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Air speed and plastic crate vent-holes for wine grape quality during postharvest dehydration: commercial and laboratory studies

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Abstract

BACKGROUND: Airflow is an important issue to favor postharvest dehydration keeping wine grape quality. The aim of this experimental work was to analyze the grape quality during postharvest dehydration: (i) in a commercial facility ('fruttaia') by monitoring the efficiency of the ventilation system and (ii) at laboratory level, studying the influence of crate type and airflow direction.

RESULTS: In the fruttaia, the airflow was provided by an air duct hanging from the ceiling, and by floor fans. A great gap in air speed from 0 up to 3.7 m s^{-1} was measured in different sectors of the fruttaia, leading to a different weight loss and grape quality in crates, depending on crate stack height and sector. At the laboratory level, two tunnels, with exhaust or supply fans, were used and four crate types with different percentages of vent-holes were adopted. A decrease of about 5% delayed the weight loss rate depending on the type of crate, and the exhaust fan guaranteed a faster dehydration.

CONCLUSION: The results clarified the inefficiency of the commercial ventilation system in ensuring homogeneous grape weight loss in all crates. In addition, the exhaust fan guaranteed a more uniform air distribution around crates, and a slightly higher air speed.

Keywords: air speed; exhaust fan; supply fan; postharvest dehydration; wine grape

INTRODUCTION

Airflow, temperature and relative humidity (RH) are the main parameters to favor water loss from wine grapes in the production of wine from grape dehydration and withering. If the effect of temperature and RH on dehydration,[1-11] and the related vapor pressure deficit,[12,13] have been extensively investigated, scarce is research on the airflow surrounding grapes during the postharvest water loss process. It has been shown that an increase of air speed at low temperature on grape berry during dehydration has the same effect on berry texture as the dehydration at higher temperature.[14-16] In fluid dynamics, the Reynolds number explains the difference between a laminar and a turbulent flow[17]: the higher the number the more turbulent is the airflow, and it is positively related to flow speed and inversely related to air viscosity and air density. When grape clusters in crates are invested by an airflow, the air turbulence depends on air speed but the contact between air and berries is affected by crate vent-holes (number, size, position, shape), grape cluster position in the crate and grape cluster compactness. Unfortunately, in huge (500–1000 tons) grape withering facilities but also in smaller size (10–20 tons) ones, floor fans are used to guarantee air distribution everywhere, overall at ground level, but these fans provide an uneven air distribution, provoking different grape water loss values, depending on the proximity of the grape crates to the fan (air speed investing the grape crate is more than 2 m s^{-1} close to the fan, but it becomes almost 0, 10 m away).[18]

In this paper we report the data of research carried out to study the air distribution in the wine grape dehydration/withering process: first of all checking air speed, temperature and RH in a commercial facility with controlled thermohygrometric ambient parameters, and analyzing the effect on wine grape quality (sugars, polyphenols, anthocyanins); then, at the laboratory level, we studied the best air supply (exhaust or supply fans) for grape dehydration by using, also, different perforated plastic crates. Both experiments were done to validate our hypothesis coming from several-year experiences in the field: airflow affecting temperature and RH distribution influences the grape quality by the end of the dehydration period. No paper has been found on this topic (design of vent-holes of plastic crates, air distribution). We

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have found a recent review by Mukama et al.[19] on design and performance evaluation, mainly of cardboard boxes, of fresh fruit ventilated distribution packaging. In that case, the number and the shape of the vent-holes had the aim of preserving fruit and vegetables from water loss, while in our case, we had to find the best condition to facilitate grape water loss at a desired rate.[20]

MATERIALS AND METHODS

Equipment and procedure

The first experiment was performed in a commercial facility ('fruttaia'), a brand new one of 15 m × 6 m × 7 m (length, width, height) built by the company Sordato srl (Verona, Italy) in the Winery Cooperativa dei Vignaioli del Morellino di Scansano (Scansano, GR, Italy) (Fig. 1).

It consists of insulated (10 cm thick polyurethane foam) walls, roof and floor with a cooling plant to guarantee a range of temperature between 0 and 25 °C, and a dehumidifier to reduce RH. The air distribution system includes a plenum (double wall) for air distribution, made by a sandwich panel, consisting of rigid polyisocyanate foam 20 mm thick and coated with aluminium, a perforated duct hanging from the ceiling on one side of the fruttaia for air distribution inside the fruttaia, made with perforated synthetic fabric, and hooked to the ceiling. Cooling plant is outside and only a fan and the duct are inside. Warm, humid air is sucked in from the lower part of the back wall. To improve the air distribution through the grape crate pallets, four fans (1.4 m in diameter, 0.75 kW h^{-1} and airflow of 3000 m^3 h^{-1} each) were placed on the floor (Fig. 2). Sordato Kinesis software permitted the automatic management of ambient parameters during the grape dehydration process. Perforated plastic crates (60 cm × 40 cm ×15 cm) were filled with Sangiovese and Ciliegiolo grape varieties (*Vitis vinifera* L.). Each crate contained about 10 kg of clusters, and 8 crates formed the first layer over a pallet (120 cm × 120 cm) and 10 layers were the final stack; on the top of this stack, another 10 layers of crates were placed, creating a column with 160 crates (plateau). The height of the stack was 3.5 m.

