they can have a negative effect on the flavour (Pelayo, Ebeler, & Kader, 2003).

Postharvest life of strawberry is short due to physical damage during handling, water loss, physiological disorders, high susceptibility to spoilage microorganisms (Caleb, Wegner et al., 2016; Chandra, Choi, Lee, Lee, & Kim, 2015; Lara, García, & Vendrell, 2006), and high respiration rate (RR) of 50–100 mL CO$_2$ kg^{-1} h^{-1} at 20 °C (Ozkaya, Dündar, Scovazzo, & Volpe, 2009). Nevertheless, refrigeration in combination with MA systems has been extensively used to extend shelf-life of strawberry. Results have shown that MAP can slow strawberry respiration rate by keeping CO$_2$ concentration between 10 and

30% (Lara et al., 2006; Nielsen & Leufvén, 2008). In this context, the aim of the study was to design, develop and investigate the effects of modified atmosphere and humidity packaging on: (a) its performance in terms of headspace gas composition and moisture condensation; (b) the physicochemical quality attributes of strawberries; and (c) the shift in VOCs profiles of packaged strawberries during storage.

2. Materials and methods

2.1. Plant materials

Fresh strawberry (cv. Elsanta) was obtained from the commercial grower (Fruchthof Hensen Erdbeerkulturen GmbH & Co. KG, Swisttal-Mömerzheim, Germany), and transported in cooled conditions to the Freshness Laboratory, Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam, Germany. The strawberries were carefully sorted and the damaged, overripe, and poor quality fruit were discarded in order to obtain uniform samples. The strawberries were precooled to the study temperature of 5 °C for 3 h.

2.2. Design of modified atmosphere and humidity packaging

Polypropylene packages (total 10) of size $13 \times 20 \times 9$ cm (total volume 2.3 L) were used as the base storage container. The lid of each package was modified by cutting windows of different sizes of 33, 66, and 100% of total lid area which is equivalent to absolute area of 69, 126.5, and 195.5 cm^2, respectively. These open windows were hermetically sealed (using double sided hermetic tapes) with different packaging films: (i) Xtend (XT) film (StePac, Tefen, Israel), (ii) Polypropylene based Propafilm (PP) (Innovia Films, Cumbria, UK), and (iii) cellulose-based NatureFlex (NF) polymeric film (Innovia Films, Cumbria, UK). Each packaging film covering the window was perforated with 2 holes of 0.7 mm diameter in order to achieve equilibrium modified atmosphere. Table 1 shows the description of the different packaging window design used in this study. Different window sizes and packaging films were used in order to create different modified humidity conditions. The water vapour transmission rate (WVTR) is 42.79, 19.34, and 0.8 g m^{-2} d^{-1} for NatureFlex, Xtend, and Propafilm, respectively and at 5 °C.

2.3. Package design performance

The packages were filled with strawberries (700 ± 5 g), closed tightly with the designed lids and stored at 5 °C for 14 days. Headspace gas composition (O_2 and CO_2 concentrations) inside each package was monitored daily by using a CheckMate 3 gas analyser (PBI Dansensor,

Table 1
Packaging films used and window sizes designed for the storage containers.

Sample	Packaging film	Window size	
		% of lid area	Area of window (cm^2)
Control	Polypropylene lid without perforation	–	–
PP33	Propafilm[a]	33	69
PP66	Propafilm[a]	66	126.5
PP100	Propafilm[a]	100	195.5
XT33	Xtend[a]	33	69
XT66	Xtend[a]	66	126.5
XT100	Xtend[a]	100	195.5
NF33	NatureFlex[a]	33	69
NF66	NatureFlex[a]	66	126.5
NF100	NatureFlex[a]	100	195.5

[a] With 2 micro-perforations of 0.7 mm.

Ringsted, Denmark). A visual documentation of moisture condensation on the lid and window film was recorded after 14 days of storage. In addition, condensation (free/condensed water) and total mass loss (mass loss of strawberry), was quantified at the end of storage on day 14. The amount of water vapour condensed inside the package (g) was quantified by weighing the empty packages before and after the removal of condensed water on the package walls, windows and the lids. The water loss through the film, due to permeability, was also calculated from the difference in the amount of water lost by the strawberry and the amount of water condensed inside the package. One replicate was carried out totalizing 10 packages.

2.4. Physico-chemical quality changes

Fresh strawberry juice was used to measure total soluble solids (TSS), pH and titratable acidity (TA). A digital refractometer (DR301-95, Krüss Optronic, Hamburg, Germany) was used to measure TSS and expressed as %. The TA concentration of the juice sample was measured potentiometrically by titration with 0.1 mol L^{-1} NaOH, to an endpoint of pH 7.0 using an automated T50 M Titra-tor with Rondo 20 sample changer (Mettler Toledo, Switzerland). The TA concentration was expressed as g L^{-1} of citric acid based on fresh mass. The pH was measured with a pH meter (inoLab pH720, WTW Series, Weilheim, Germany) after calibrating with pH buffers 4 and 7. The measurements were done in triplicate on day 0 and on day 14.

2.5. Visual and ortho-nasal quality evaluation

Twelve untrained panelists who are regular consumers and familiar with the quality attributes of strawberry carried out visual and ortho-nasal quality evaluation. Strawberry quality attributes such as texture, odour, and decay were evaluated on a scale of 1–5 (Table 2). In addition, visual observation of water vapour condensed on the lid window was also scored on a scale of 1–5.

2.6. Evolution of volatile organic compounds

Volatile compounds were extracted by static headspace sampling (SHS). Strawberries from each package were crushed into puree and 5 g of aliquot was placed in 20 mL glass vial with 100 μL of 3-octanol (diluted in absolute methanol to a concentration of 0.1 g L^{-1}) as internal standard. The vials were tightly capped and equilibrated at 80 °C for 20 min in the headspace auto-sampler incubator. Gas sample (1 mL) was automatically withdrawn from the headspace of each vial (HS-20 automated-sampler, Shimadzu Europa GmbH, Duisburg, Germany). Sampling condition for HS-20 auto-sampler was maintained as follows: the oven, sampling line and transfer line temperature was 80 °C, 150 °C and 150 °C, respectively; pressurizing pressure and time was 76 kPa and 2 min, respectively. To increase the sensitivity of the SHS sampling method on the GC–MS, vial shaking level of 3, load time of 0.5 min and injection time of 1 min with single injection parameters were used.

Gas samples were transferred from HS-20 sampler into the GCMS-QP2010 (Shimadzu Europa GmbH, Duis-burg, Germany) for separation of volatile compounds. Due to the volatility, nonpolar character and reactivity of volatile sulphur compounds a mid-polar 1.4 μm film thickness ZebronTM capillary column, with 30 m length and 0.25 mm inner diameter was used (ZB-624, Phenomenex, Aschaffenburg, Germany). Analyses were carried out using helium as carrier gas with a total flow of 16.4 mL min^{-1} and a column flow of 1.22 mL min^{-1}. The GC temperature was held at 50 °C for 1 min, then ramped to 110 °C at 5 °C min^{-1}, then to 180 °C at 20 °C min^{-1}, held for 3 min and finally to 200 °C at 5 °C min^{-1}, and held at this temperature for 1.5 min in total run time of 25 min and split ratio (1:10). The mass selective detector (MSD) was operated in full scan mode and mass spectra in the 35–350 m/z range were recorded. The ion source and interface temperature were maintained at 200 °C and 230 °C, respectively. Individual

Table 2
Quality scores and descriptors for strawberry.

Descriptors	Scores and description					Reference
	1	2	3	4	5	
[a]Humidity window condensation	Humidity window is extensively covered with water vapour	Humidity window is partially covered with water vapour ≥ 50%	Humidity window is partially covered with water vapour ≤ 50%	Humidity window is partially covered with water vapour ≤ 25%	Humidity window is completely free of water vapour condensation	Rux, Caleb, Geyer, & Mahajan (2017)
Texture	Very poor (fruit are extremely soft)	Poor (fruit are very soft)	Fair (fruit exhibit minor signs of softness)	Good (fruit are firm)	Very good (fruit are firm and turgid)	Nunes, Emond, & Brecht (2003)
Odour	Dislike very much	Dislike moderately	Neither like nor dislike	Like moderately	Like very much	–
Decay	76–100 % decay (extreme decay/ completely rotten)	51–75 % decay (moderate to severe decay)	26–50% decay (spots with decay)	1–25 % decay (probable decay)	0 % decay (no decay)	Rux et al. (2017)

[a] Adapted from other studies.

volatile compound were identified by their retention time (RT) and calculated Kovats retention index (RI) using *n*-alkane group. The compounds were compared to those registered on the National Institute for Standards and Technology (NIST) mass spectral libraries (NIST v. 08 and 08 s, Gaithersbug, MD, USA) and other literature. Only compounds with the square of the correlation coefficient (R^2) above 90% between experimental spectra and NIST MS library were considered. Semi-quantification of the identified compounds was estimated according to Bugaud and Alter (2016) using Eq. (6):

$$RA = \frac{Ai_c}{A_{its}} C_{its}$$

where RA is the relative abundances of the identified compound ($g L^{-1}$), Ai_c is the peak area of the identified compound, A_{its} is the peak area of the internal standard, and C_{its} is the final concentration of internal standard in the sample ($0.1 \, mg \, mL^{-1}$).

2.7. Statistical analysis

The data obtained were submitted to analysis of variance (ANOVA) and Tukey's test with significance set at $p < 0.05$ using the Statistica software (version 10.0, StatSoft Inc., Tulsa, USA). In addition, Duncan multiple range test was used to analyse the volatile organic compounds of strawberries in order to determine the difference between mean values at $p < 0.05$. Results were presented as mean ± standard deviation.

