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

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27 **Measurement and modelling of transpiration losses in packaged and unpackaged**  
28 **strawberries**

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41  
42 **Abstract**

43 Transpiration and respiration are physiological processes well-known as major sources of  
44 fresh produce mass loss. Besides causing impairment of external quality, it is associated with  
45 economic loss since it inevitably decreases saleable weight. To prevent postharvest mass  
46 losses, by improved modified atmosphere and humidity packaging, comprehensive knowledge  
47 on the mechanistic basis of both processes and their interactions is essential. The objective of  
48 this study was to evaluate the contribution of these processes on mass loss of packaged and  
49 unpackaged strawberries. Experiments on a single strawberry were performed at 4, 12 and  
50 20°C; and 76, 86, 96 and 100% RH. Mass loss was also investigated as a function of number  
51 of strawberries and package volume at 12°C. A combined model based on Arrhenius equation  
52 and Fick's first law of diffusion for an unpackaged single strawberry and a model based on  
53 degree of filling was developed and validated with packaged strawberries. These models have  
54 potential application towards the selection of optimal moisture control strategies for  
55 strawberries.

56  
57 **Keywords:** Modified atmosphere and humidity packaging, Water loss, Strawberry,  
58 Transpiration, Degree of filling (DOF)

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## 64 **Nomenclature**

65	DOF	Degree of filling
66	MAP	Modified atmosphere packaging
67	MAHP	Modified atmosphere and humidity packaging
68	RH	Relative humidity (%)
69	TR	Transpiration rate
70	RR	Respiration rate
71	VPD	Water vapour pressure deficit
72	TR <sub>m</sub>	Transpiration rate on mass basis (g kg <sup>-1</sup> h <sup>-1</sup> )
73	m <sub>i</sub>	Initial mass of the product (g)
74	m <sub>t</sub>	Product mass (g) at a determined time (t) in hours (h)
75	P <sub>s</sub>	Saturation vapour pressure (kPa)
76	P <sub>a</sub>	Actual vapour pressure (kPa)
77	T	Surrounding temperature (°C)
78	BOPP	Bi-axially oriented polypropylene
79	K <sub>i</sub>	Mass transfer coefficient
80	a <sub>wi</sub>	Water activity of the commodity
81	a <sub>w</sub>	Water activity of the storage air
82	a	Model constant coefficient
83	M <sub>sub</sub>	Mass loss due to substrate
84	TMLR	Total mass loss rate
85	V <sub>product</sub>	Product's volume (mL)
86	V <sub>package</sub>	Package's volume (mL)

87

## 88 **1. Introduction**

89 Modified atmosphere packaging (MAP) systems have been extensively used to reduce  
90 physiological activity of fresh produce by modifying in-package gas composition as well as to  
91 reduce mass loss by maintaining high in-package air humidity (Caleb, Mahajan, Al-Said, &  
92 Opara, 2013a). Most of the packaging materials used for MAP have low water vapour  
93 permeability, and, therefore, the water vapour released by the product due to transpiration  
94 remains trapped inside the package, often leading to undesirable condensation (Bovi, Caleb,  
95 Linke, Rauh, & Mahajan, 2016). Thus, in order to lessen in-package water vapour  
96 condensation it is essential to shift the system design from MAP to modified atmosphere and  
97 humidity packaging (MAHP). The main challenge of MAHP is to reduce condensation while

98 still maintaining produce water loss as low as possible (Rodov, Ben-Yehoshua, Aharoni, &  
99 Cohen, 2010). The design based on MAHP not only takes into account the gas composition  
100 but also the in-package air humidity and moisture control strategies to maintain desirable  
101 relative humidity (RH) and thus reduce condensation (Bovi & Mahajan, 2017).

102 In order to design appropriate MAHP it is essential to understand how much water is released  
103 by the product. Water loss in fresh produce is commonly measured by quantifying the amount  
104 or the mass of water lost per unit of time, the transpiration rate (TR). Many models based on  
105 Fick's first law of diffusion have been proposed to calculate the TR of a wide range of  
106 horticulture products such as strawberry (Sousa-Gallagher et al., 2013), pomegranate arils  
107 (Caleb, Mahajan, Al-Said, & Opara, 2013b), whole mushroom (Mahajan, Oliveira, &  
108 Macedo, 2008), tomatoes (Xanthopoulos, Athanasiou, Lentzou, Boudouvis, & Lambrinos,  
109 2014), and pears (Xanthopoulos, Templalexis, Aleiferis, & Lentzou, 2017). These models are  
110 efficient and valid for single unpackaged products, but their application in a dynamic system  
111 to estimate the TR of packaged products have not yet been tested.