Sangiovese grapes were harvested at 24 ± 2 °Brix (refractometric index), 2720 ± 120 mg L^{-1} (total polyphenols), 380 ± 50 mg L^{-1} (total anthocyanins). Ciliegiolo grapes were harvested at 25 ± 2 °Brix, 3120 ± 220 mg L^{-1} (total polyphenols), 560 ± 60 mg L^{-1} (total anthocyanins). To monitor the air distribution through the clusters in the crates during dehydration, air speed was measured by a commercial fan anemometer (Lutron LM-8000, Coopersburg, PA, USA) and also temperature and RH were measured by the same instrument; the measurements were taken just above the grape cluster, between two crates placed one over the other. The accuracy of the instrument is not high, but, for our purposes, because of the expected great variation according to our knowledge, was acceptable. Twenty-four clusters selected from crates placed in four different pallets which were located at different heights (1 and 3 m), and in different fruttaia sectors, were marked to monitor weight loss and sugar concentration (refractometric index °Brix). All the measurements were taken on the same day chosen for the sampling. The readings were done with the ventilation on, both from the ceiling duct and floor fans. This operation required a couple of hours but guaranteed the repeatability of the response by using the same instrument.

In the second experiment (laboratory level), Gamay grape bunches (*Vitis vinifera* L.) were manually harvested at Fattoria di Calappiano (Sensi Vigne & Vini, Lamporecchio, Italy) and placed in four different types of perforated crates, suitable for the dehydration process (Plastic Box srl, Castagnaro, VR, Italy): black crate = B, gray crate = G, white crate = W, red crate = R, characterized by different shape, and a different number of vent-holes (Fig. 3). To further reduce the number of vent-holes, thus decrease the open space of the crate walls, scotch tape was applied to the crate walls (these crates were named as GT, BT, WT) to close the vent-holes, and the percentage of open space over the total crate surface is reported in Table 1. Scotch tape was not applied to red crate because is built specifically for grape withering by the company and it is the most expensive (for us it was like a control).

Sorted grape clusters for soundness were placed in the crate in one layer (about 6 kg), and stacked in two dehydration tunnels, one with two (one over the other) exhaust fans and the other one with two supply fans (Fig. 4). The size of the metallic tunnel was 1.1 m in width, 0.8 m in height and 2.0 m in length. Each tunnel was filled with 4 crates of each type, with a total of 16 crates. Inside the tunnels, sensors made by DIBAF (University of Tuscia, Viterbo) were set up for daily monitoring of temperature and RH; an anemometer (Lutron LM-8000, Coopersburg, PA, USA) measured the air speed in and out of the tunnel. The tunnels were placed in a room (12 m × 6 m× 3 m) without temperature and RH

Figure 1. External and internal views of the new commercial fruttaia where the air distribution was studied. In the right-hand picture, the white perforated air duct hanging from the ceiling is shown.