3. Results and discussions

3.1. Modified atmosphere and moisture condensation

Gas composition inside the packages varied between 5–14% for O_2 and 8–19% for CO_2 (Fig. 1), with exception of the control package. The gas composition of the control package was not shown in Fig. 1, nevertheless, it was measured. It reached 1.29% of O_2 already on day 3 of storage and 0% on the remaining days. For CO_2 the concentration reached 23.27% on day 5 and 45% by the end of storage. The PP33, PP66, and NF66 packages had the lowest O_2 steady state conditions (around 6%). However, it was still within the recommended MA conditions for strawberries of 5–10% O_2 and 15–20% CO_2 (Brecht et al., 2003). A decline of O_2 below critical limits (5%) should be avoided as this might lead to in-package anoxia; which in turn results in fermentation and off-odour development (Luca, Mahajan, & Edelenbos, 2016). Overall, the values obtained show similar trends with experimental micro-perforated wild strawberries packed in containers (8–14% O_2) covered with polyethylene terephthalate/polypropylene (PET/PP) multilayer films with three micro-perforations stored for 4 days at 10 °C (Almenar, Catala, Hernandez-Muñoz, & Gavara, 2009). Furthermore, this study showed that the use of fixed window with 2 micro-perforations has the capability of preventing anoxic conditions on packaged
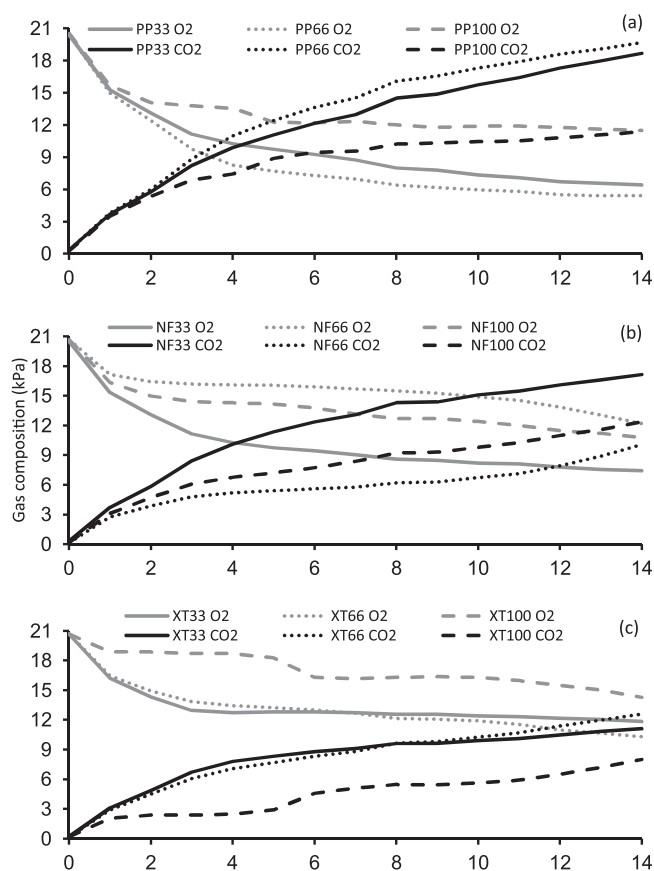

Fig. 1. Changes in headspace gas composition for packaged strawberries sealed with fixed window of (a) Polypropylene based Propafilm (PP), (b) NatureFlex (NF), and (c) Xtend films (XT).

strawberries.

Packages fitted with NatureFlex and Xtend windows, independent of their sizes, effectively prevented water vapour condensation (free/condensed water) in comparison to those fitted with Propafilm and the control package (Figs. 2 and 3). This is directly related to the WVTR of the films. Natureflex and Xtend films have very high WVTR, 42.79 and 19.34 $g \, m^{-2} \, d^{-1}$ measured at 5 °C, respectively when compared to Propafilm, 0.8 $g \, m^{-2} \, d^{-1}$ (Sousa-Gallagher, Mahajan, & Mezdad, 2013). However, the prevention of water vapour accumulation on the package film led to higher mass loss of strawberries. Results show that the type of film and its size had an influence on the rate of mass loss strawberries (Fig. 3). The highest product mass loss was observed in the packages covered with NatureFlex (0.57–1.46%), while samples in Propafilm (0.20–0.27%) had the lowest mass loss. The bigger the

Fig. 2. Visual documentation of lid and film condensation after 14 days of storage.

window size the higher was the mass loss recorded, with the exception of samples PP33 and P66 that presented similar mass loss independent of the window size, probably, due to the very low permeability of PP film to water vapour. Nevertheless, the overall mass lost by strawberries in this study did not exceed 1.5%, and therefore was significantly below the recommended maximum acceptable loss of 6% (Nunes & Emond, 2007). Similarly, Caleb, Ilte, Fröhling, Geyer, and Mahajan (2016) investigated the effects of appropriate design of modified atmosphere and humidity packaging (MAHP) systems, with NatureFlex film window on polypropylene film on the postharvest quality of minimally processed broccoli branchlets. Results also showed that the use of the window effectively prevented water vapour condensation on the film surface when compared to bi-axially oriented polypropylene and cling-wrapped commercial control, however, at the expense of a higher product mass loss compared to the control package. Nevertheless, the use of lid window covered with high WVTR films has the capacity of reducing water vapour from the package headspace and therefore, might retard microbial spoilage and increase shelf life. Furthermore, the use of such films as humidity windows is innovative and efficient as these

containers are re-usable and there is only the need to change the window film.

3.2. Physico-chemical quality changes

The traditional physical and chemical quality attributes detected no significant ($p \leq 0.05$) changes by the Tukey test in packaged strawberries after 14 days of storage at 5 °C. The range of total soluble solids (TSS), total acidity (TA), and pH obtained in this study was 4.0–5.2%, 0.9–1.2 g L^{-1}, and 3.9–4.1, respectively. TSS and TA are important parameters to determine the fruit quality as they have a direct effect on the flavour. They vary significantly among different strawberry varieties (Kallio, Hakala, Pelkkikangas, & Lapveteläinen, 2000). The authors investigated the sugar and acid composition of six strawberry varieties. They reported that the major acids in strawberries are citric (7.3–15.8 g L^{-1}) and malic (2.2–6.9 g L^{-1}) and total sugar content varied from 5.35 to 10.96%. Nevertheless, both the TSS and the TA obtained in this study were lower than that reported by Kallio et al. (2000), which indicated that the strawberries contained less sugar and
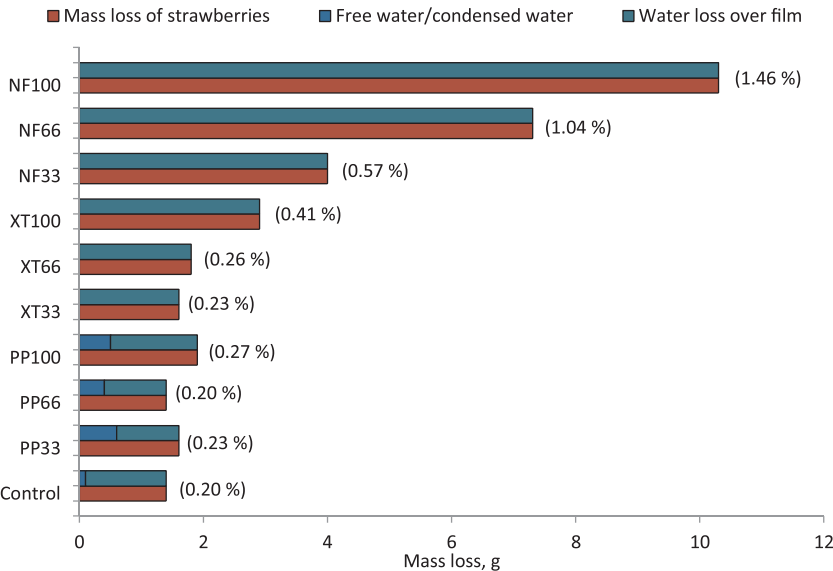

Fig. 3. Mass loss of strawberry and in-package condensation during the storage period of 14 days at 5 °C. *The values in bracket represent the percentage strawberry mass loss.
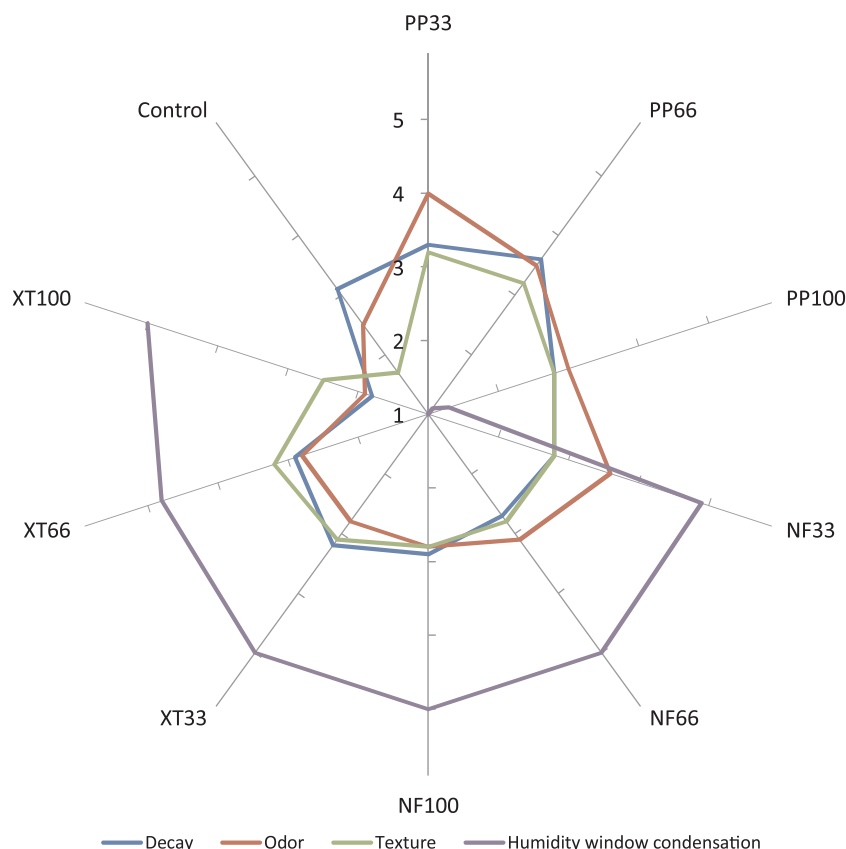
Fig. 4. Changes in visual quality attributes of packaged strawberries and observed water vapour condensation on the humidity window after 14 days of storage at 5 °C.

were very acid. On the other hand, the pH obtained in this study for cv. Elsanta strawberries was within the range reported for `Sonata` strawberry by Caleb, Wegner et al. (2016), which was in the range of 3.9 to 4.7. Furthermore, the size and type of film did not affect the physico-chemical quality attributes as there were no significant changes from the initial to the end of storage.