112 Furthermore, the quantity of mass loss over a given period of time has long been accepted as  
113 being the TR of fresh produce. This was based on the assumption that mass loss due to the  
114 oxidative breakdown of organic reserves (substrate loss) and the effects that respiration exerts  
115 on TR, by generating metabolic heat and by supplying additional water that can be lost in  
116 transpiration, are negligible (Shirazi & Cameron, 1993; Xanthopoulos et al., 2017). Recent  
117 studies, however, have pointed out the important role respiration plays on TR of fresh  
118 produce, under water vapour saturated environments which is normally seen in packaged  
119 fresh produce (Bovi, Caleb, Herppich, & Mahajan, 2018). For instance, Mahajan et al. (2016)  
120 developed a model to calculate TR based on respiration rate (RR). The authors calculated this  
121 effect on TR by multiplying RR with a conversion factor of 8.6 obtained from the respiratory  
122 heat and adding it to model of TR calculations based on Fick's first law of diffusion.  
123 Furthermore, the authors indicated that the heat of respiration increased the surface  
124 temperature of fresh mushroom above that of the surrounding air, thereby creating a water  
125 vapour pressure deficit (VPD) that may further drive transpirational water losses. In addition,  
126 Xanthopoulos et al. (2017) developed a model that analyses the contribution of transpiration  
127 and respiration on water loss using pears as a model product. Water loss indirectly resulting  
128 from respiration accounts for 39% of the total water loss as a result of water vapour pressure  
129 deficit at an air temperature of 20 °C and 95% RH.

130 The critical challenge in modelling TR and, consequently, water loss in fresh produce is that  
131 the parameters and/or coefficients of the model are product specific. Similarly, the appropriate  
132 moisture control strategy also needs to be product specific and has to be optimized  
133 considering the transpirational properties of each fruit or vegetable (Bovi, Caleb, Klaus, et al.,  
134 2018). This challenge implies that the respective physiological features of each type of fresh  
135 produce needs to be studied in detail and individually under each different storage condition  
136 and packaging system. In this context, the aim of this work was to develop a model to predict  
137 water loss from packaged fresh produce, with the potential application towards the selection  
138 of optimal moisture control strategies. With this aim, a comprehensive case study was carried  
139 out on the mass loss of packaged and unpackaged strawberries.

## 140 **2. Materials and methods**

### 141 **2.1. Sample preparation**

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

147 CO<sub>2</sub>-based respiration rates (RR) of strawberries were determined by continuously monitoring  
148 rates of CO<sub>2</sub> production by a novel closed-system respirometer previously described by Rux,  
149 Caleb, Geyer, and Mahajan (2017). The respirometer consisted of acrylic glass cuvettes (8.2  
150 L), each fitted with non-dispersive infrared CO<sub>2</sub> sensor (GMP222, Vaisala GmbH, Bonn,  
151 Germany). The RR was calculated as the amount of CO<sub>2</sub> per unit mass of the fruit per unit  
152 time (mg CO<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup>). Measurements were carried out for 6 h at 4, 12 and 20 °C.

### 153 **2.2. Transpiration rate of single unpacked strawberries**

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

162 
$$TR_m = \frac{m_i - m_t}{t \cdot \left(\frac{m_i}{1000}\right)} \quad (1)$$

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

169 
$$VPD = P_s - P_a \quad (2)$$

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

171 
$$P_s = \left[ \exp \left( 52.57633 - \frac{6790.4985}{T+273.16} - 5.02808 \ln T + 273.16 \right) \right] \quad (3)$$

172 
$$P_a = P_s \times RH \quad (4)$$

173 where T is surrounding temperature ( $^{\circ}\text{C}$ ), RH is relative humidity (%), and  $P_s$  and  $P_a$  are given  
 174 in kPa.

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

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

### 186 **2.3. Transpiration measurement of packaged strawberries**

187 Two separate experiments were performed in order to evaluate total mass loss of packaged  
 188 strawberries. In the first experimental set-up, different number of strawberries (1, 3, 6 and 15)  
 189 were placed inside closed polypropylene containers (0.93 l) weighing ( $12.26 \pm 1.73$  g); ( $40.33$   
 190  $\pm 8.80$  g), ( $78.57 \pm 12.78$  g) and ( $215.73 \pm 49.01$  g), respectively. A total of six repetitions  
 191 were carried out and the mass loss of individual strawberries was measured daily using an  
 192 electronic balance. This experimental data was then used to test the hypothesis that different

193 numbers of strawberries packaged in the fixed size of a package (0.93 l) behave differently  
194 than a single strawberry.

195 In the second experiment, the mass loss of fixed amount of strawberries ( $200 \pm 4$  g) placed in  
196 packages with different volumes was evaluated. For this investigation, three different  
197 polypropylene packaging trays were used: a small (0.8 l), a medium (1.4 l), and a large (2.3 l);  
198 and the proportion of strawberry per package size (strawberry volume: package volume) was  
199 1:4, 1:7, and 1:12, respectively. All packages were filled with strawberries and covered with  
200 bi-axially oriented polypropylene (BOPP) Propafilm<sup>TM</sup> RGP25 (25 mm thickness;  
201 permeability rate to O<sub>2</sub>,  $8.5 \times 10^{-12}$  mol m<sup>-2</sup> s<sup>-1</sup> Pa<sup>-1</sup> at 23 °C and 0% RH; water vapour,  $5.7 \times$   
202  $10^{-6}$  mol m<sup>-2</sup> s<sup>-1</sup> Pa<sup>-1</sup> at 23 °C and 85% RH, Innovia Films, Cumbria, UK). The covering film  
203 on the trays was perforated with 6, 5, and 4 micro-perforations of diameter 0.82 mm, for the  
204 small, medium, and large tray, respectively. These perforations were made in order to  
205 maintain the package atmosphere close to air and reduce condensation. Packages were stored  
206 for 5 d at 12 °C and the mass loss of strawberries was measured gravimetrically.