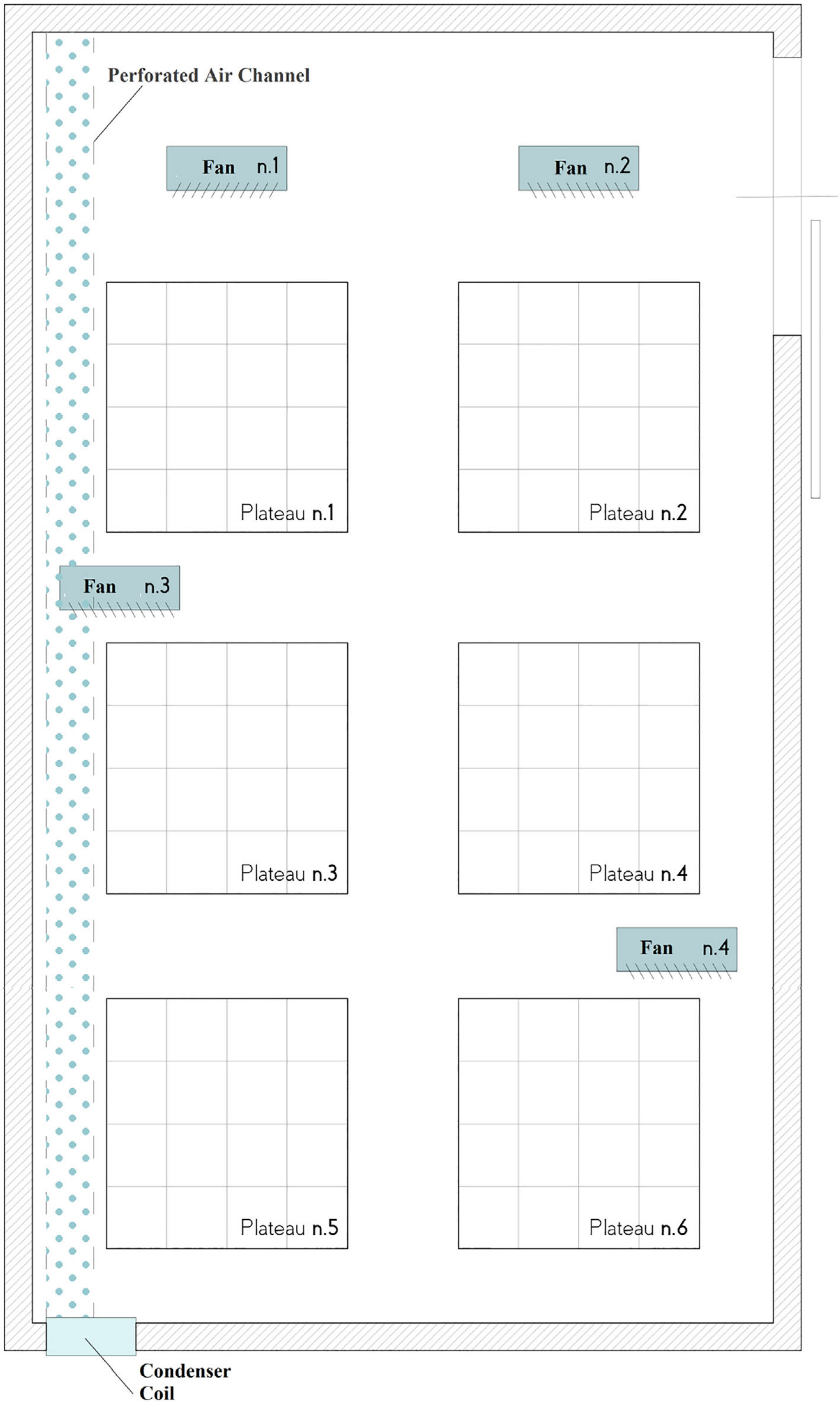

Figure 2. Top view of the fruttaia with grape crate pallet tower (plateau), coil, perforated air duct (channel) and fans. Each square represents a column of two pallets, one over the other, each one with 80 crates as shown in Fig. 1.

control, with closed window and door which was opened a couple of hours every day during the experiment period. The dehydration process lasted about one month; the crates were weekly moved (back and forth) in the tunnels, to ensure that all the crates received, approximately, similar air speed for the same time period.

Chemical analyses

In the commercial facility experiment, grape berries sampled from clusters close to those marked to measure weight loss (wl) and for refractometric index analyses were hand squeezed, and the must was obtained by means of a juice extractor (JU3701 Frutelia Centrifuge Moulinex, Ecully, France). The extracted must was

Figure 3. Crates used in the experiment, from top-left to bottom-right: white W, gray G, red (red handle) R, black B.

Table 1. Plastic perforated crates used in the experiment with symbol and open space percentage (% vent-hole)

Crate	Symbol	% vent-hole
Gray	G	25.7
Gray taped	GT	21.3
Red	R	25.8
Black	B	24.5
Black taped	BT	20.4
White	W	24.1
White taped	WT	19.8

Figure 4. Dehydration tunnel (front) with the two fans (back) used in the laboratory experiment.

centrifuged (6869 × g for 5 min at 22 °C) and filtered (paper filter, 0.82 μm), and then used for chemical analyses of titratable acidity, total polyphenols and total anthocyanins using the OIV methods as previously reported.[21]

In the laboratory-level experiment, total weight of the grape clusters inside the crates was measured weekly, weighing each crate (analytical scale PCE-BT 2000, PCE Italia srl, Capannori, Italy) and computing wl. At each weighing time, small clusters (pedicel with few berries) from cluster placed in the crates, were cut off by scissor, and berries were hand squeezed, and the must obtained was treated as described above for the commercial experiment. Supernatant was collected and analyzed by a calibrated Fourier transform infrared WineScan™ FT 120 (Foss Analytics, Hillerod, Denmark) to determine the following oenological parameters in triplicate: sugars (g L^{-1} hexoses), pH, titratable acidity (g L^{-1} tartaric acid), volatile acidity (g L^{-1} acetic acid), malic acid (g L^{-1}), tartaric acid (g L^{-1}), citric acid (g L^{-1}), total extract (g L^{-1}), ashes (g L^{-1}), yeast assimilable nitrogen (YAN; g L^{-1}), glycerol (g L^{-1}), gluconic acid (g L^{-1}), total anthocyanins (mg L^{-1} malvidin) and total polyphenols (mg L^{-1} gallic acid). The accuracy of the WineScan™ analyses was validated, periodically, by destructive analyses performed with reference methods (OIV) as previously reported in Bianchi *et al.*[22]

Statistical analysis

One-way ANOVA was run (CoStat, Version 6.451, CoHort Software, Pacific Grove, CA, USA) and Tukey's honestly significant difference test with $P \leq 0.05$ for multiple comparison was used.

RESULTS AND DISCUSSION

Commercial facility

In Fig. 5 (top view), the air speed values in different sectors of the fruttaia are reported. The fans placed on the fruttaia floor pushed air with a speed of about 3.7 m s^{-1} (data not reported). Thus, the plateau in front of fans no. 1 and no. 2 received air at 3.7 m s^{-1} but then the air was split in the left, right and central corridors, thus reducing its speed to 0.3 m s^{-1} (right), 0.5 m s^{-1} (left) and 1.5 m s^{-1} (central). Fan no. 3, placed laterally in the fruttaia between plateau no. 1 and no. 3, received air at 0.3 m s^{-1} and pushed it at 3.0 m s^{-1} to plateau no. 3, and, at the bottom of the fruttaia (plateau no. 5), at 1.8 m s^{-1}. In the left corridor, near plateau no. 4, the air speed was 0 m s^{-1} (the air speed is not really zero but undetectable by our anemometer at a constant rate; measuring with smoke, there was anyway air movement, thus we can assume it was 0.1–0.2 m s^{-1}). Thus fan no. 4 was placed, increasing the air speed to 2.6 m s^{-1} at plateau no. 6. In the central corridor, the presence of laterally placed fans allowed for increasing the air speed from 1.5 to 1.8 m s^{-1} at the bottom of the fruttaia.