3.3. Visual and ortho-nasal quality evaluation

All sensory attributes received scores below 3 which indicated that all the packages presented compromised quality, especially the control package as it had the lowest score for most of the evaluated attributes (Fig. 4). Low scores for the strawberry texture can be associated with mass loss as this leads to shriveling and wilting of the product. Furthermore, our sensorial analysis scores were in accordance with Figs. 2 and 3, containers fitted with NatureFlex and Xtend films as lid windows reduced condensation when compared to other packages. This reduction was very important as in-package condensation led to poor quality. Moreover, condensation was quantified as zero, however in the sensory evaluation it was visible. Possibly the films NatureFlex and Xtend absorbed water and formed droplets; therefore, it was visible but could not be quantified. This was due to the fact that the films were not coated with anti-mist and therefore showed droplets adhered to the film as condensed water. On the other hand, Propafilm is a standard material coated with anti-mist; nevertheless, due to the low WVTR the moisture condensation was still visible. It is worth mentioning that anti-mist are chemicals that absorb water and spread it throughout the coated surface. This keeps water droplets from becoming big enough to be visible as condensation.

3.4. Evolution of volatile organic compounds

A total of 8 secondary VOCs were detected at the end of storage day 14 in the different packaging conditions (Table 3). The development of acetaldehyde, acetone, and ethyl acetate are well known to be a result of fermentative metabolism (Nielsen & Leufvén, 2008). Ethanol was below detection limit on day 0. The other fermentative volatiles were detected at low concentrations already on day 0, but further accumulated during the storage of the strawberries. Strawberries kept on the control package had the highest tissue accumulation of ethanol, which indicated that anaerobic respiration was triggered. The increase in ethanol concentration can be associated with the critical gas composition of 45% CO_2 measured on day 14 of storage. High CO_2 concentration could result in the disruption of enzyme activities such as the lipoxygenase pathway (Giuggioli, Briano, Baudino, & Peano, 2015). The production of ethanol and esters varied according to the different modified atmosphere conditions. The influence of headspace gas composition on the accumulation of alcohols and further synthesis of esters was reported by Giuggioli et al. (2015) and Belay, Caleb, and Opara (2017).

Moreover, the strawberries reacted in a different manner to the packaging system conditions. Similar results were found by Nielsen and Leufvén (2008). Authors pointed out that there can be large differences between strawberry cultivars, especially with regard to the aroma development. Their study indicated that storage in a modified atmosphere affected negatively the aroma development in Korona strawberries; however, the aroma production in Honeoye was not affected in a similar manner. Furthermore, what can be observed from these results is that the traditional physico and chemical properties from strawberries had very little changes within the 14 days of storage compared to the emission of VOCs and the development of off-odour. Thus, this study indicates that the investigation of off-odour during storage can serve as

Table 3
Volatile organic compounds of strawberries stored for 14 days at 5 °C (mean values (n = 3) ± standard deviation).

Volatiles (mg/mL)	RT	K-RI Est.	K-RI Lit.	Day 0	Day 14									
					Control	PP33	PP66	PP100	XT33	XT66	XT100	NF33	NF66	NF100
Acetaldehyde	4.28	540	518	0.03[d]	0.25 ± 0.01[a]	0.1 ± 0.01[b]	0.09 ± 0.06[b]	0.03 ± 0.01[d]	0.06 ± 0.001[c]	0.12 ± 0.03[b]	0.04 ± 0.00[d]	0.04 ± 0.02[cd]	0.07 ± 0.00[c]	0.10 ± 0.01[b]
Ethanol	5.41	602	668	nd	1.98 ± 0.08[a]	0.29 ± 0.03[b]	0.06 ± 0.004[c]	0.05 ± 0.00[c]	0.02 ± 0.00[d]	0.02 ± 0.00[d]	0.03 ± 0.00[d]	0.18 ± 0.06[b]	0.07 ± 0.01[c]	0.02 ± 0.00[d]
Acetone	6.03	660	455	0.66[a]	0.02 ± 0.01[c]	0.09 ± 0.002[b]	0.10 ± 0.03[b]	0.08 ± 0.003[b]	0.10 ± 0.02[b]	0.09 ± 0.02[b]	0.04 ± 0.00[c]	0.08 ± 0.01[b]	0.09 ± 0.01[b]	0.09 ± 0.00[b]
Acetic acid, methyl ester	6.48	554	487	0.001[e]	0.06 ± 0.002[c]	0.10 ± 0.04[a]	0.02 ± 0.00[d]	0.17 ± 0.06[a]	0.10 ± 0.04[a]	0.16 ± 0.08[a]	0.18 ± 0.04[a]	0.09 ± 0.05[abc]	0.12 ± 0.004[b]	0.18 ± 0.01[a]
Ethyl Acetate	8.76	632	628	0.002[f]	1.60 ± 0.07[a]	1.52 ± 0.50[a]	0.33 ± 0.03[b]	0.97 ± 0.06[a]	0.13 ± 0.02[d]	0.17 ± 0.00[c]	0.06 ± 0.00[e]	1.12 ± 0.54[a]	0.04 ± 0.01[e]	0.33 ± 0.05[b]
Butanoic acid, ethyl ester	15.15	836	785	nd	0.06 ± 0.01	nd	nd	nd	nd	nd	nd	nd	nd	nd
Butanoic acid, 2-methyl-, ethyl ester	16.35	919	820	nd	0.03 ± 0.002	nd	nd	nd	nd	nd	nd	nd	nd	nd
Hexanoic acid, ethyl ester	19.47	1157	984	nd	0.03 ± 0.02	nd	nd	nd	nd	nd	nd	nd	nd	nd

Mean value ± standard deviation in the same row with different lower case superscripts are significantly different based on Duncan (Post – hoc test) at $p ≤ 0.05$.
nd: implies that volatile was below detection limit/ not detected; K-RI: kovats retention index Est. (estimated) and Lit. (based on literature).

a better indicator of product quality.

4. Conclusion

The overall results indicated that the modified atmosphere and humidity conditions were capable of preventing condensation when the window was covered with films with high permeability to water vapour. Therefore, the concept of such packaging system equipped with a control window represents an innovative approach to minimize the risk of moisture condensation. Moreover, this study showed that the fixed window with micro-perforations was capable of preventing anoxic conditions. Furthermore, the traditional quality parameter detected no significant changes in packaged strawberries, however, the evolution of volatile organic compounds in the package headspace showed significant changes during storage. Therefore, the investigation of off-odour by GC–MS served as a better early indicator of the product quality during storage when compared to the traditional quality parameters (pH, TA, and TSS). Further studies are needed to elucidate the performance of such packaging system under fluctuating temperature conditions, which normally occurs during the long distance supply chain of fresh produce. Measuring actual relative humidity inside the package headspace will also be helpful to understand the dynamics of moisture evolution and condensation on different parts of the package.

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6. Condensation regulation of packaged strawberries under fluctuating storage temperature

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Condensation regulation of packaged strawberries under fluctuating storage temperature

Graziele G. Bovi[1,2] | Oluwafemi J. Caleb[1,3] | Cornelia Rauh[2] | Pramod V. Mahajan[1]

[1] Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany

[2] Department of Food Biotechnology and Food Process Engineering, Technical University of Berlin, Berlin, Germany

[3] Post-Harvest and Agro-Processing Technologies (PHATs), Agricultural Research Council (ARC) Infruitec-Nietvoorbij, Stellenbosch, South Africa

Correspondence
Graziele G. Bovi, Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany.
Email: gbovi@atb-potsdam.de

Disruption in cold chain during distribution and retail could have a significant impact on in-package condensation of optimally designed packaged fresh produce. The aim of this work was to regulate in-package condensation and evaluate the performance of different packaging design systems for strawberries under fluctuating temperatures (between 10°C and 20°C) for 5 days. The design included the use of condensation control strategies, namely, enhanced permeable films (NatureFlex and Xtend) and FruitPad of different fructose content (0%, 20%, 30%, 35%, and 40%). Package performance was evaluated in terms of headspace gas composition, mass loss, condensation, physico-chemical changes, and visual and ortho-nasal quality evaluation. Percentage mass loss of packaged strawberries ranged from 0.6% to 4% and was 33% for unpackaged. Results also showed that compared with the control sample, both strategies (enhanced permeable films and FruitPads) were effective in reducing condensation. In addition, transpirational water loss, results of the water absorbed by the FruitPads and transferred through the films were used to understand the packaging design needs under fluctuating temperature.

KEYWORDS
condensation, moisture regulation, packaging, quality, strawberry

1 | INTRODUCTION

According to Food and Agricultural Organization (FAO), fresh produce has the highest wastage rates (45%) of any food product as almost half of all fresh produce produced are wasted.[1] These high wastage rates are due to the fact that fresh produce is unique among food products as they remain metabolically active (eg, respiring and transpiring) and their shelf and storage life are shortened as consequence of these physiological processes. Nevertheless, improved packaging (eg, modified atmosphere packaging [MAP]) can slow down such processes and consequently prolong product shelf life from growers to consumers by protecting and maintaining quality of product.[2] The beneficial effects of application of MAP technology on fresh produce as well as the ideal modified atmosphere (MA) conditions for a wide variety of fresh produce have been reviewed in numerous studies.[3-5] Even though the benefits of MAP technology are known, this technology is still not yet fully applied in practice. This was confirmed by analysing packaged strawberries sold in two different supermarkets in the Potsdam area, Brandenburg, Germany (Table 1).[6]

Nonetheless, over the last 5 years, great attention has been given to condensation regulation in MAP for a wide variety of fresh and fresh-cut produce. This is due to fact that the most commonly used material for MAP, polypropylene (PP), has a high gas and water barrier property, and as a result, the low water vapour transmission rate (WVTR) of the lid film causes high humidity in the package headspace. This creates an ideal environment for the mould growth and decay of packaged fresh produce. Studies addressing condensation regulation have been carried out such as by the use of salt trays,[7-9] humidity windows with enhanced permeable films,[10-15] fructose pads,[16] and water absorbers.[17,18] These strategies have been experimentally tested for different products including strawberry,[8,10,16] avocado,[17] pomegranate arils,[13] mushroom,[7] fresh-cut cauliflower,[12] tomato,[8,15] and fresh-cut iceberg lettuce.[11] Moreover, from Table 1, it is possible to see that at supermarket display points, the use of ventilated packages

TABLE 1 Practiced packaging and storage conditions of strawberries in the Potsdam area, Brandenburg, Germany

Parameters Analysed	Supermarket 1	Supermarket 2		
	1	1	2	3[a]
O_2, kPa	17.1	20.7	20.7	20.7
CO_2, kPa	4.6	0.0	0.0	0.0
Declared mass, g	500	300	500	1000
Strawberry mass, g	499.9	308.7	507.0	1137.7
Package dimensions, cm	19 × 10.5 × 5	19 × 11 × 4	18.5 × 11.5 × 8	29.5 × 19.5 × 4.5
Type of package	Plastic clamshell tray and film cover	Paper-based tray and film pouch	Plastic clamshell tray with plastic lid	Wooden container covered with paper and film cover
Number of perforations	0	18 (Ø = 7.5 mm)[b]	12 (area = 87.9 mm^2)[b]	18 (Ø = 8.33 mm)[b]
Condensation	Yes	No	No	No
Refrigeration	No	No	No	No

Note. Adapted from Grossi-Bovi-Karatay.[6]

[a]Contained the following message on the packaging film: "to maintain the quality please store in the refrigerator."