#### 207 **2.4. Model development and experimental validation**

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

213 For the validation of the model based on DOF, strawberries were pre-cooled to the study  
214 temperature of 12 °C for 3 h, and packed (15 strawberries of  $200 \pm 10$  g) in polypropylene  
215 trays (16 x 12 x 5 cm), in the proportion of strawberry and package of 1:4. The trays were  
216 covered with BOPP and perforated with 6 micro-perforations of diameter 0.82 mm. Packages  
217 were stored for 5 d at 12 °C. Headspace gas composition (O<sub>2</sub> and CO<sub>2</sub> concentrations) inside  
218 each package was monitored daily using a CheckMate 3 gas analyser (PBI Dansensor,  
219 Ringsted, Denmark). Mass loss was determined by weighing the strawberries at the beginning  
220 of the experiment and after storage. Five replicates were carried out.

#### 221 **2.5. Statistical analysis**

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

### 226 3. Results and discussion

#### 227 3.1. Transpiration rate of single unpacked strawberry

228 At the lowest RH the TR was highest (Fig.1) because the VPD, i.e. the driving force for  
229 transpiration, was generally highest. Raising RH at 20°C from 76% to 96%, i.e. reducing  
230 VPD by approx. 83% lowered TR by only 43% from 1.28 to 0.73 g kg<sup>-1</sup> h<sup>-1</sup>. Similarly, with  
231 increase in air temperature higher TR was recorded when RH was kept constant. For instance,  
232 with the rise in temperature from 4°C to 20°C at 96% RH the TR increased more than 5 times  
233 (from 0.13 to 0.73 g kg<sup>-1</sup> h<sup>-1</sup>) although VPD increased only approx. threefold from 0.033 kPa  
234 to 0.094 kPa. These results indicate how both temperature and VPD, or less accurately RH,  
235 affect the transpiration. Similar results were found in Sousa-Gallagher, Mahajan, and Mezdad  
236 (2013). In their study the TR for strawberries varied from 0.24 to 1.16 g kg<sup>-1</sup> h<sup>-1</sup> (at 5, 10 and  
237 15 °C and 76, 86 and 96% RH), whereas in the present study TR varied from 0.13 to 1.28 (at  
238 4, 12 and 20°C and same RH).

239 This was further highlighted by a comparison of residual transpiration rates in water vapour  
240 saturated air (100 % RH), which pronouncedly increased 6.5-fold from 0.02 g kg<sup>-1</sup> h<sup>-1</sup> at 4 °C  
241 to 0.13 g kg<sup>-1</sup> h<sup>-1</sup> at 20 °C (Fig. 1). This clearly indicated that there remained a driving force  
242 for transpiration even when the air surrounding the strawberry was water vapour saturated.  
243 The driving force for such water loss resulted from a higher fruit body temperature due to heat  
244 generated by respiration, which was indeed more than five times higher at 20 °C than at 4°C,  
245 from 30.26 to 153.18 mg CO<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup> (Fig. 1). The linear variation of TR as a function of  
246 VPD is shown in Fig. 2. At VPD = 0 kPa (i.e. 100 % RH), there was a residual transpiration  
247 rate of 0.1737, 0.0675 and 0.0057 g kg<sup>-1</sup>h<sup>-1</sup>, at 20, 12 and 4 °C, respectively. This residual TR  
248 resulted from heat of respiration which showed estimated fruit surface temperature of 20.12  
249 °C, 12.07 °C and 4.01 °C.

250 Comparison of the variations of surface temperature of a strawberry and the temperatures of  
251 the surrounding air allows visualisation of the effect of respiratory heat generation on  
252 strawberry mass loss (Fig. 3). Fruit temperature was indeed higher than that of the  
253 surrounding air. This fact implied that the heat of respiration of strawberry increased its  
254 surface temperature. In turn, this temperature difference led to an increase in water vapour  
255 pressure gradient for the mass transfer between the strawberry and its surrounding conditions  
256 and a continuous decline of fruit mass. Therefore, results from this study agree with the  
257 hypothesis that respiratory heat can significantly influence water losses from fresh fruit and  
258 vegetables under water vapour saturated conditions (Chau & Gaffney, 1990; Kang & Lee,  
259 1998). This was also validated by Mahajan et al. (2016) using a mushroom and a spherical

260 evaporation dummy apparatus (Linke, Schlüter, & Geyer, 2008), both stored under water  
261 vapour saturated conditions. The mushroom continuously lost mass while that of the  
262 evaporation sphere remained constant over time.