It is interesting to emphasize that when the supply floor fan receives air at a very low air speed (below 0.5 m s^{-1}), air pushed from the fan is not at the maximum speed as expected (3.7 m s^{-1}), but the outlet air speed drops, to approximately 1 m s^{-1}. This drop is due to the static pressure of the fan, the portion of the fan pressure needed to overcome friction in the air flow system, and it is calculated by the difference between the inlet and outlet pressure of the fan. Thus, in our case speaking in terms of air speed, as there is an air speed inlet in the fan, the pressure difference is reduced, and thus the air speed.[23]

The central corridor had an air speed higher than in the lateral corridors, and this was due to the larger central corridor which drew air from both fans, thus increasing the air speed. In the lateral corridor, fruttaia wall friction must be considered which depends, essentially, on the Reynolds number in the case of laminar flow but, in our case, a turbulent flow must be taken into account, and thus the friction factor is affected not only by Reynolds number but also by the roughness of the surfaces invested by air.[17]

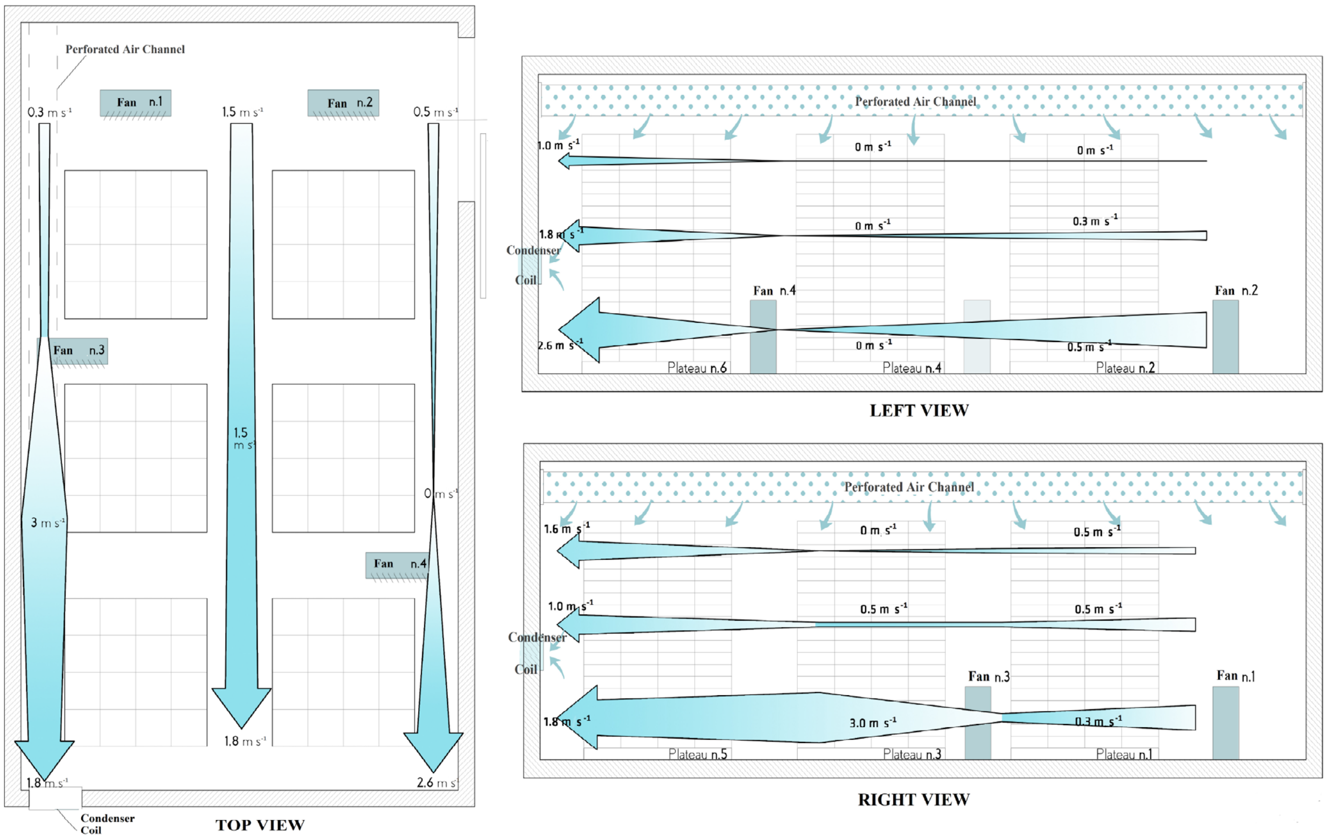

Figure 5. Top view (left) and longitudinal views (right; left and right corridor) of the fruttaia. Blue arrows indicate the air movement in the fruttaia. The size of arrows is approximately related to the air speed. The numbers above or in the arrows refer to the air speed.

Observing in Fig. 5 (right and left views), the air speed measured at different heights (about 1 and 3 m high) in the left and right corridors of the fruttaia showed an insufficient value, 0–0.5 m s^{-1} between plateau no. 1 and no. 3, despite the proximity of the cold air coming from the perforated air duct hanging from the ceiling on the right side of the fruttaia. Even worse was the situation in the corridor far from the duct (left corridor), between plateau no. 2 and no. 4. In contrast, the positive effect of the cold air coming from the perforated duct is demonstrated by the air speed at the back wall of the fruttaia (on the left-hand side of the top view in Fig. 5): the air speed was 1.0 and 1.6 m s^{-1} in the left and right corridor, respectively. This result reveals that the air coming from the perforated air duct is insufficient, and only at the beginning of the duct, close to the coil, provides enough air speed due to the high outlet static pressure of the fan. The presence of floor supply fans improves air speed only at floor level as discussed above. Air temperature surrounding the grape clusters depended on air speed and was higher where air speed was lower, 0–0.5 m s^{-1} (Table 2).