[b]Ø = diameter of perforation.

(eg, use of macroperforations) is being used to help control condensation and heat flow.

The increased interest in condensation regulation is due to the fact that improper condensation control could result in very high or low humidity inside the package, which leads to decrease in product quality and reduced shelf life. In the case of high humidity, there is a risk of in-package condensation, leading to promotion of spoilage microorganism growth, while, in the case of lower humidities excessive mass loss, leading to defects in external appearance, such as wilting and shrivelling.[19] Thus, it is clear that condensation regulation is extremely important to further extend shelf life of fresh produce and it plays an important role in reducing food waste and food loss. This has led to a paradigm shift from research focusing on MAP to integrated modified atmosphere and humidity packaging (MAHP) systems (Table 2).

Moreover, a wide range of condensation control strategies have been tested for fresh produce packed under MAP and MAHP conditions at constant temperature.[10,12,13,16] However, few studies have been carried out under fluctuating temperature.[20] Hence, the hypothesis of this study is that minor temperature fluctuation during the supply chain can lead to water condensation and optimal package design can effectively regulate in-package humidity under such fluctuations. In this context, the aim of this work was to regulate condensation

and evaluate the performance of different packaging design under fluctuating retail market temperatures for 5 days on the quality attributes of strawberries. The design included the use of condensation control strategies, namely, enhanced permeable films (NatureFlex and Xtend) and FruitPad of different fructose content (0%, 20%, 30%, 35%, and 40%).

2 | MATERIALS AND METHODS

2.1 | Plant materials

Fresh strawberries (cv. Flair) were obtained from a commercial grower's fresh market (Karls, Erlebnis-dorf, Elstal, Germany). The strawberries were harvested in the evening and sold within 24 hours the next day, and the average display temperature at the time of purchase was 15 ± 3°C. The strawberries were transported to the Freshness Laboratory, Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam, Germany, under cool conditions. The strawberries were carefully sorted and the damaged, overripe, and poor quality fruits were discarded in order to obtain uniform samples. The strawberries were

TABLE 2 Number of articles on MAP and MAHP over the last decade

Keywords	Number of Articles		Percentage Change, %
	Before 2009	After 2009	
MAP	1652	2250	36.2
MAP AND fresh produce	192	254	32.3
MAHP	75	134	78.7
MAHP AND fresh produce	15	32	113.3

Note. Based on a keyword-based search, using "AND" as a connector between keywords, on all databases of Web of Science on March 2019.

Abbreviations: MAHP, modified atmosphere and humidity packaging; MAP, modified atmosphere packaging.

precooled at temperature of 4°C for 2 hours prior to starting the experiments.

2.2 | Transpirational water loss

It is known that in-package headspace plays an important role in mass loss of packaged strawberries, and therefore, a model based on the degree of filling (DOF) is suitable to address this issue. In this context, the water vapour flux because of transpiration of packaged strawberries was calculated using the model developed by Bovi et al.[21] The proposed model (Equation 1) based on percentage DOF (Equation 2) was therefore used to calculate the transpiration rate (TR) of packaged strawberries at constant temperature of 12°C.

$$TR\left(g\ kg^{-1}h^{-1}\right) = -0.0009\ DOF + 0.0398, \tag{1}$$

$$DOF\ (\%) = \frac{V_{product}}{V_{package}}\ x\ 100, \tag{2}$$

where TR is the amount of water lost per kilogram of product and per hour, $V_{product}$ is the product's volume and equals to 250 mL (strawberry density was considered to be 1 g mL^{-1}), and $V_{package}$ is the package's volume and equals to 1020 mL.

Moreover, TR measurements were carried out in packaged strawberries under fluctuating temperature (as described in section 2.4). For this investigation, a fixed amount of strawberries (250 ± 2 g) were placed in PP packaging tray (17 × 12 × 5 cm), with corresponding percentage DOF of approximately 25%. The trays were manually filled with strawberries and hermetically sealed (using double sided hermetic tapes) with biaxially oriented polypropylene (BOPP) Propafilm (Innovia Films, Cumbria, UK). The lidding film on the trays was perforated with six microperforations of diameter of 0.82 mm. These perforations were made in order to maintain the package atmosphere close to air and reduce condensation. The TR was calculated by a gravimetric approach according to Equation (3):

$$TR = \frac{m_i - m_t}{t.\left(\frac{m_i}{1000}\right)}, \tag{3}$$

where TR is the TR (g kg^{-1} h^{-1}), m_i is the initial mass of the product (g); m_t is product mass (g) at a determined time (t) in hours (h). A total of three repetitions were carried out and the mass loss was measured after 5 days using an electronic balance CPA10035 (Sartorius, Göttingen, Germany).

2.3 | Modified atmosphere and humidity packaging design

FruitPads incorporated with varying fructose content (as active absorbing component) were used to evaluate package performance under the fluctuating temperature. The structure of the Fruitpads (McAirLaid's Vliesstoffe GmbH, Steinfurt, Germany) is as described in Bovi et al.[16] Package types were named according to the percentage

of fructose contained were FP-00, FP-20, FP-30, FP-35, and FP-40 for FruitPad containing 0%, 20%, 30%, 35%, and 40% of fructose, respectively. For comparison purpose, other packaging materials with relatively high WVTR such as Xtend film (StePac, Tefen, Israel) and cellulose-based biodegradable NatureFlex film (Innovia Films, Cumbria, UK) were used (Table 3). The control package and the packages containing FruitPads were covered with BOPP film. Additionally, unpacked strawberries were also analysed to depict the conditions in local farmers' market. All lidding films were perforated with six microperforations of diameter of 0.82 mm (preoptimized design, based on preliminary studies). All packaging trials were performed with PP trays (17 × 12 × 5 cm) and strawberries of 250 ± 5 g. Three replicates of each sample were performed making it a total of 27 packages.

2.4 | Package performance under fluctuating temperature

All packages were stored for 5 days under fluctuating temperature. The temperature fluctuation profile applied was to mimic the postharvest chain and included precooling, distribution, supermarket, and consumer step and was adapted from Matar et al.[22] Strawberries were packaged in MAHP at 10°C and remained at this temperature for 2 days. This step mimicked distribution from field to supermarket. Packages were considered to be at the supermarket for 1 day 12 hours at 20°C (supermarket shelves) and for 12 hours at 10°C (in supermarket refrigerator). After that, packages were considered to be bought, and consumers kept it outside the refrigerator for 2 days at 20°C. Following quality, parameters were assessed at regular intervals.

TABLE 3 Package design of the different packaging systems used in this study

Package Type	Lidding Film	Film WVTR, g m^{-2} d^{-1}	Film Permeability Rate to O$_2$	Percentage of Fructose in the FP
FP-00	BOPP	0.8	8.5 × 10^{-12}a	0
FP-20	BOPP			20
FP-30	BOPP			30
FP-35	BOPP			35
FP-40	BOPP			40
Control	BOPP			N/A
NatureFlex	NF	42.79	6.1^b	N/A
Xtend	XT	19.34	24 × 10^{-14} to 48 × 10^{-14}c	N/A
Unpacked	N/A	N/A	N/A	N/A

Abbreviations: BOPP, biaxially oriented polypropylene; FP, FruitPad; N/A, not applicable; WVTR, water vapour transmission rate.

^{a}mol m^{-2} s^{-1} Pa^{-1} (23°C and 0% RH).

^{b}mL m^{-2} d^{-1} (20°C and 56% RH).

^{c}mol m^{-2} s^{-1} Pa^{-1} (conditions not stated).

2.4.1 | In-package RH and headspace gas composition

Headspace gas composition (O_2 and CO_2, kPa) inside each package was monitored daily by using a CheckMate 3 gas analyser (PBI Dansensor, Ringsted, Denmark), with an accuracy of ±0.01% for O_2 in the range of 0% to 1% and of ±1% for O_2 > 1% and ±0.05 for CO_2. Air humidity sensor FHA646R (Ahlborn, Holzkirchen, Germany) was used to monitor air temperature and relative humidity (RH) with an accuracy of ±0.1°C and ±2% in the range less than 90% RH at nominal temperature (25°C ± 3°C), respectively.

2.4.2 | Mass loss and condensation

Condensation and total strawberry mass loss were quantified at the end of storage on day 5. The amount of water vapour condensed in the film (g) was quantified by weighing the films before and after the removal of condensed water on the lidding films. The water loss through the film, because of permeability, was also calculated from the difference between initial and final weight of the complete package according to Rux et al.[3,4] Moreover, the experimental values of water absorbed by pad and water loss over film (Figure 4), under fluctuating temperature, were used to calculate the water vapour flux because of the film and water flux of FruitPad absorption (Figure 1). The water vapour flux of both condensation control strategies was calculated dividing total mass of water absorbed/transferred by 120,

which is the number of hours under which the fluctuating temperature experiment ran.

2.4.3 | Physico-chemical changes

Strawberries were squeezed, and juice was extracted. The strawberry juice was then used to measure total soluble solids (TSS), pH, and titratable acidity (TA). A digital refractometer (DR301-95, Krüss Optronic, Hamburg, Germany) was used to measure TSS and expressed as %. The TA concentration of the juice sample was measured potentiometrically by titration with NaOH of 0.1 mol L^{-1}, to an endpoint of pH of 7.0 using an automated T50 M Titrator with Rondo 20 sample changers (Mettler Toledo, Switzerland). The TA concentration was expressed as g L^{-1} of citric acid based on fresh mass. The pH was measured with a pH meter (inoLab pH 720, WTW Series, Weilheim, Germany) after calibrating with pH buffers 4 and 7. Measurements were done in triplicate on days 0, 3, and 5.