### 263 **3.2. Transpiration rate as a function of fruit quantity and package volume**

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

272 It is well documented that the surface area available for water vapour diffusion plays an  
273 important role on fresh produce water loss (Sastry, 1985). Similarly, when strawberries are  
274 kept close together their overlapping area reduces the surface available for transpiration and,  
275 therefore, water loss is reduced. Furthermore, the time needed for the package to reach water  
276 vapour saturation is also important since when the saturation point is reached the TR  
277 decreases considerably. Thus, the package headspace plays an indirect, but important, role in  
278 water loss because the smaller the headspace, the quicker water vapour saturation is reached.  
279 The observations recorded on the effects of varying container volumes on total mass loss (Fig.  
280 4b), confirmed the hypothesis that package headspace played a major role on mass loss. When  
281 the headspace was 0.6 l, mass loss was  $0.019 \text{ g kg}^{-1} \text{ h}^{-1}$ ; increasing the free headspace to 2.1 l  
282 (i.e.  $\approx 350\%$ ) the rate of mass loss increased to  $0.035 \text{ g kg}^{-1} \text{ h}^{-1}$  (185 %). Therefore, in order to  
283 minimise mass loss from fresh produce it is important to minimise package headspace.  
284 Overall, these results showed that package headspace played an important role in strawberry  
285 mass loss and, therefore, TR measurements of single strawberries measured in large chambers  
286 with unrestricted surrounding air flow conditions are not realistic to calculate water loss from  
287 packaged fresh produce.

### 288 **3.3. Mathematical models**

#### 289 **3.3.1. Unpackaged strawberries**

290 Transpiration of fresh produce has been well studied with several reports have been published  
291 on mathematical modelling of transpiration rate as a function of extrinsic factors such as

292 temperature, RH and air velocity (Bovi et al., 2016; Mahajan et al., 2008; Sastry &  
293 Buffington, 1983). One such model is described by:

$$294 \quad TR = K_i(a_{wi} - a_w)(1 - e^{-aT}) \quad (6)$$

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

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

$$308 \quad M_{sub} = RR \times \left(\frac{180}{264}\right) \quad (7)$$

309 where,  $M_{sub}$  is the mass loss due to substrate, RR is the respiration rate in  $\text{mg CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$  and  
310 the ratio 180/264 indicates that when glucose is the substrate, 180 g of this sugar is lost for  
311 each 264 g of  $\text{CO}_2$  produced due to respiration reaction. However, this calculation does not  
312 take into consideration air humidity and, therefore, the calculated value of  $M_{sub}$  remained the  
313 same despite different water vapour pressure gradients under varying RH. Nevertheless, the  
314 calculations were performed and compared to the TR of a single unpackaged strawberries at  
315 different RH and temperatures (Fig. 1). The percentage contribution of substrate loss on TR at  
316 RH lower than 96% was between 3 to 20%. This indicated that the water vapour pressure  
317 gradient dominated the transpiration process. However, at saturated humidity (100%) as  
318 normally observed in packaged fresh produce, the contribution of substrate loss on  
319 transpiration rate of strawberry was very high (81 - 223%). It is established that the actual  
320 transpiration rate or mass loss of fresh produce constitutes not only substrate loss but also  
321 moisture loss due to heat of respiration which plays an important role in packaged produce  
322 (Bovi, Caleb, Herppich, et al., 2018; Saltveit, 2004). Therefore, this approach to calculating  
323 water loss based on substrate loss was not valid in the case of packaged fresh produce where

324 RH is very high. Calculation of transpiration rate of packaged fresh produce either based on  
325 water vapour pressure gradient due to increase of surface temperature, heat of respiration,  
326 substrate loss or carbon loss is still unresolved challenge and needs further attention.

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

### 333 **3.3.2. Packaged strawberries**

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

$$336 \quad DOF = \frac{V_{product}}{V_{package}} \times 100 \quad (8)$$

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

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

### 351 **3.4. Experimental validation using packaged strawberries**

352 In-package gas composition varied between 17 - 21% for  $\text{O}_2$  and 0 - 4% for  $\text{CO}_2$  during 5 d of  
353 storage at  $12 \text{ }^{\circ}\text{C}$ . After 2 d of storage, the in-package gas composition of all packages reached  
354 equilibrium-modified atmosphere and it effectively maintained  $\text{O}_2$  and  $\text{CO}_2$  concentrations of

355 17 and 4%, respectively. Almenar, Catala, Hernandez-Muñoz, and Gavara (2009) reported O<sub>2</sub>  
356 concentration of up to 14% for wild strawberries packed in containers covered with  
357 polyethylene terephthalate/polypropylene multilayer films with three micro-perforations  
358 stored at 10 °C for 4 d.

359 Furthermore, results showed that the micro-perforations led to saturated conditions within 1 h  
360 of packaging. This observation can be compared with larger size chamber, 190 l (Fig. 3), with  
361 a single strawberry where it reached the water vapor saturation after 10 h. This reinforced  
362 the hypothesis that lower headspace played a major role on TR as it was directly related to the  
363 time needed for a system to reach water vapour saturation. The TR of packaged strawberries  
364 was  $0.03 \pm 0.001 \text{ g kg}^{-1}\text{h}^{-1}$ . The initial respiration rate of the packaged strawberries was  $33.50$   
365  $\pm 1.45 \text{ mgCO}_2 \text{ kg}^{-1} \text{ h}^{-1}$  and after 5 days of storage it was  $54.12 \pm 0.40 \text{ mgCO}_2 \text{ kg}^{-1} \text{ h}^{-1}$ . Based  
366 on the average respiration rate of day 0 and day 5 ( $43.81 \text{ mgCO}_2 \text{ kg}^{-1} \text{ h}^{-1}$ ), the substrate loss  
367 for packaged strawberries was  $0.03 \text{ g kg}^{-1}\text{h}^{-1}$ . This indicates that the contribution of substrate  
368 loss on actual measured TR was 100%. Therefore, once again this calculation seems not to be  
369 realistic to calculate substrate loss due to respiration.