RH varied significantly ranging from 60% up to 80% in the different sectors of the fruttaia but without a clear pattern. This unfortunately is a common commercial situation in fruttaia. Running a regression between temperature and air speed measured in the fruttaia, a logarithmic decrease of temperature around the clusters with an increase of air speed is noted and, as a consequence, a rising logarithmic line is observable in the regression between air speed and wl (Fig. 6). It might seem strange to make a regression between temperature and air speed but, in reality, in the dehydration situation where moisture is also involved, the higher the air flow the greater the moisture removed (we are not in the fog space of the psychrometric chart), so this allows cold air to come into contact with the cluster, lowering the temperature. These results confirm the importance of the air speed on levelling the temperature in the fruttaia and, consequently, on grape cluster wl.

An air velocity limit threshold, beyond which wl occurs with a similar intensity, was identified, and was about 1.5 m s^{-1}; whereas, with an air speed below 0.5 m s^{-1}, wl of grape clusters was similar to that of clusters in crates where air speed was not detected. The wl daily rate (percentage wl/20 days from Table 2) ranged between about 0.6% and 1.0% with a distribution of 9 samples ≥0.8% per day, 11 samples between about 0.6 and 0.8, and 4 samples below 0.6, thus an extreme heterogeneity.

As regards grape quality, sugar content was closely related to wl (meaning that the values were greater where the wl was also greater), as expected due to a concentration effect, and it was positively related with the air speed, as expected, because it facilitates wl (Table 2). Also, in the case of total polyphenols and total anthocyanins, the higher the wl, the greater the concentration. Anyway, a variability was measured probably due to the fact that phenolic as well as aroma compounds (here not measured) are either concentrated or produced[16,24,25] when water loss occurs, depending on the ambient condition.[13] As concerns sugar concentration, it is highlighted that the SD varies with air speed: the lower the air speed, the greater the SD. This finding is important because it entails the need of high air speed to have more uniform ambient conditions in the whole room volume, but excessive air speed accelerates wl too much, and this event, in most of cases

Table 2. Air parameters, weight loss and grape quality in different positions of commercial facility (fruttaia)

Air speed (m s^{-1})	Plateau number, position	Temperature (°C)	Weight loss (%)	Sugar (°Brix)	Total polyphenols (mg L^{-1} gallic acid)	Total anthocyanins (mg L^{-1} malvidin)
3.7	1, low	10 ± 1	17.5 ± 0.5 a	30.1 ± 0.7 a	3280 ± 71 a	749 ± 32 a
0.5	1, high	12 ± 1	13.0 ± 1.0 b	27.7 ± 1.5 b	3008 ± 152 b	620 ± 43 b
3.7	2, low	10 ± 1	15.5 ± 0.5 a	30.2 ± 0.3 a	3340 ± 99 a	477 ± 38 a
0–0.5	2, high	12 ± 2	13.0 ± 1.0 b	27.9 ± 2.1 b	2980 ± 110 b	350 ± 48 b
3	3, low	10 ± 1	15.5 ± 0.5 a	30.0 ± 0.1 a	5009 ± 109 a	761 ± 54 a
0	3, high	13 ± 2	12.5 ± 0.5 b	28.9 ± 0.9 a	4130 ± 99 b	580 ± 26 b
3	4, low	10 ± 1	18.5 ± 0.5 a	31.7 ± 0.2 a	3290 ± 92 a	610 ± 48 a
0	4, high	14 ± 2	11.5 ± 0.5 b	27.5 ± 1.5 b	2960 ± 109 b	480 ± 49 b
1.8	5, low	10 ± 1	17.0 ± 1.0 a	30.8 ± 0.3 a	3980 ± 77 a	560 ± 36 a
1.6	5, high	10 ± 1	15.5 ± 0.5 a	28.7 ± 0.4 b	4029 ± 80 a	530 ± 23 a
2.6	6, low	10 ± 1	19.5 ± 1.0 a	31.6 ± 0.1 a	5050 ± 100 a	890 ± 65 a
1.8	6, high	10 ± 1	17.5 ± 0.5 b	29.8 ± 0.1 b	4960 ± 95 a	820 ± 75 a

Air speed and temperature were measured, during 20 days, among the crates placed on the pallet tower (plateau); low and high refer to the position of the sensor measurement: low = 1 m height, high = 3 m height. Reported wl is at the end of 20 days of dehydration and is the mean (± SD) of two clusters for each crate monitored in the fruttaia, while chemical data are the mean (± SD) of three grape juices from different clusters taken in the same crates used to measure wl. Crates in plateau nos. 3, 5 and 6 were filled with Ciliegiolo grapes; crates in plateau nos. 1, 2 and 4 with Sangiovese grapes. Different letters in the rows of each plateau number (two rows each plateau) refer to significant differences (Tukey, $P \leq 0.05$).