2.4.4 | Visual and ortho-nasal quality evaluation

Seven untrained panelists who are regular consumers and familiar with the quality attributes of strawberry carried out visual and ortho-nasal quality evaluation. Strawberry quality attributes such as texture, appearance, brilliance, odour, and decay were evaluated on a scale of 1 to 5. In addition, visual observation of in-package condensation on the lidding film was also scored on a scale of 1 to 5. The quality scores (1-5) were adapted from Bovi et al[10] as represented in Table 4.

2.5 | Statistical analysis

The statistical analysis was carried out using Statistica software (version 10.0, StatSoft Inc., Tulsa, USA), and data obtained were subjected to one-way analysis of variance (ANOVA), and Tukey's test was used to test statistically significant difference set at $P \leq .05$. All the results were presented as the mean (n = 3) ± standard deviation (SD).

3 | RESULTS AND DISCUSSIONS

3.1 | Water vapour flux of product and package

The water vapour flux range because of transpiration of packaged strawberries was 0.0042 to 0.0047 g h^{-1} at 12°C, whereas the experimental was 0.0080 to 0.0088 g h^{-1} at fluctuating temperature, both having the DOF percentage of 25.51% (Figure 1). The differences in the water flux can be attributed to the fluctuating temperature. These results thus emphasize that fluctuating temperature affect the TR of packaged strawberries as well as the RH as indicated in Figure 2. To a great extent, fluctuating temperature should be avoided along the supply chain. In theory, in order to avoid condensation inside the package, the flux of water vapour through the package, as well as the FruitPad absorption water flux, should be as close as possible to
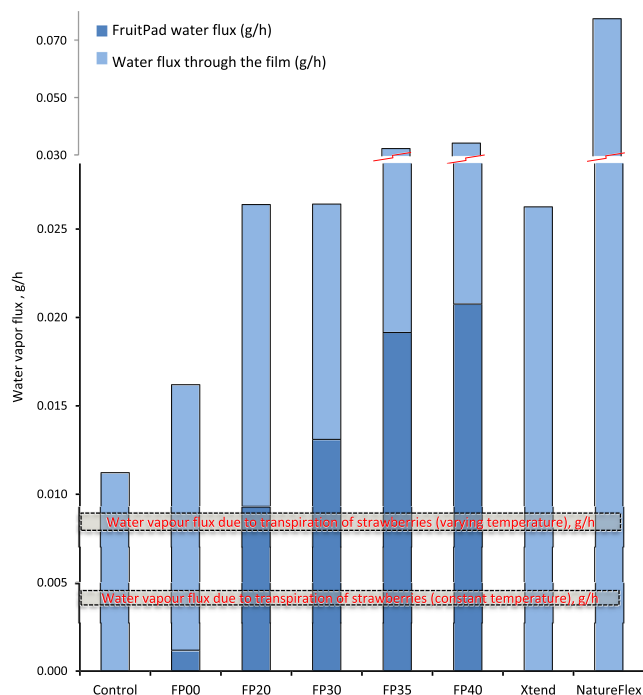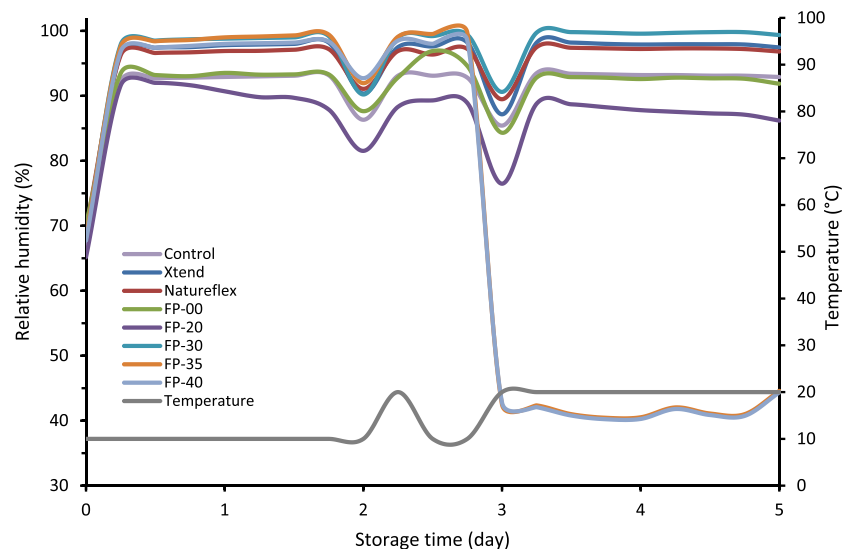

FIGURE 1 Water vapour flux because of the film and water flux of FruitPad absorption (vertical bars) and the rate of transpirational losses from packaged strawberries (horizontal bars) at constant (12°C) and varying temperature (4°C to 20°C). Standard deviation of 0.001 g kg^{-1} h^{-1} was used to calculate the range of transpirational loss

TABLE 4 Quality scores and descriptors for strawberry

Descriptors	Scores and Description				
	1	2	3	4	5
In-package condensation	Package surface is completely free of water vapour	Package surface is extensively covered with water vapour	Package surface is partially covered with water vapour ≥50%	Package surface is partially covered with water vapour ≤50%	Package surface is partially covered with water vapour ≤25%
Texture	Very poor (fruit are extremely soft)	Poor (fruit are very soft)	Fair (fruit exhibit minor signs of softness)	Good (fruit are firm)	Very good (fruit are firm and turgid)
Brilliance	Very dull looking	Dull looking	Glossy looking (halfway between shiny and dull)	Shiny looking	Very shiny looking
Odour	Dislike very much	Dislike moderately	Neither like nor dislike	Like moderately	Like very much
Decay	76%-100% decay (extreme decay/ completely rotten)	51%-75% decay (moderate to severe decay)	26%-50% decay (spots with decay)	1%-25% decay (probable decay)	0% decay (no decay)

Note. Adapted from Rux et al.[7]

FIGURE 2 Impact of temperature fluctuation on relative humidity of package containing strawberries

the rate of transpirational losses of packaged strawberries. As shown in Figure 1, only the control package fulfils this condition. However, as seen from Figure 4, these packages were not able to avoid condensation. This could be due to higher initial transpiration than in the final days of storage, and therefore, the permeability of the films, as well as the perforations, is not enough to deal with the initial water flux and leads to condensation. For that reason, it is necessary that the packaging systems should either allow the excess water to exit the package (water prevention) or be absorbed by the pads (water elimination) in order to avoid the formation of condensation. Therefore, in reality, it is needed that not only the flux of packaging system matches the transpiration losses of the produce but also condensation control strategy is added to the packaging design.

3.2 | In-package RH and gas composition

Temperature fluctuation had a significant impact on the in-package RH (Figure 2) and in the process of deliquescence. Deliquescence is a phase transition from solid to solution, induced by water uptake from the atmosphere, which in turn is triggered when the in-package RH is above the deliquescence point (RH_o).[23] RH_o is the RH at which crystalline materials, such as fructose, begin absorbing large quantities of water from the atmosphere. Below that point, the process of slow water adsorption takes place. In turn, it is known that RH_o is an important temperature dependent stability parameter.[23] For example, at 20°C, RH_o for fructose is 64.8%, whereas for 25°C and 30°C, it is of 63.4% and 61.7%, respectively.[24] In the present study, as soon as

the packages were closed, the headspace RH was above the deliquescence point of fructose as a result of the transpiration process of strawberry. High headspace RH was observed in all packages until day 3. However, the packages containing FruitPads with higher fructose content (FP-35 and FP-40) showed unexpected rapid decrease of RH when temperature was increased to 20°C on day 3. At this point, the water from the headspace began to be absorbed by the FruitPads at a much faster rate as compared with other packages. This was evident from Figure 4 which showed significant amount of water absorbed by FP-35 and FP-40. Overall, the amount of water absorbed was directly related to the amount of fructose added in FruitPads. The higher the fructose content, the higher the amount of water absorbed by the deliquescence process was. Therefore, it is important to consider this relation for optimizing fructose content in FruitPads that will maintain RH in the range of 90% to 95%, which is ideally recommended for packaging and storage of fruit and vegetables. In addition, the impact of raising the temperature from 10°C to 20°C on the last 2 days of experiment affected the RH of FP-35 and FP-40 packages compared with other packages. Moreover, as shown in Figure 2, the increase in temperature led to an immediate decrease in the RH. The reason for that is that at higher temperatures, air can hold more water vapour and as a consequence, RH is decreased.[25] After day 1, there already seemed to be a trend to equilibrium, nevertheless, after the temperature fluctuation (from day 2), the equilibrium was affected.