370 Moreover, the model based on DOF was used to predict mass loss of packaged strawberries  
371 and was then compared with the experimental values (Fig. 7). The predicted mass loss of  
372 strawberries packaged with BOPP film was only 446 mg which was much lower than  
373 experimental value (717 mg). This experimental value of mass consisted of 20 mg  
374 condensation in the tray, 47 mg condensation on the film, and 649 mg transmitted through the  
375 micro-perforated packaging film. This analysis showed that it is possible to use water loss  
376 predictive model, despite large error, to quantify the amount of moisture in the packaged fresh  
377 produce. Such analysis can be used for selection of packaging materials and other active  
378 moisture control strategies for controlling humidity and minimising condensation in packaged  
379 strawberries. This modelling could eliminate the “pack and pray” approach normally adopted  
380 for designing modified atmosphere and modified humidity packaging for respiring fresh  
381 products.

#### 382 **4. Conclusion and future research needs**

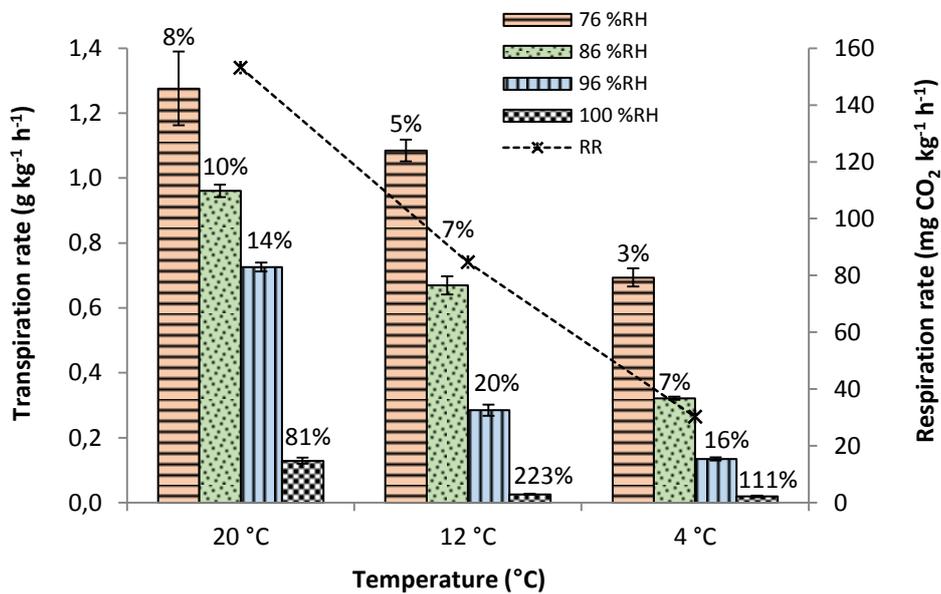
383 A key finding of this study is that headspace plays an important role in mass loss of packaged  
384 strawberries and, therefore, the development of a model based on the DOF seems to be an  
385 alternative to overcome the difficulties of developing water loss predictive models.  
386 Furthermore, the findings of this study raised up some points that should be taken into  
387 account for modelling of water loss, such as the deduction of substrate loss and consideration

388 of the degree of filling. Nevertheless, the question of how to quantify substrate loss in  
389 packaged fresh produce still needs to be addressed.

### 390 Acknowledgement

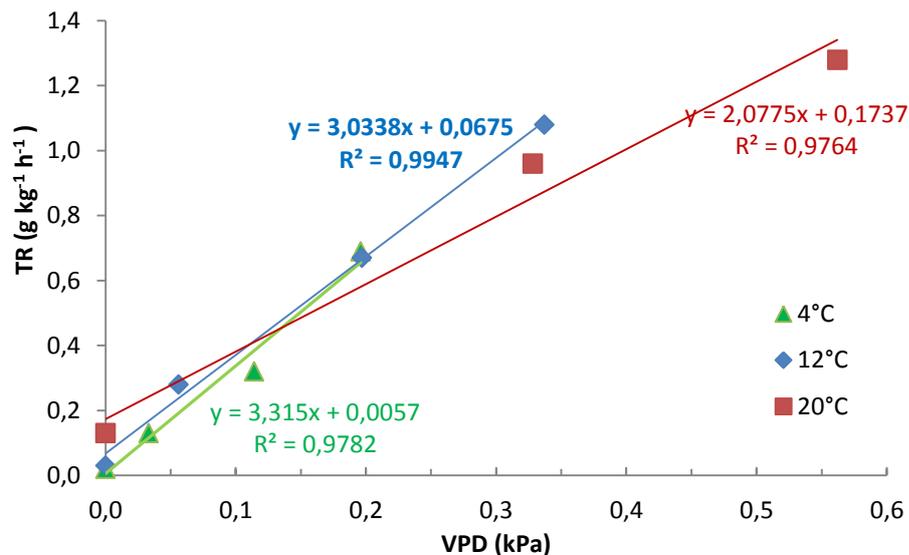
391 This work was supported by Conselho Nacional de Desenvolvimento Científico e  
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393 Research Fellowship (HERMES) programme from the Alexander von Humboldt Foundation  
394 (Ref. ZAF-1160635-GFHERMES-P) is also appreciated.