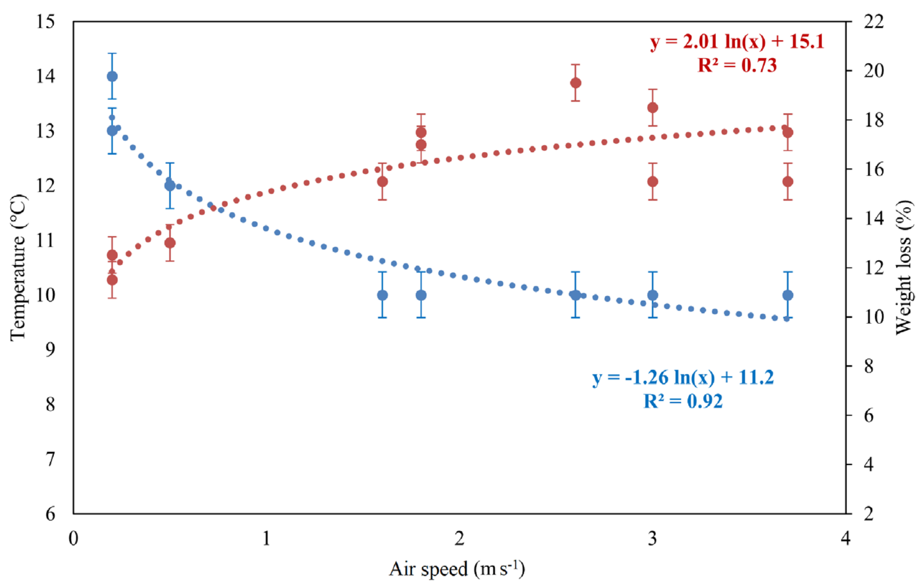

Figure 6. Regression line between temperature and air speed (blue line) and regression line between wl and air speed (red line). Temperature was set at 10 °C and RH at 70% but with great variations in the fruttaia.

when fruttaia is used, is not appreciated because a withering and not a dehydration process is required, where wl and cell senescence occur slowly.[20] Accordini[18] previously reported the inefficiency of the actual system of ventilation used in fruttaia in Valpolicella, similar to the one here reported.

Laboratory level

In the laboratory experiment, the pattern of temperature and RH recorded during the dehydration test is shown in Fig. 7. Approximately, no difference in both parameters between the two tunnels was measured and this was our need.

Temperatures decreased from 23 to 24 °C down to around 18 °C, and RH rose initially from about 65% up to 75%, and successively decreased, oscillating between 53% and 65%. Despite the variation in temperature and RH, the grape wl pattern rose, uniformly, in all the plastic crates, but differently depending on the crate type (Table 3).

Grapes in B and BT crates kept in the exhaust tunnel lost water at a greater rate than those in the supply tunnel, 13% and 7%, respectively; wl difference between the two crates B and BT was about 8% and 6% in exhaust and supply tunnels, respectively (Table 3). The G crates showed a wl difference between the two tunnels like B crates, and there was a significant difference between G and GT (Table 3); the final wl was similar to that the other crates. The white crate (W and WT) showed, in the end, a minimal difference between the crates in exhaust and supply tunnels (Table 3), the value of difference between W and WT in both tunnels being 6–7%. The R crate showed the highest difference in wl between the two tunnels, about 8%. In this case, we recall, no adhesive tape was applied. The percentage of vent-holes in the G crate is similar to that in the R crate (25.7% *versus* 25.8%) but it is higher than in the B and the W crates (this latter with similar shape to the G crate except for wider vent-holes on the walls; see Fig. 3). Despite the similarity in percentage of vent-holes between R and G crates, the grape wl in the two tunnels is double in R than in G. This is due to the crate type, characterized by lower wall height and shaped walls (Fig. 3). Referring to the study on fruit packaging, fresh fruit packages are designed with vent-holes that enhance the rate of removal of field and respiration heat from the produce.[26,27] As we explained above, in our case vent-hole number and distribution are required to facilitate water loss.

A recent study by Curto *et al.*[28] reported that fewer, larger and strategically distributed vent-holes allow a better result in terms of temperature homogeneity inside the box and significant reduction in fruit cooling times. Comparatively, we can assume that the same issue occurs for wine grape ventilation in fruttaia but, as mentioned above, in the case of wine grape dehydration, it depends how fast a process is required; thus, the choice of crate is important.

We have observed that the supply tunnel, in all the crates but G, delayed grape cluster wl. The measured air speed among the crates was 0.9–1.1 m s^{-1} in the exhaust fan tunnel and 0.7–0.9 m s^{-1} in the supply fan tunnel. Since the ambient conditions were similar, this small difference in air speed contributed to a delay in water loss. The reason is that, for each fan, the airflow was 0.5 and 0.4 m^3 s^{-1} in exhaust and supply fans, respectively, which when multiplied by two fans, 1 and 0.8 m^3 s^{-1} invested the grape clusters in the crates, meaning a difference of 200 L each second. The boundary layers around the berry and the rachid are swept 20% more in the exhaust fan tunnel causing faster water loss. Moreover, SD in the supply fan tunnel is always greater than in the exhaust fan tunnel (Table 3); this would