After 5 days of storage, under fluctuating temperature, the in-package gas composition of different packages varied between 13 to 19 kPa for O_2 and 2 to 8 kPa for CO_2 (Figure 3). Packages covered with NatureFlex films had the lowest CO_2 (2.15 kPa) and highest O_2 (18.8 kPa). The marginal atmosphere modification in the NatureFlex films can be attributed to differences in RH throughout storage (as a consequence of the temperature fluctuation and product transpiration losses). Rosenkranz[15] reported that the oxygen transmission rate (OTR) of NatureFlex films increased 24 times with increasing RH from 56% RH (6.1 mL m^{-2} d^{-1}) to 100% RH (148 mL m^{-2} d^{-1}) at constant temperature of 20°C. Thus, temperature fluctuation led to changes in RH and directly affected the permeability of the film, which in turn influenced the headspace gas composition as O_2 from the environment permeated into the packages covered with NatureFlex film.
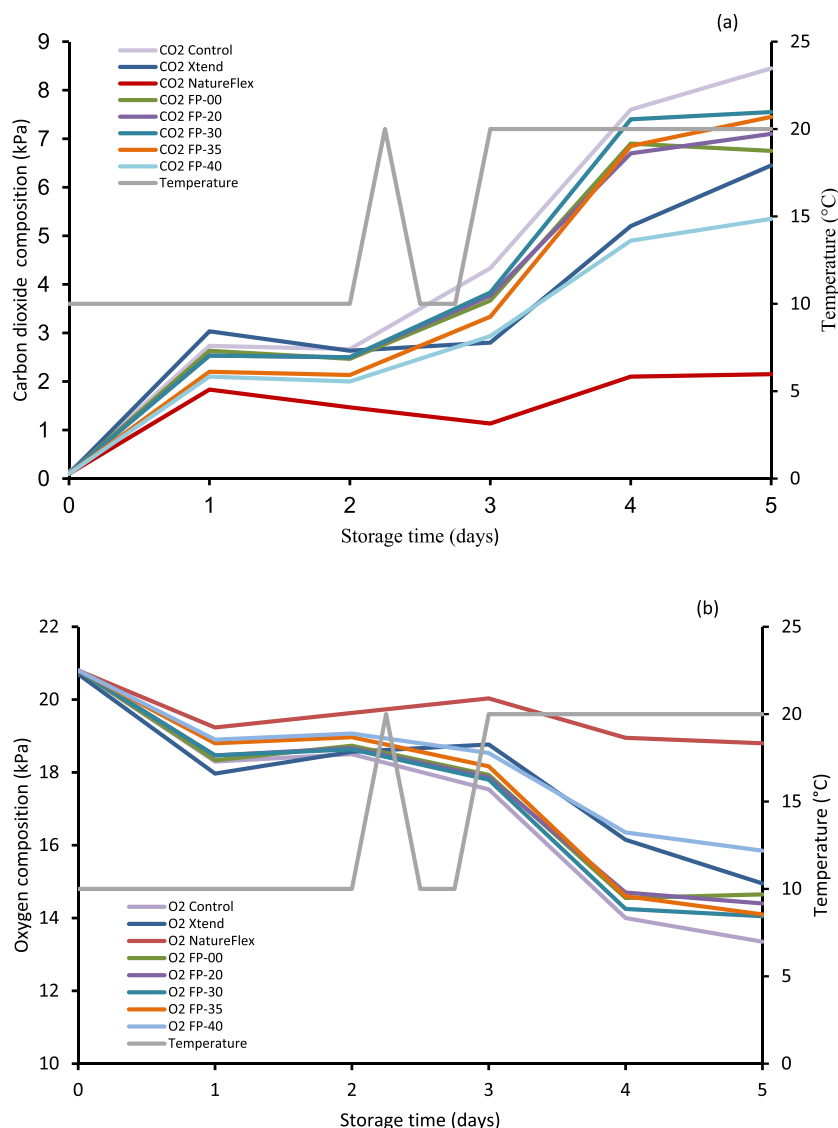

FIGURE 3   Changes in headspace gas composition of packaged strawberries stored under fluctuating temperature (A) carbon dioxide (kPa) and (B) oxygen (kPa)

Moreover, none of the packages had a declined of O_2 below 13% indicating that anaerobic respiration did not take place. All packaging systems used in this study were efficient in preventing anoxic conditions for packaged strawberries. The temperature fluctuation affected the CO_2 production to higher extend as compared with O_2 consumption.

3.3 | Mass loss and condensation

Strawberry total mass loss was significantly influenced by type of condensation control strategy used (Figure 4). Highest strawberry mass loss was observed in packages covered with NatureFlex film (3.68%) and lowest at the control (0.61%). On the other hand, control had the highest in-package water condensation (≈ 0.19 g), whereas all other packages had 10 times less in-package condensation (less than 0.02 g). Tukey's test showed that there was no significant difference in mass loss between the control, Xtend, FP-00, FP-20, and FP-30, sample, whereas significant difference in mass loss was observed in packages covered with NatureFlex film ($P \leq .05$). This outcome confirms the high WVTR of NatureFlex film and the need for integrated product-specific package design (Figure 4) (eg, use of humidity windows). Moreover, mass loss for the unpacked sample was 33.15 g (33.16 ± 0.33%), this amount is significantly above the recommended maximum acceptable percentage mass loss for strawberries of 6%.[26] This once more emphasizes the role MAP plays in minimizing mass loss of strawberries.

In addition, results showed that the fluctuating temperature led to a higher mass loss when compared with experiments carried out at 12°C for the same 5 days.[16] Under constant temperature, with two microperforations of 0.7-mm diameter, the percentage mass loss of strawberries was 0.92%, 0.62%, 0.26%, and 0.21%, which represents an increase of 1.4, 1.7, 2.7, and 2.9 times higher for FP-30, FP-20, FP-00, and control, respectively. Nevertheless, not all of this increase

can be attributed to temperature fluctuation as in this study there were six microperforations of diameter of 0.82 mm; therefore, part of the water released by the product probably escaped through the optimized microperforations.

3.4 | Physico-chemical changes

The range of TA, pH, and TSS obtained in this study was 8.5 to 12.0 g L^{-1} for citric acid, 3.6 to 3.8, and 8.7% to 12.4%, respectively (Table 5). In this study, changes in citric acid were within the range of 7.3 to 15.8 g L^{-1} for six different varieties of strawberries as reported by Kallio et al[27] for cvs. "Senga Sengana," "Jonsok," "Korona," "Polka," "Honeoye," and "Bounty." The authors evaluated six strawberry varieties in terms of their acid composition. Also, there were no significant difference ($P > .05$) within the storage days for control, Xtend, NatureFlex, FP-00, FP-20, FP-30, FP-35, and FP-40 (Table 5). Within the packaging systems, day 3 had no significant difference ($P > .05$), whereas for day 5, there was a significant difference between the packaging systems ($P < .05$). Moreover, as can be seen from Table 5, there was not a clear reduction nor increase of the TA within the storage days meaning that not a significant amount of organic acid was used as a substrate for respiratory activity.[28]

The pH values obtained in this study for cv. "Flair" strawberries (Table 5) were a little below the range reported for cv. "Elsanta" strawberries by Bovi et al[10] and for cv. "Sonata" strawberries by Caleb et al[29] which were in the range of 3.9 to 4.1 and 3.9 to 4.7, respectively. Similarly to TA, there was no significant difference between storage days for all packages except for unpacked and FP-30 samples; the magnitude of changes in pH was not higher than 0.3 in any of the samples. Within the packaging systems, day 3 had no significant difference ($P > .05$), whereas for day 5, there was significant difference between the packaging systems ($P < .05$). This indicates that there
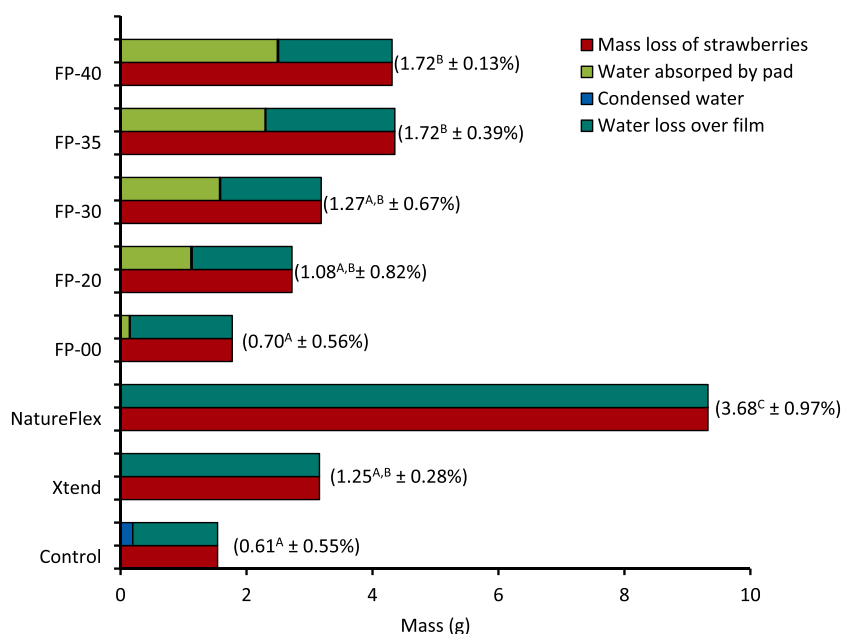

FIGURE 4 In-package moisture dynamics of strawberries packaged with different moisture control strategies stored under fluctuating temperature for 5 days. The values in bracket represent the percentage mean values (mean value ± standard derivation, n = 3) for total strawberry mass loss. Different upper case superscript is significantly different based on Tukey test at $P \leq .05$

TABLE 5 Effect of package design and storage duration on physicochemical properties of strawberries stored under fluctuating temperature for 5 days

Parameter	Storage, d	Package Type								
		Control	Unpacked	Xtend	NatureFlex	FP-00	FP-20	FP-30	FP-35	FP-40
TSS, %	0	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]	9.8 ± 0.1 [A]
	3	10.2 ± 0.4 [A,a]	11.5 ± 1.1 [A,B,a]	12.4 ± 1.7 [B, a]	10.9 ± 0.0 [A,B,a]	10.2 ± 0.4 [A, a]	10.3 ± 1.5 [A, a]	11.0 ± 0.7 [A, a]	10.3 ± 0.6 [A, a]	9.4 ± 0.1 [A, a]
	5	11.1 ± 1.0 [A,a]	11.9 ± 0.8 [B,a]	11.5 ± 0.3 [B,a]	11.6 ± 0.9 [B,a,b]	10.8 ± 1.1 [A,a,b]	10.2 ± 0.9 [A,a]	10.1 ± 1.9 [A,a]	8.7 ± 0.5 [B,a]	9.8 ± 1.1 [A,b]
TA (citric acid), g L⁻¹	0	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]	9.0 ± 0.6 [A,]
	3	9.8 ± 0.8 [A,a]	10.2 ± 1.1 [A,B,a]	10.7 ± 1.1 [A,a]	10.5 ± 1.4 [A,a]	9.7 ± 0.1 [A,a]	10.3 ± 1.5 [A,a]	8.5 ± 0.1 [A,a]	9.8 ± 0.1 [A,a]	9.4 ± 1.1 [A,a]
	5	9.8 ± 0.4 [A,a,b]	12.0 ± 1.1 [B,b]	9.9 ± 0.8 [A,a,b]	11.0 ± 1.2 [A,a,b]	9.5 ± 0.6 [A,a,b]	9.1 ± 0.2 [A,a]	10.2 ± 1.8 [A,a,b]	8.5 ± 1.5 [A,a]	9.2 ± 1.9 [A,a]
pH	0	3.8 ± 0.1 [A]	3.8 ± 0.1 [A]	3.8 ± 0.1 [A]	3.8 ± 0.1 [A]	3.8 ± 0.1 [A]	3.8 ± 0.1 [A]	3.8 ± 0.1 [A,B]	3.8 ± 0.1 [A]	3.8 ± 0.1 [A]
	3	3.6 ± 0.2 [A,a]	3.7 ± 0.0 [A,B,a]	3.8 ± 0.1 [A,a]	3.7 ± 0.1 [A,a]	3.7 ± 0.0 [A,a]	3.7 ± 0.0 [A,a]	3.9 ± 0.0 [A,a]	3.8 ± 0.0 [A,a]	3.7 ± 0.0 [A,a]
	5	3.7 ± 0.1 [A,a,b]	3.7 ± 0.0 [B,a,b]	3.6 ± 0.1 [A,a]	3.7 ± 0.1 [A,a,b]	3.7 ± 0.1 [A,a,b]	3.7 ± 0.0 [A,a,b]	3.7 ± 0.1 [B,a,b]	3.8 ± 0.1 [A,b]	3.8 ± 0.1 [A,a,b]

Note. Mean values (mean value ± standard derivation, n = 3) for each analysis. Column and row with different upper case superscript and different lower case superscript, respectively, are significantly different based on Tukey test at $P \leq .05$.