### 395 List of Figures



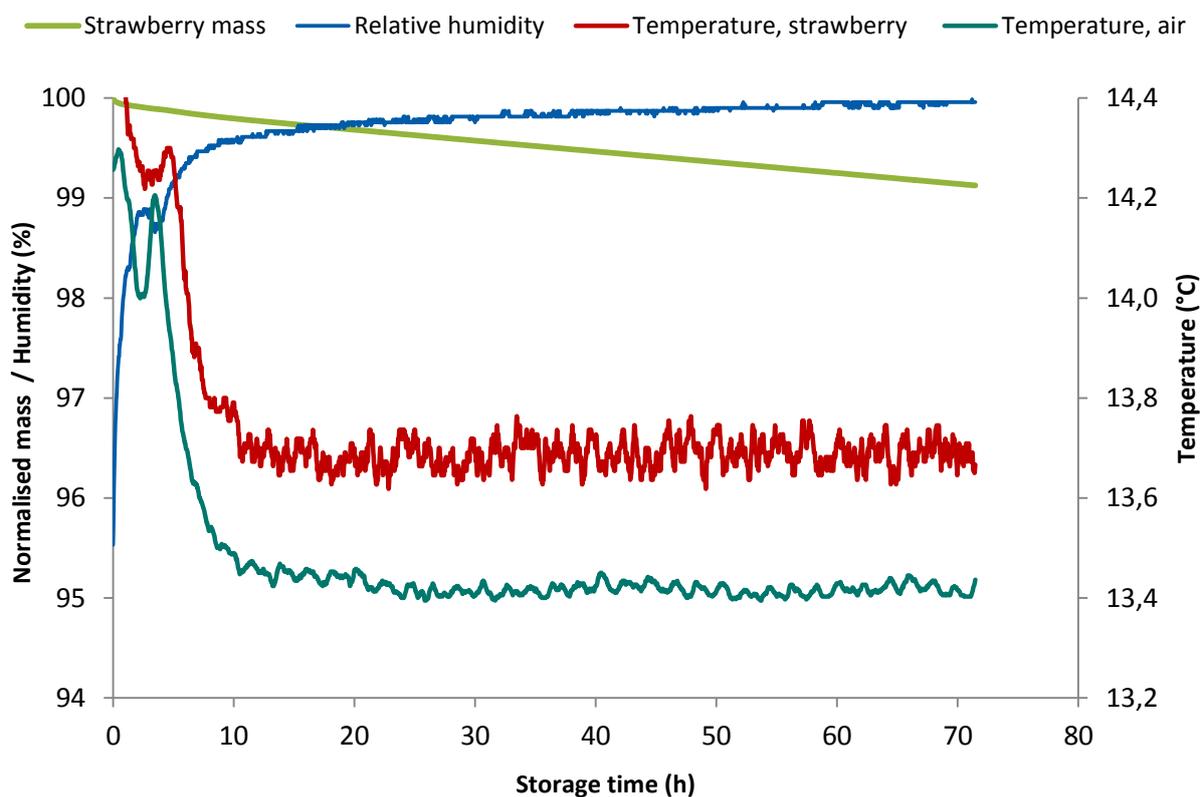
396

397 **Fig. 1** – Transpiration rate of single unpackaged strawberry and respiration rate of  
398 strawberries under different storage conditions. The values on top of the bars represent the  
399 percentage (%) of mass loss due to substrate usage or consumption.