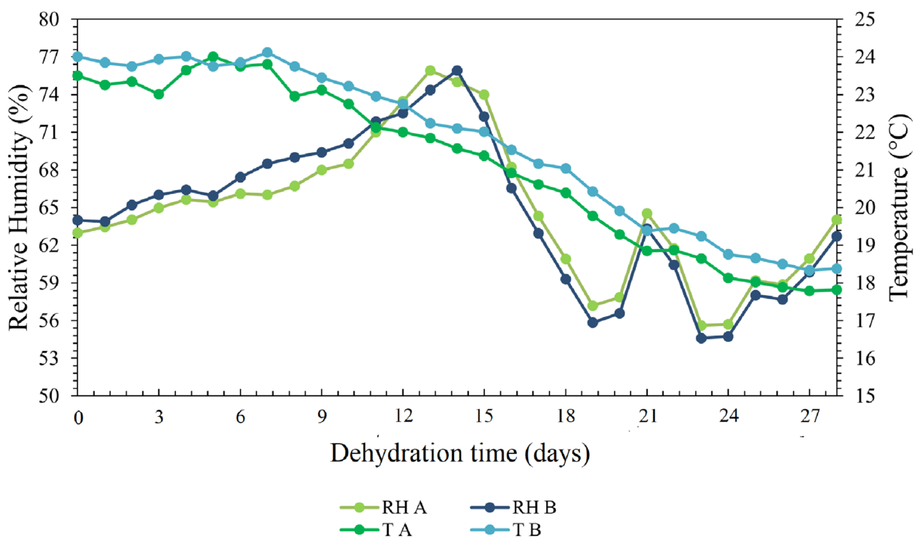

Figure 7. Pattern of temperature and RH recorded during the dehydration test. A, exhaust fan tunnel; B, supply fan tunnel.

Table 3. Weight loss of grapes kept in different types of crates, in the two tunnels, during postharvest dehydration

Crate	Tunnel	Weight loss (%) (*t* = 7 days)	Weight loss (%) (*t* = 14 days)	Weight loss (%) (*t* = 21 days)	Weight loss (%) (*t* = 28 days)
B	Exhaust	13.08 ± 0.50 de	30.66 ± 1.63 a	51.21 ± 2.07 a	64.51 ± 2.98 a
BT	Exhaust	12.66 ± 0.42 ef	25.98 ± 0.32 d	44.26 ± 1.23 cd	56.02 ± 2.04 cd
B	Supply	12.47 ± 0.71 ef	23.76 ± 1.03 fg	41.43 ± 2.43 e	53.51 ± 3.20 de
BT	Supply	11.05 ± 0.76 g	21.74 ± 1.87 g	35.68 ± 2.34 g	48.56 ± 3.08 f
G	Exhaust	12.55 ± 0.39 ef	27.97 ± 1.00 bc	51.20 ± 2.09 a	63.38 ± 3.02 a
GT	Exhaust	11.46 ± 0.52 g	24.30 ± 2.01 e	44.03 ± 2.45 cd	55.39 ± 3.16 cd
G	Supply	11.41 ± 0.43 g	25.25 ± 1.54 de	43.82 ± 2.78 de	59.55 ± 3.30 b
GT	Supply	10.18 ± 0.43 h	22.19 ± 1.89 f	38.73 ± 2.04 f	52.29 ± 2.99 e
W	Exhaust	13.34 ± 0.43 cd	28.96 ± 0.99 ab	48.30 ± 2.01 b	61.75 ± 2.89 ab
WT	Exhaust	12.19 ± 0.70 fg	25.58 ± 1.23 de	41.59 ± 1.80 e	55.04 ± 2.54 cd
W	Supply	13.14 ± 0.54 d	27.30 ± 1.00 c	44.50 ± 1.98 cd	59.88 ± 3.02 b
WT	Supply	10.41 ± 0.67 h	22.42 ± 1.65 fg	37.68 ± 2.90 fg	51.12 ± 2.90 ef
R	Exhaust	14.67 ± 0.76 ab	29.84 ± 0.99 a	50.69 ± 1.78 ab	64.45 ± 2.67 a
R	Supply	13.43 ± 0.65 bcd	27.69 ± 1.28 bc	43.53 ± 2.05 de	56.66 ± 3.10 c

In crate column, T indicates the presence of scotch tape on the crate walls. The values are the mean (± SD) of four crates. Different letters in each column refer to significant differences (Tukey, $P \leq 0.05$).