Abbreviations: TA, titratable acidity; TSS, total soluble solids.

FIGURE 5 Changes in visual quality attributes of packaged strawberries and observed water vapour condensation after 5 days of storage under fluctuating temperature

was no significant changes in the acidity of the strawberry juice samples.

Also, for TSS, values obtained in this study were above the reported by Caleb et al[29] Bovi et al[10] and Kallio et al[27] which were in the range of 8.3% to 10.8%, 4.0% to 5.2%, and 5.35% to 10.96% respectively. This could suggest that the strawberries in this studies contained more sugar and were sweeter. There were no significant difference ($P > .05$) within the storage days for control, FP-00, FP-20, FP-30, and FP-40. Within the packaging systems, day 3 had no significant difference ($P > .05$), whereas for day 5, there was significant diffe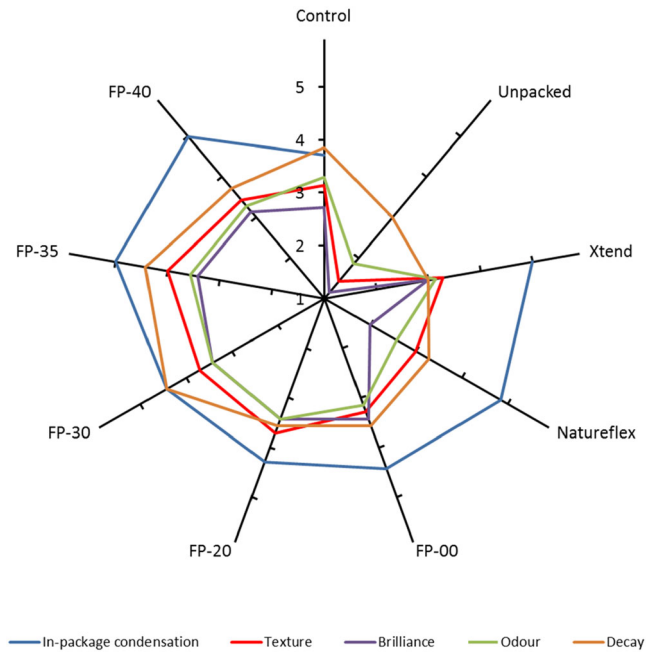rence between the packaging systems ($P < .05$). This could suggest that soluble sugars is converted and used up for the fruit respiratory metabolism. Nevertheless, taking into consideration the duration of the study, the observed differences could also be due to natural variability of the strawberries such as the stage of ripeness.[27]

3.5 | Visual and ortho-nasal quality evaluation

All packages, except for unpacked and NatureFlex, received scores above 3, indicating that the packaged strawberries were marketable at the end of storage day 5 (Figure 5). The extreme low scores for the unpacked can be associated with the excessive mass loss (33%) as this led to extreme shrivelling and wilting of the product, which in turn affect the texture, brilliance, and decay directly. The sensorial analysis scores were in accordance with Figure 3, as packages covered with NatureFlex and Xtend films, and containing FruitPads had little or almost no visual condensation (scores between 5 and 4). This reduction was very important as it plays a very important role in consumer's choice.

Moreover, results obtained in this study are in accordance with Bovi et al[10] as condensation was quantified as being close to zero (Figure 4), but in the visual and ortho-nasal evaluation, it was visible. As already discussed in the authors' work, a possible reason for that is that the films absorbed water and formed droplets, being therefore visible to panelists but not detected in the quantification. Regarding quality attribute odour, the perceived odour for all packaged strawberry samples received an average score of 3, except for unpacked and NatureFlex, indicating that no critical off odour was recorded at the end of storage. This could be attributed to the fact that O_2 did not decline below critical limit in any of the packages. Moreover, based on the results obtained by the Tukey's test, ortho-nasal evaluation showed that there were no significant differences only in decay between the packaged strawberry samples ($P < .05$); all other parameters had significant differences.

4 | CONCLUSIONS

A key finding of this study was that both enhanced permeable films and the FruitPads were able to reduce condensation as compared with the control sample under fluctuating temperature without affecting product quality. Furthermore, it was observed that both water elimination and water prevention strategies, namely, FP-00, FP-20, FP-30, and Xtend, were the best in terms of reducing condensation while maintaining the mass loss without any significant difference. Furthermore, the water vapour flux needs of packaging materials under fluctuating temperature showed that the important parameter is not only ensuring that the package material water flux is as close as possible to the rate of the product transpiration losses but also having a condensation control strategy. Therefore, in addition, packaging design should take into consideration a condensation control strategy that can eliminate, prevent, or reduce excessive initial water released by product.

ORCID

Graziele G. Bovi https://orcid.org/0000-0001-8610-6583

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7. Conclusions and future perspectives

Overall, the potential of using these two innovative moisture control strategies for packaging of strawberry in MAHP systems was reflected in the different parts of this PhD thesis. Exemplarily on strawberries, this research deepened the understanding of how physiological processes, temperature management and package geometry affect the in-package humidity and condensation. These results provided substantial contributions to the scientific knowledge on MAHP as well as to the packaging industry by aiding in the selection of most adequate moisture control strategy to be used. Moreover, this PhD thesis adequately tested and confirmed all formulated hypotheses.

The first hypothesis of this thesis was that TR models for unpacked products cannot be used for packaged fresh produce as the environmental conditions differ to a great extent. This hypothesis was confirmed in Chapter 3. The results showed that packaged strawberries transpired in a much lower rate than unpacked strawberries. This emphasized that all TR models that have been developed and reported in literature for unpacked products are not suitable to predict moisture loss for packaged fresh produce. Moreover, results showed that different numbers of strawberries packaged in a fixed package volume (0.93 L) behaved different than a single strawberry; the TR for one strawberry was 2.5 times higher than for 15 strawberries. Two possible reasons for that are: i) with higher number of strawberries they tend to overlap, which leads to a reduction of the effective surface area needed for the transpiration to take place and ii) with higher number of strawberries, at constant package volume, the package headspace is less, consequently saturation can be reached faster as compared to packages with less strawberries (higher package headspace). The transpiration process is driven by a concentration difference in water activity or in other words water vapour pressure between product surface and its surroundings. At saturated conditions, as normally observed in packaged fresh produce, there is a reduction in this driving force, thereby, transpiration is reduced. From these findings it is now clear that the package headspace plays a significant role in quantifying the transpiration of packaged fresh produce. Considering this, a new TR model for packaged strawberry based on degree of filling (DOF) was developed and further applied for packaging design of strawberries in Chapter 6. As future perspective, an integrated approach is needed to study water loss in packaged fresh produce, considering product surface tissues, respiratory heat, produce surface and body temperatures,

carbon loss, ethylene production, volatile organic compounds and DOF. In addition, such study should include the effect of dynamic temperature variation on the mass loss of the product.

The second hypothesis of this thesis was that the commonly used calculation to express substrate loss (M_{sub}= RR x 180/264), based on product respiration rate (RR) was not suitable for quantifying actual mass loss of packaged fresh produce. This hypothesis was experimentally confirmed in Chapter 3. Results showed actual total mass loss of strawberries was of 0.030 ± 0.001 g kg^{-1} h^{-1} as against only substrate mass loss of 0.033 g kg^{-1}h^{-1} (calculated based on RR). Higher substrate loss than the total mass loss is not possible unless changes occurred inside the package headspace or the product itself. These could be due to moisture condensation on the product surface, carbon loss of product, loss of volatile organic compounds, including ethylene, ethanol or acetaldehyde. In the past years the role played by respiration in the transpiration process has been investigated and unarguably it is clear that respiratory heat can significantly influence moisture evolution in packaged fresh produce, especially under saturated storage conditions. However, it still remains an unsolved challenge to quantify how much the additional mass loss is due to carbon loss. Moreover, there are other flow components that pass through the product surface tissue, such as volatile organic compounds and ethylene, which are usually considered to be negligible. As future prospective further studies addressing total mass loss of fresh produce is needed so that it is possible to subdivide total mass losses (M_{tot}) in the following:

$$M_{tot} = M_{wat} + M_{sub} + M_{eth} + M_{vol}$$

where M_{wat} = moisture mass loss due to transpiration, M_{sub} = substrate mass loss due to respiration, M_{eth} = mass loss due to ethylene production and subsequent emission and M_{vol} = mass loss due to emitted volatile organic compounds.

The third hypothesis was that fructose has good potential, when incorporated to pads, to absorb headspace water vapour. Results in Chapter 4 not only confirmed the hypothesis but also quantified the kinetics of moisture absorption of FruitPad containing different contents of fructose (0, 20 and 30 %) as an active ingredient for moisture absorption. Moreover, a Weibull model combined with the Flory-Huggins model was developed and adequately described changes in the moisture content of the FruitPad with respect to storage time and RH (R^2 = 0.93 – 0.96). Further attempt was made to use this model to predict water gain by FruitPad at specific RH. When fruit were added to the packages the water absorption behaviour of pads containing

fructose was different than the behaviour of pads not containing strawberries. Therefore, a more detailed study is needed to understand the moisture absorption under product load and exposed to varying temperatures. The reason for that can be that when in contact with the fruit, the FruitPads absorb water vapour from the headspace and liquid water directly from the strawberries. Overall, strawberry quality parameters were not affected with the extra water uptake by FruitPad. A consumer ortho-nasal analysis was carried out and all quality attributes scored above 3 (from a scale from 1-5), indicating that the packaged strawberries were marketable at the end of storage day 5 (Table 3).