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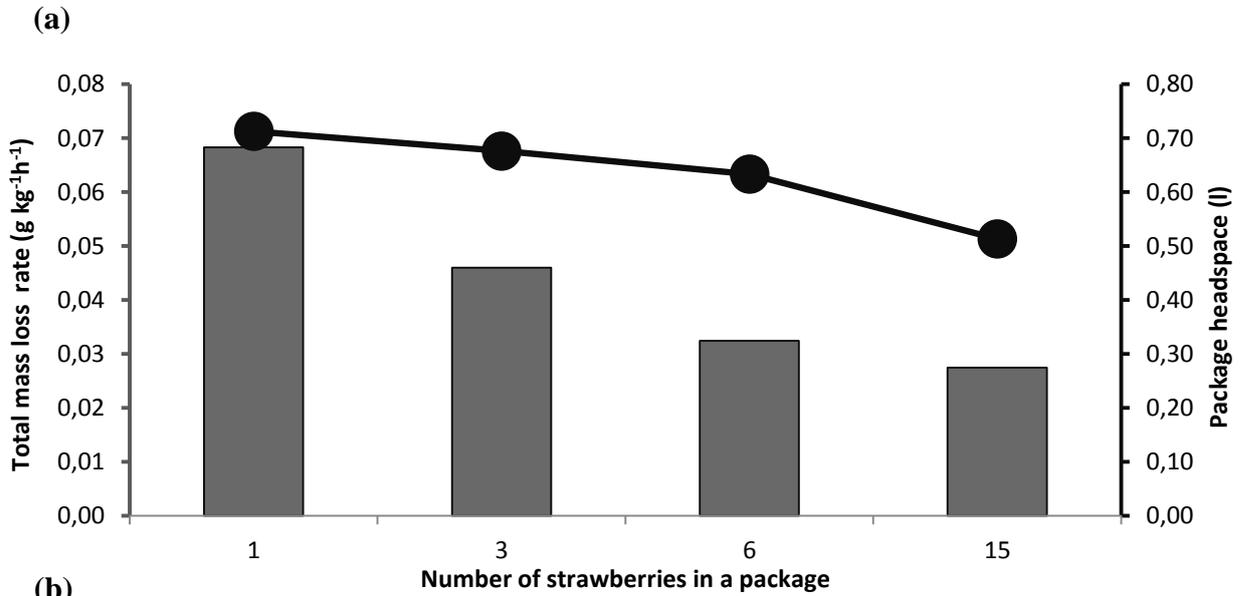
401 **Fig. 2** – Experimentally determined transpiration rates (TR) of single unpackaged strawberry  
 402 versus water vapour pressure deficit (VPD).



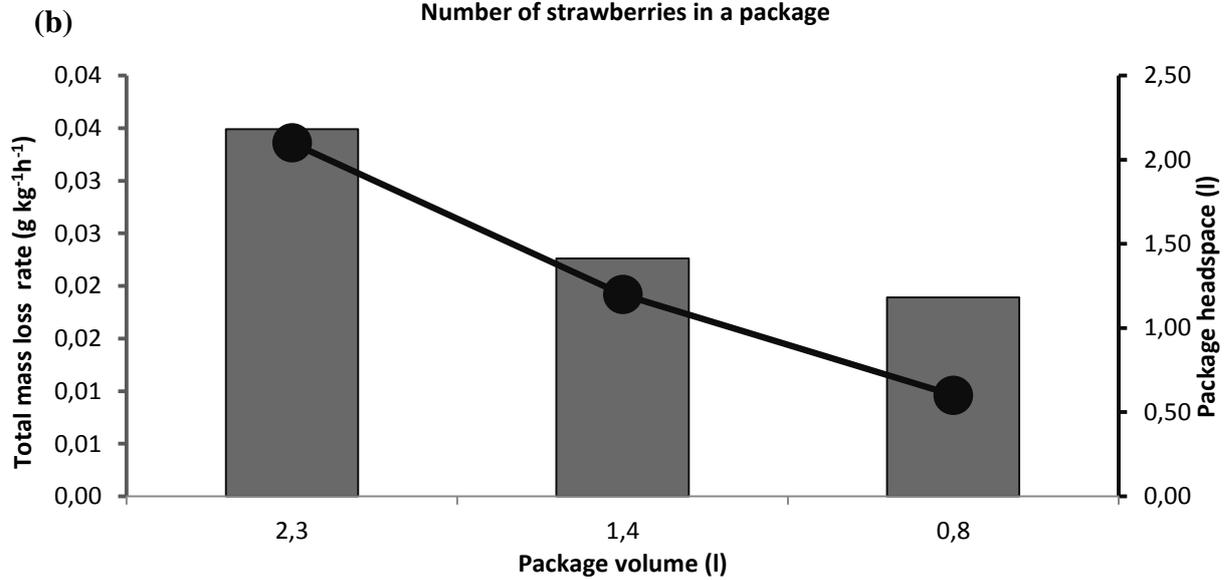
403

404 **Fig. 3** – Impact of relative humidity on surface temperature and associated mass loss of a  
 405 single strawberry.

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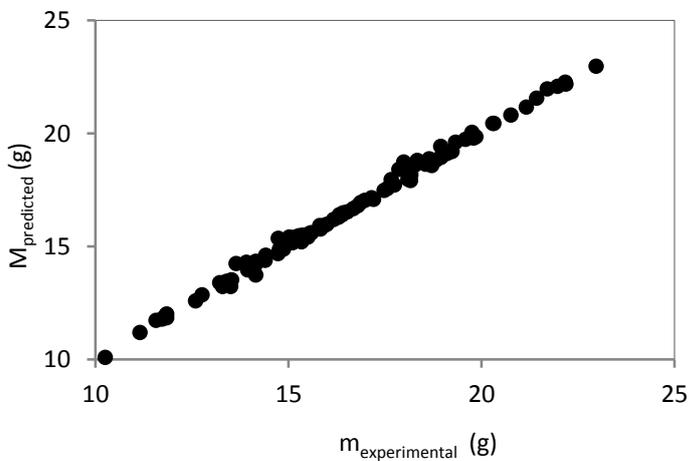