Table 4. Enochemical parameters of grapes dehydrated in supply or exhaust tunnel

Parameter	t = 0 days	t = 7 days		t = 14 days		t = 21 days		t = 28 days	
	Harvest	Exhaust	Supply	Exhaust	Supply	Exhaust	Supply	Exhaust	Supply
Sugars (g L^{-1})	214 ± 5 h	247 ± 7 f	236 ± 3 g	300 ± 2 e	291 ± 7 e	403 ± 2 c	375 ± 6 d	465 ± 4 a	435 ± 3 b
pH	3.47 ± 0.03 c	3.46 ± 0.01 c	3.55 ± 0.02 b	3.67 ± 0.03 a	3.58 ± 0.02 b	3.53 ± 0.03 b	3.64 ± 0.04 a	3.65 ± 0.03 a	3.58 ± 0.02 b
Titratable acidity (g L^{-1} tartaric acid)	7.17 ± 0.17 b	6.69 ± 0.12 cd	6.57 ± 0.11 d	6.89 ± 0.18 c	6.74 ± 0.15 c	7.02 ± 0.13 b	6.94 ± 0.14 c	7.64 ± 0.22 a	7.17 ± 0.15 b
Volatile acidity (g L^{-1} acetic acid)	0.07 ± 0.02 e	0.15 ± 0.04 d	0.13 ± 0.06 d	0.22 ± 0.03 c	0.19 ± 0.04 c	0.33 ± 0.03 b	0.31 ± 0.06 b	0.63 ± 0.03 a	0.53 ± 0.08 a
Malic acid (g L^{-1})	1.70 ± 0.04b	1.17 ± 0.05e	1.45 ± 0.06c	0.89 ± 0.04 f	1.08 ± 0.06e	1.45 ± 0.05c	1.32 ± 0.07d	1.97 ± 0.04 a	1.86 ± 0.08 a
Gluconic acid (g L^{-1})	n.d.	0.62 ± 0.07 f	1.12 ± 0.09 e	1.74 ± 0.08 d	1.33 ± 0.07 e	4.22 ± 0.08 b	3.94 ± 0.08 c	6.16 ± 0.12 a	4.85 ± 0.10 b
Glycerol (g L^{-1})	n.d.	1.52 ± 0.12 f	2.32 ± 0.13 e	3.53 ± 0.17 d	3.36 ± 0.09 d	7.82 ± 0.12 c	7.53 ± 0.13 c	9.87 ± 0.26 a	9.02 ± 0.18 b
Total extract (g L^{-1})	255.6 ± 0.6 e	275.5 ± 0.9 d	274.3 ± 0.47 d	319.3 ± 0.8 c	309.4 ± 0.7 c	423.9 ± 0.9 b	402.1 ± 0.7 b	493.1 ± 0.7 6a	467.4 ± 0.7 ab
YAN (mg L^{-1})	253 ± 5 f	222 ± 8 g	274 ± 10 e	260 ± 9 ef	345 ± 12 d	333 ± 13 d	398 ± 9 c	480 ± 15 b	561 ± 8 a
Total anthocyanins (mg L^{-1} malvidin)	1712 ± 55 f	1878 ± 75 e	1763 ± 60 f	2144 ± 66 d	1932 ± 83 e	2339 ± 86 c	2294 ± 88 c	3142 ± 78 a	2933 ± 94 b
Total polyphenols (mg L^{-1} gallic acid)	3225 ± 102 f	3318 ± 88 f	3214 ± 129 f	3969 ± 98 e	3891 ± 74 e	4717 ± 136 c	4571 ± 108 d	5651 ± 90 a	5412 ± 106 b

Values for each tunnel are the mean (± SD) of grape juices sampled from four crates. Different letters in each row refer to significant differences (Tukey, $P \leq 0.05$). n.d., not detected.

indicate that the exhaust fan guarantees a more uniform wl, because of the laminar airflow.

In conclusion, if using an exhaust ventilation system would be better to make uniform ambient conditions[29] most of the commercial fruttaie work with a supply air system and to address the uneven air distribution, floor fans are used with the result of increasing the ambient condition variation. An efficient technique would be a concurrent supply and exhaust ventilation which has been seen to perform better than an exhaust-only system in controlling carbon monoxide in parking lots.[30] In Italy, a supply air distribution for grape dehydration has been proposed where the flow direction is inverted, from right to left passing through grape crates and from left to right.[31]

The final compound concentration was strictly related to the concentration effect: in the exhaust tunnel, wl was higher than in the supply one (Table 4). The rate of sugar increase was similar in the two tunnels, 4.2–4.4 g L^{-1}/% wl, and, also, the rate of polyphenol increase, 44 and 40 mg L^{-1}/% wl, in supply and exhaust tunnels, respectively. The values of malic acid confirmed what was observed by D'Onofrio *et al*.[32] with an initial decrease due to respiration and then an increase by the concentration effect. Volatile acidity increased at a low rate with wl, until the time to reach 25–28% wl, while, successively, the rate greatly increased, and, at the end, it was higher in the exhaust tunnel than in the supply one, due to the greater wl. The first observed increase in volatile acidity is a physiological response, already observed, due to water loss[2] but, in the last step, the concentration effect contributes to the significant rise. This physiological response of volatile acidity is confirmed by the glycerol increase, indicating a high rate of glyceropyruvic metabolism,[2] while the low level of gluconic acid indicates that microorganism contamination was absent.

CONCLUSIONS

If air distribution has been considered of little influence to date, commercially it is known that the correct positioning and sizing of fans, the direction of the outlet and intake flow, the maximum stacking height, the different flow penetration depending on the crate characteristics and the analysis of the moisture pockets in the fruttaia substantially improve the dehydration management, because of a better knowledge of the process.[18] The results of this research clarify the importance of the uniform distribution of air inside a commercial fruttaia to guarantee a homogeneous wl in all the crates and, thus, similar grape quality in all the sectors of the fruttaia. The actual system with a ceiling perforated air duct, if it is not assisted by floor fans, as we have shown, is completely inefficient. Anyway, we have demonstrated, finally, that the presence of the floor fans does not guarantee that all the stacked crates receive enough ventilation. An air speed of at least between 0.5 and 1 m s^{-1} is required to reach the goal of uniformity and 0.5 m s^{-1} is not enough. In the laboratory experiment, we have demonstrated how important is the crate type and its characteristics such as wall height and shape, number of vent-holes and thus the percentage of open space. The choice of crate will depend on how fast a process is needed, and in the case of a fruttaia without an accurate thermohygrometric ambient control, the choice can make a difference. Finally, exhaust or supply air system has been always a big question for the dehydration plant for wine grapes. A supply system is easier to construct, but a better efficiency is provided by an exhaust system.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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