Table 3. Sensory evaluation and incidence of decay (%) for strawberries after 5 days of storage at 12 °C

Package[1]	Attributes						Incidence of decay (%)[2]
	Condensation	Texture	Appearance	Brilliance	Odour	Decay	
Control	$3.4^B \pm 0.2$	$4.4^A \pm 0.5$	$3.8^A \pm 0.5$	$4.0^A \pm 0.0$	$3.0^B \pm 0.0$	$3.2^B \pm 0.4$	3.3^B
FruitPad00	$3.5^B \pm 0.1$	$4.2^A \pm 0.4$	$4.2^A \pm 0.8$	$4.0^A \pm 0.7$	$3.0^B \pm 0.0$	$3.0^B \pm 0.0$	6.7^C
FruitPad20	$4.3^A \pm 0.5$	$4.8^A \pm 0.5$	$4.3^A \pm 0.5$	$4.0^A \pm 0.0$	$2.8^B \pm 0.2$	$4.2^A \pm 0.4$	0.0^A
FruitPad30	$4.2^A \pm 0.3$	$3.8^A \pm 0.5$	$4.6^A \pm 0.5$	$3.8^A \pm 0.5$	$3.8^A \pm 0.4$	$4.5^A \pm 0.3$	0.0^A

Mean values (mean value $\pm$ standard deviation, $n = 5$) for the same attributes, column with same upper case superscript are not significantly different based on Tukey test at p < 0.05.
[1]Package: Control with no absorbing pad; FruitPad30 contained 30% of fructose; FruitPad20 contained 20% of fructose; and FruitPad00 contained 0% of fructose. [2] the incidence of decay was quantified as the percentage of strawberries with visual fungal contamination. Incidence of decay (%) was calculated as the average of the replicates.

For the visual observation of water condensation on the lidding films, packages with FruitPad20 and FruitPad30 were scored higher compared to the control and FruitPad00 packages. Based on the results obtained by the Tukey's test, sensory evaluation showed that there were no significant differences in texture, appearance, and brilliance between the packaged strawberry samples (p < 0.05). Moreover, images of the packaged strawberries on day 0 and after 5 days of storage reinforces that quality was not visually affected during storage time of 5 days.

Generally, the perceived odour for all packaged strawberry samples received an average score of 3, indicating that no critical off-odour was recorded at the end of storage. This could be attributed to the fact that O_2 did not decline below the critical limit (5 kPa) in any of the packages (Figure 5). Furthermore, no visual fungal decay incidence was found on strawberries packed with

FruiPads containing 20% and 30% of fructose. In contrast, the samples packed in control package and with FruiPad00 had 3.3% and 6.7 % decay incidence, respectively. The incidence of decay could be associated with the higher impact of water vapour condensation inside the control and FruiPad00 packages.

Overall, Chapter 4 highlighted that the FruitPad containing fructose were effective in absorbing water vapour from the package headspace and liquid water from the produce, thereby reducing the risk of condensation and, thus, potentially preventing decay incidence. Furthermore, it is worth mentioning that the amount of fructose integrated into the absorbent pads could be adjusted product specifically. Hence, as future perspective the fructose content needs to be optimized considering both the water losses of each fruits or vegetables and the packaging properties. If fructose content is too high, drying of the product may can occur; if it is too low, the effects of condensation may become significant. Either of these situations will have a negative impact on fruit quality. Moreover, , the effectiveness of incorporating other types and proportions of low cost food grade desiccants (e.g. NaCl, $CaCl_2$, xylitol, sorbitol, and KCl) to the FruitPads should also be explored to obtain equilibrium relative humidity in a package.
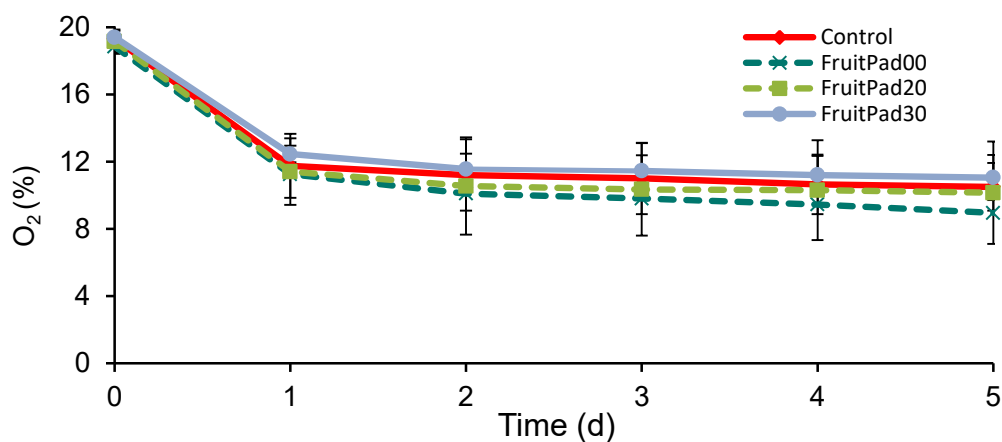

Figure 5. Changes in headspace oxygen composition inside packaged strawberries stored at 12 °C for 5 days. Error bars represent standard deviation (SD) of mean values (n = 2).

The forth hypothesis was that limited fixed area (33, 66 and 100 % of total upper package area) of highly water vapour permeable films used as window in the package film covering can help to

prevent excessive product mass loss while minimizing moisture condensation. This hypothesis was confirmed in Chapter 5. Results showed that in packages fitted with NatureFlex™ and Xtend®, independent of the window size, condensation was effectively prevented compared to the Propafilm™ fitted control package. Nevertheless, condensation prevention led to higher mass loss of fruit than observed in control packages. However, by the selection of the appropriate window film size it is possible to minimize mass losses of strawberries. Moreover, the required size of the window is product specific and depends on mass loss rates of products. Also, results from this study showed that even though condensation on the product was quantified as zero, it was visible in the sensory evaluation of the package. The reason for that can be that both NatureFlex™ and Xtend® possibly absorbed water and formed droplets, thereof being visible despite not being quantified. Nevertheless, such problem can be solved by coating the films with anti-mist compound. Anti-mist chemicals reduce surface tension of water therefore spread water as a layer on the surface of packaging material. The advantage of its use is that it keeps water droplets of becoming big enough to be visible as condensation. Also by preventing the formation of big droplets it aids in the prevention of such droplets possibly falling onto products and leading to accelerate microbial growth. From the quality aspect, the use of the fixed highly permeable windows prevented anoxic conditions and did not significantly affect pH, titratable acidity and total soluble solids of strawberries. Nevertheless, significant changes were observed in the evolution of the volatile organic compounds during the 14 days of storage at 5 °C. As future perspective, the suitability of other commercially available highly water permeable films in terms of controlling condensation and minimizing product mass loss should be further investigated. Other commercial film that claim to have highly water vapour permeable permeability property are PackConnect films under the "H_2O Films" project (http://www.packconnect.nl/projects) and Mylar® harvest fresh (DuPont Teijin Films™, Middlesbrough, United Kingdom). These films, as well as other that claim such property, should be individually tested and optimized according to specific fresh produce to be packed.

The fifth hypothesis was that FruitPads and highly permeable films have potential in controlling in-package relative humidity and reducing condensation under fluctuating storage temperature. This hypothesis was confirmed in Chapter 6. It is known that even minor temperature fluctuation leads to condensation. It is, therefore, essential to investigate whether the proposed feasible and innovative humidity control strategies are effective in preventing condensation under dynamic

conditions. Any disruption in the cold chain during distribution and retail could have a significant impact on optimally designed packaged fresh produce. Results from Chapter 6 showed that both strategies (highly water vapour permeable films and FruitPads) were effective in reducing condensation compared to the control sample. Moreover, percentage mass loss ranged from 0.6 % to 4 % for packaged strawberries and was 33 % for unpackaged. In addition, the model developed in Chapter 3 was used to predict the water vapour flux range due to transpiration of packaged strawberries. The model predicted a water vapour flux of 4.2-4.7 mg h^{-1} at fixed temperature of 12 °C whereas the experimental was 8.0-8.8 mg h^{-1} at fluctuating temperature. The differences in the water vapour flux can be attributed to fluctuating temperature. Moreover, results also emphasized that in order to be able to develop models for mass loss of packaged fresh produce under dynamic conditions, many factors need to be taken into account such as: i) the product, ii) the film used, iii) the number of film perforation , iv) the headspace volume and v) the storage temperature. As future perspective, the effects of fluctuating temperature and humidity on the film cover and window permeability should also be investigated. There is evidence that cellulose based films can change to a great extend due to RH variations. In terms of quality, both strategies were effective in maintaining the optimal packaging requirements.

Overall, results from this PhD thesis showed that the proposed moisture control strategies are capable of reducing condensation even under dynamic conditions, exemplarily for strawberries. Therefore they have potential to maintain product quality for a longer period, consequently increase shelf life and possibly reducing food loss. These strategies were tested for strawberries, therefore, to evaluate its effectiveness on other fresh produce it should be adjusted according to product transpiration rates. Moreover, in order to be able to achieve a significant food loss reduction one should not only focus on individual solutions but to have a more holistic approach. In order to be able to really bring the numbers of food waste down, all the players involved in the supply chain, from farmers to consumers, need to take action on preventing food losses. Only with all of them working together a significant role in preventing and reducing food waste will happen. In addition, more attention should be given on studies focusing on consumer behaviour as they also play an important role in food loss reduction as they are the final decision makers in the sense that they are the ones who will decide whether or not to consume the product. Very few studies on improved packaging have focused on that (Matar et al., 2018). Nevertheless the importance of that has been highlighted in recent studies (Porat et al., 2018).

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Declaration

I hereby declare that the work presented in this dissertation is an authentic record of my own work. All used resources and sources are cited. All published parts of this dissertation are listed in the publication list.

Graziele Grossi Bovi Karatay

Berlin, 24.09.2019