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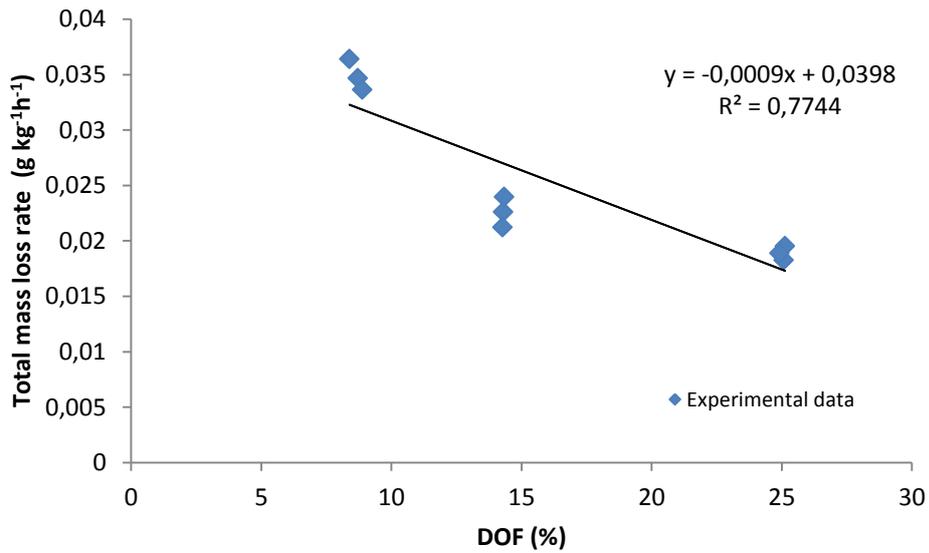
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409 **Fig. 4** – Effect of (a) number of packaged strawberries on total mass loss and (b) container  
 410 volume on total mass loss of strawberries. The bars represent the total mass loss rate (g kg<sup>-1</sup>h<sup>-1</sup>)  
 411 whereas the dots represent the package headspace (l).



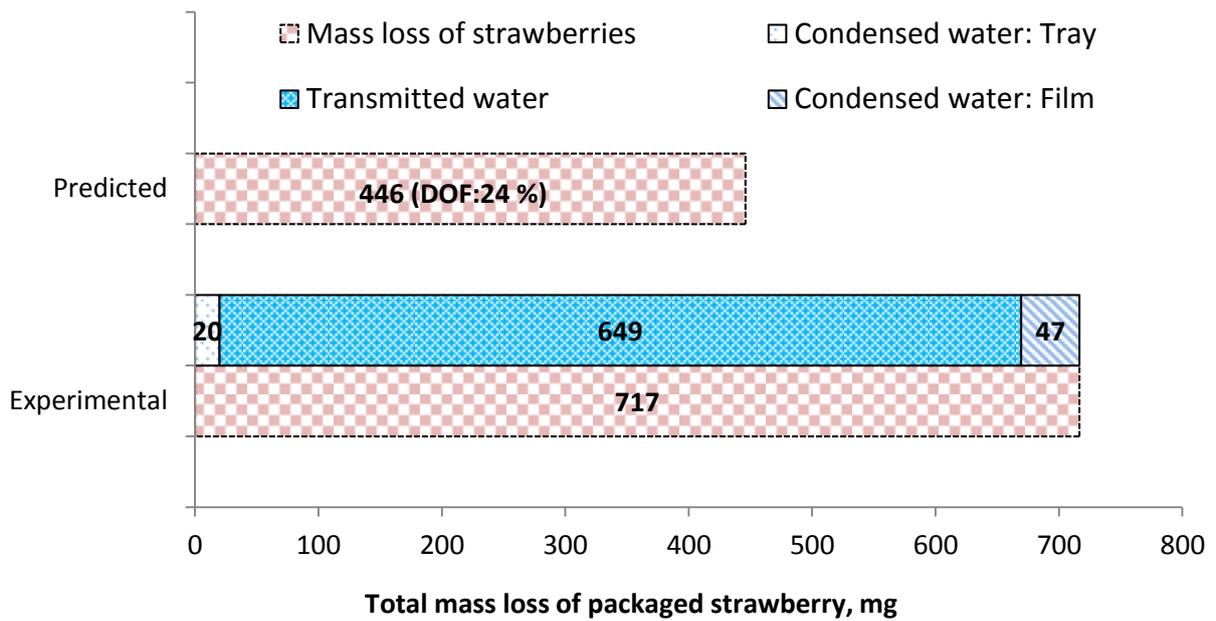
412

413 **Fig. 5** – Description of changes in strawberry mass (g) for predicted versus experimental data,  
 414 and the model parameters.



415

416 **Fig. 6** – Total mass loss rate of strawberry packaged in containers of different volumes and  
 417 proposed model based on percentage degree of filling (DOF).



418

419 **Fig. 7** – Experimental distribution of total mass loss in packaged strawberries after 5 d at  
 420 storage and the predicted value of total mass loss at 24% degree of filling (DOF) at 12 °C.

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